HYDROGEOLOGICAL ASSESSMENT OF SURFACE RIVERS AND TRADITIONAL QANAT SYSTEMS FOR AGRICULTURAL WATER SUPPLY IN FUZULI DISTRICT

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Abstract. This study evaluates the surface water hydrochemistry and the physical condition of traditional groundwater *qanat* (karez) systems in the Fuzuli District (Karabakh region, Azerbaijan) to assess their potential for post-liberation agricultural restoration. Field monitoring across seven historic *qanats* established physical parameters, geographic coordinates, annual and seasonal discharge rates, and structural degradation states, identifying key sites requiring maintenance or full structural rehabilitation. Concurrently, physicochemical analysis (restricted to surface waters; the chemistry of qanat water was not assessed) was conducted on two major local surface water bodies, the Kondalanchay and Guruchay rivers, evaluating key parameters including pH, electrical conductivity, total hardness, total dissolved solids (TDS), major cations (Ca^{2+}, Mg^{2+}), major anions (HCO_3^-, Cl^-, SO_4^{2-}), and nutrient levels (NH_4^+, NO_2^-, NO_3^-, PO_4^{3-}). Both rivers exhibited slightly alkaline, moderately hard, fresh water conditions with low nutrient concentrations, complying with national (AZS 929:2023) and international (EU Directive 98/83/EC, WHO) standards for agricultural and domestic use, though the Kondalanchay River showed slightly higher mineralization and nitrate levels than the Guruchay River. The findings demonstrate that combining surface river runoff management with the physical restoration of traditional *qanat* infrastructure provides a sustainable strategy for rural water supply and climate resilience, directly supporting United Nations Sustainable Development Goals (SDGs) 2, 6, 12, 13, and 15.

Key words: hydrogeological assessment; soil management; agricultural impact; qanat systems; Fuzuli District

1. INTRODUCTION

The Fuzuli District covers an area of approximately 1,390 square kilometres, with the city of Fuzuli as its administrative centre. The district is located in the southwestern part of the Republic of Azerbaijan. It borders the Islamic Republic of Iran along the Araz River to the southeast and south, the Jabrayil District to the southwest, the Khojavand District to the west and northwest, the Aghjabadi District to the north, and the Beylagan District to the east (Guliyev *et al.*, 2024; Ministry of Ecology and Natural Resources of the Republic of Azerbaijan, 2022).

The region has favourable conditions for the cultivation of various agricultural crops, including winter wheat, cotton, maize, grapes, fruits, and vegetables. The irrigation requirements of these crops are primarily met by surface water from rivers and groundwater supplied by qanats. The Kondalanchay and Guruchay rivers, together with qanat systems, serve as important and sustainable water resources supporting agricultural activities in the area (Ministry of Ecology and Natural Resources of the Republic of Azerbaijan, 2022).



Fig. 1. Geographic Location of Fuzuli District.

The reliability of these water sources depends on their annual water availability and the stability of flow throughout different seasons. Seasonal fluctuations in river discharge can influence irrigation planning and water supply management, whereas qanats generally provide a more consistent and continuous source of water during the year.

The Fuzuli region is recognized as one of the territories in Azerbaijan with a long history of *qanat* systems. *Qanats* are traditional underground water collection and distribution structures designed to transport groundwater to the surface for various purposes, particularly irrigation and domestic water supply. In the Fuzuli region, these systems were constructed by local communities many centuries ago and served as essential sources of drinking water and agricultural irrigation (Guliyev, 2021).

A *qanat* system generally includes several interconnected components, such as underground water sources (springs and infiltration zones), horizontal tunnels that facilitate water movement, and vertical access points or outlets used for maintenance and water extraction. Throughout history, *qanats* have contributed significantly to agricultural development and sustainable water management, especially in regions characterized by dry and semi-arid climatic conditions (Guliyev, 2016).

This study had two objectives. First, it documented the geographic position, physical condition, seasonal discharge and rehabilitation needs of seven historical *qanat* systems in the Fuzuli region (Table 1). Second, it characterized the hydrochemistry of the two principal surface rivers, the Kondalanchay and Guruchay (Table 2), to assess the suitability of river water for agricultural use following the liberation of Karabakh from occupation. The chemical composition of *qanat* water was not analysed in this study. The investigation and rehabilitation of historical *qanat* systems in the region are of considerable importance for improving water resource management, preserving ecological balance, and understanding the traditional water-use practices of Azerbaijan (Guliyev *et al.*, 2024).

Ensuring the long-term performance and sustainability of drainage infrastructure requires ongoing investment in its maintenance, improvement, and rehabilitation, particularly to cope with extreme climate events. This includes reinforcing underground tunnels and manholes to minimize the risk of structural damage and ground subsidence.

Sustainable water management is considered a fundamental element of environmental protection and the achievement of long-term development goals. This concept goes beyond meeting current water needs and encompasses preserving freshwater ecosystems, maintaining water quality, and ensuring reliable water resources for future generations.

The core principles of this concept include rational use of water resources, pollution prevention, ecosystem protection, integrated management strategies, and the development of adaptive measures in response to climate change. These approaches are reflected in global initiatives such as the United Nations Sustainable Development Goals, particularly SDG 6 ("Clean Water and Sanitation"), which emphasizes the importance of ensuring sustainable access to water while protecting the aquatic environment.

Recent scientific studies on sustainable water management demonstrate that modern approaches increasingly rely on interdisciplinary frameworks that combine environmental, social, and economic perspectives. Current research emphasizes the importance of cooperation among stakeholders, effective governance mechanisms, policy implementation, and the application of the Water–Energy–Food–Ecosystem Nexus approach, which promotes a balanced consideration of different resource demands and ecological requirements.

Furthermore, technological advances in water treatment and water resource recovery, including wastewater reuse, recycling methods, and advanced filtration technologies, have become important tools for improving water security. Such innovations help reduce the exploitation of natural water resources, limit the impact of pollution, and promote sustainable water management. Research in sustainable water resource management highlights the need to develop flexible and adaptive approaches to address the growing pressures caused by climate variability and declining water availability. Research applying participatory assessment methods, including concepts such as DPSIR integrated with the Analytical Hierarchy Process, demonstrates that active stakeholder engagement and continuous assessment of water resource systems can enhance their resilience to environmental change and maintain long-term sustainability, particularly in areas experiencing water scarcity.

Overall, available scientific evidence suggests that sustainable water resources management goes beyond engineering solutions and is a complex task involving

governance, planning, and policy coordination. Successful water resources management requires integrating measures to protect ecosystems, equitable water resource allocation, and socioeconomic considerations to maintain environmental stability and support human development.

2. METHODOLOGY

This study assessed the physical condition of traditional groundwater *qanat* (karez) systems and the surface water hydrochemistry of primary rivers (Kondalanchay and Guruchay) located in the Fuzuli District of the Karabakh region, Azerbaijan. The geographic coordinates (X, Y) and elevations of the study sites were determined and documented using handheld GPS technology to ensure precise spatial identification and facilitate future monitoring.

Field surveys were conducted across seven historic *qanat* systems to document their geographical parameters, structural integrity, operational status, average annual discharge, seasonal flow variations, and recommended maintenance actions (Table 1). Water chemistry was not analysed for the *qanats*; the *qanat* component of the study is therefore limited to the physical and hydrological survey. Physicochemical water quality analyses were carried out only for the two main surface rivers supporting agricultural irrigation in the district (Table 2). The resulting hydrochemical parameters were evaluated by comparison against national regulatory standards (AZS 929:2023 "Drinking water. Hygienic requirements and quality control") and European Directive 98/83/EC (Council of the European Union, 1998).

The national standard AZS 929:2023 was prepared in accordance with the principles of the UN Protocol on Water and Health under the Convention on the Protection and Use of Transboundary Watercourses and International Lakes. Sampling procedures and analytical protocols followed established international frameworks, including ISO 5667-1:2006, ISO 5667-3:2012, ISO 7888:1995, ISO 10523:2008, ISO 7027:1999, ISO 11923:1997, and USEPA guidelines.

River water samples were collected from the Kondalanchay River and the Guruchay River. Samples were collected in specific recipient for testing, preserved, stored and transported in accordance with ISO 5667-3:2012. pH, dissolved oxygen and electrical conductivity were measured in the laboratory.

Table 1. Geographical and physical monitoring characteristics of the investigated qanat systems located in the Fuzuli district (Karabakh region, plain zone of the Lesser Caucasus).

No	Qanat Name	Location / Nearby Landmark	Geographic Coordinates (X, Y)	Elevation (m)	Average Annual Discharge (L/s)	Seasonal Water Flow (L/s)	Current Physical Condition	Recommended Action
1	Namazlı	West of Horadiz village	39°27'09"N, 47°14'06"E	150	12.0	Spring: 3.0; Summer: 3.0; Winter: 0	Operational	No intervention required
2	Topa	Mulberry garden, west of Horadiz	39°27'36"N, 47°13'15"E	800	8.6	Spring: 10; Summer: 10; Winter: 2	Requires maintenance	Rehabilitation recommended
3	Yenicə	Near the cemetery, west of Horadiz	39°27'43"N, 47°13'17"E	200	11.0	Spring: 3.5; Summer: 3.5; Winter: 1.5	Several wells remain open	Repair and secure wells
4	Çinar Bulaq	Central part of Gochahmadli village	39°32'16"N, 47°07'16"E	800	16.0	Spring: 6.0; Summer: 6.0; Winter: 2.0	Degraded condition	Full restoration required
5	Shirlan	West of Gochahmadli village	39°31'58"N, 47°06'25"E	225	12.0	Spring: 5.0; Summer: 5.0; Winter: 1.5	Acceptable	Monitoring recommended
6	Hacı-Şükür	East of Gorazilli, near Fuzuli–Hadrut highway	39°29'53"N, 47°05'25"E	200	10.5	Spring: 13.0; Summer: 13.0; Winter: 4.5	Acceptable	Monitoring and preventive maintenance recommended
7	Bəhbətli	East of Dilagarda village	39°40'41"N, 47°08'58"E	250	10.75	Spring: 1.0; Summer: –; Winter: 0.5	Damaged	Restoration recommended

Table 2. Physicochemical properties of surface water samples.

Parameter	Unit	Kondalanchay River	Guruchay River
pH	–	8.17	8.10
Dissolved oxygen	%	77.60	83.70
Electrical conductivity	µS/cm	56.00	35.40
Total hardness	meq/L	4.50	2.80
Calcium (Ca^{2+})	mg/L	63.40	39.90
Magnesium (Mg^{2+})	mg/L	16.27	10.40
Chloride (Cl^{-})	mg/L	35.70	22.40
Sulfate (SO_4^{2-})	mg/L	142.10	89.70
Bicarbonate (HCO_3^{-})	mg/L	151.53	111.10
Carbonate (CO_3^{2-})	mg/L	0.00	0.00
Ammonium (NH_4^{+})	mg/L	0.16	0.05
Nitrite (NO_2^{-})	mg/L	0.12	0.10
Nitrate (NO_3^{-})	mg/L	4.50	1.40
Orthophosphate (PO_4^{3-})	mg/L	0.02	0.00
Total dissolved solids (TDS)	mg/L	411.97	274.90

Major cations / nutrients and anions were determined by laboratory instruments, (NH_4^{+}, NO_2^{-}, NO_3^{-}, and PO_4^{3-}). Total hardness and TDS were calculated by calculation using measured data. Quality control comprised in comparing results over various samples.

The development of this standard also considered the relevant international guidelines and technical documents, including recommendations of the World Health Organization Regional Office for Europe, Directive (EU) 2020/2184 of the European Parliament and of the Council concerning the quality of water intended for human consumption (European Union, 2020), as well as internationally recognized analytical standards such as ISO 5667-1:2006, ISO 5667-3:2012, ISO 7888:1995, ISO 10523:2008, ISO 7027:1999, ISO 11923:1997, ISO 15705:2002, ISO 5815-1:2023, ISO 8288:1986, SanPiN 2.1.4.1074-02, and USEPA guidelines (Babayeva *et al.*, 2024).

3. RESULTS AND DISCUSSION: QANAT CHARACTERISTICS AND RIVER HYDROCHEMISTRY

The primary agricultural and domestic water resources of the Fuzuli district form a closely coupled hydrologic system comprising the Guruchay River, the Kondalanchay River, and an extensive network of traditional subterranean aqueducts (*qanats* or *karezes*). The Guruchay River (82 km length, 201 km² catchment) is predominantly rain-fed (75–80% pluvial contribution) and shows extreme seasonal discharge variability: peak spring flood flows (65% of total annual runoff; mean annual discharge 1.91 m³/s) exceed average levels by 30 to 35 times before channel flow drops sharply during the July–August baseflow period, often resulting in temporarily dry, *wadi*-like beds. In contrast, the Kondalanchay River (89 km length, 166 km² catchment), which originates from mineralized alpine springs on Chakhmagdag Mountain (1780 m a.s.l.) within the Karabakh volcanic plateau, receives a substantial groundwater baseflow contribution (29% groundwater, 59% rainfall, 12% snowmelt) and maintains a more stable mean discharge of 0.63 m³/s.

As presented in Table 2, both rivers are slightly alkaline (pH 8.10–8.17), a condition driven by atmospheric CO_2 exchange and bicarbonate buffering, and are well oxygenated (dissolved oxygen 77.6–83.7%). Electrical conductivity was low (35.4–56.0 µS/cm), reflecting rapid meteoric runoff and limited rock–water interaction time along steep mountain gradients. The Kondalanchay River was more strongly mineralized than the Guruchay River (TDS 411.97 vs. 274.90 mg/L; Ca^{2+} 63.40 vs. 39.90 mg/L; Mg^{2+} 16.27 vs. 10.40 mg/L; SO_4^{2-} 142.10 vs. 89.70 mg/L), consistent with its mineralized spring source and groundwater contribution. Nutrient concentrations were low in both rivers (NO_3^{-} 1.40–4.50 mg/L; NH_4^{+} 0.05–0.16 mg/L; NO_2^{-} 0.10–0.12 mg/L; PO_4^{3-} 0.00–0.02 mg/L) and were slightly higher in the Kondalanchay River.

All measured parameters were below the parametric values of EU Directive 98/83/EC for nitrate (50 mg/L), nitrite (0.5 mg/L), ammonium (0.5 mg/L), chloride and sulphate (250 mg/L each), and the waters also met the requirements of AZS 929:2023 and the WHO (2017) guidelines. For irrigation, TDS (275–412 mg/L) is below the 450 mg/L level up to which FAO guidelines indicate no restriction on use, and chloride (22.4–35.7 mg/L) and nitrate are far below levels that affect sensitive crops (Ayers and Westcot, 1985). Bicarbonate (111–152 mg/L) falls in the slight-to-moderate range, which

is relevant only for overhead sprinkler irrigation. The sodium adsorption ratio (SAR), which governs infiltration and sodicity hazards, could not be calculated because sodium and potassium were not determined; SAR and percent sodium should be included in future monitoring to complete the irrigation-suitability assessment.

The survey summarized in Table 1 shows that the *qanat* network is in markedly uneven condition. Namazlı is operational but requires intervention, Shirlan and Hacı-Şükür are in acceptable condition, Topa requires maintenance, Yenicə has several open wells, and Çinar Bulaq (degraded) and Bəhbətli (damaged) require full restoration and restoration, respectively. Combined discharge of the surveyed *qanats* was about 41.5 L/s in spring and about 12 L/s in winter; at the six *qanats* with summer measurements, summer discharge equalled spring discharge (about 40.5 L/s combined), in contrast to the sharp summer decline of the Guruchay River. Rehabilitated *qanats* could therefore complement river abstraction during the irrigation season and support integrated surface–groundwater resource management (Guliyev *et al.*, 2024; İslamzade *et al.*, 2025). Because the chemical quality of *qanat* water was not assessed, this conclusion concerns water quantity and structural condition only. As *qanats* are fed by infiltration beneath cultivated land, monitoring of salinity and nitrate at *qanat* outlets is a priority for future work.

4. CONCLUSIONS

This empirical study provides a baseline physical survey and surface hydrochemical characterization of local aquatic resources in the Fuzuli District (Karabakh region, Azerbaijan) to inform post-liberation agricultural restoration and sustainable regional water resource management. Field investigations across seven historical *qanat* (karez) systems established their spatial coordinates, structural integrity, and seasonal discharge dynamics, identifying the maintenance, well-securing and restoration priorities required to return these traditional underground channels to service. Hydrochemical monitoring of the region's primary surface watercourses, the Kondalanchay and Guruchay rivers, showed slightly alkaline (pH 8.10–8.17), fresh, and moderately hard water with low total dissolved solids (TDS < 412 mg/L) and minimal nutrient concentrations (NO_3^- < 4.50 mg/L; PO_4^{3-} ≤ 0.02 mg/L), complying with national (AZS 929:2023) and international (EU Directive 98/83/EC, WHO) guidelines.

These specific empirical metrics directly illustrate how local water resource management can support progress toward targeted United Nations Sustainable Development Goals (SDGs):

- **SDGs 2 (Zero Hunger) & 12 (Responsible Consumption and Production):** Utilizing surface waters with low electrical conductivity (35.4–56.0 µS/cm) and low mineralization limits the risk of secondary soil salinization during crop irrigation, safeguarding long-term soil fertility and agricultural productivity.
- **SDGs 6 (Clean Water and Sanitation) & 15 (Life on Land):** Low baseline concentrations of ammonium, nitrite, nitrate, and orthophosphate indicate negligible agricultural or domestic contamination, preserving stream ecological balance and freshwater biodiversity in the Fuzuli region.
- **SDG 13 (Climate Action):** Rehabilitating gravity-driven, zero-emission *qanat* infrastructure provides a climate-resilient alternative for augmenting agricultural water supplies during low-flow summer periods without requiring energy-intensive pumping.

Although current surface water quality parameters confirm general suitability for regional use, the chemical quality of *qanat* groundwater was not assessed here. Continuous hydrochemical monitoring, including direct sampling of *qanat* waters and the calculation of irrigation suitability indices such as the sodium adsorption ratio (SAR) and percent sodium (%Na), will be vital to ensure comprehensive long-term agricultural safety and aquatic ecosystem conservation in semi-arid environments (Guliyev *et al.*, 2024).

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