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Sustainable agriculture through qanat systems in Karabakh: Water and soil characteristics in the context of climate change

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Abstract

This study investigates the water quality and soil characteristics associated with qanat systems in the Cebrail district of the Karabakh region, Azerbaijan. Qanat systems, traditional underground channels designed for water transport, play a crucial role in providing reliable water sources for drinking and irrigation. Water and soil samples were collected from seven qanat systems and analyzed for various physicochemical properties. Water quality parameters included pH, electrical conductivity, hardness, mineralization, and concentrations of calcium, magnesium, sodium, and other ions. Soil analyses focused on pH, electrical conductivity, organic matter content, salinization degree, and the presence of key ions like sulfate and nitrate. The results indicated that qanat water is generally of high quality, with pH levels suitable for both drinking and irrigation. However, some qanat systems exhibited high electrical conductivity and mineralization levels, suggesting potential salinity issues for sensitive crops. Soil samples showed favorable conditions for agriculture, with good pH levels, low salinity, and high organic matter content. The analysis revealed a significant interaction between water quality and soil characteristics, emphasizing the importance of integrated management practices. In the context of climate change, the sustainability of qanat systems is critical. Recommendations include regular monitoring of water and soil quality, soil amendments to mitigate salinity, efficient irrigation techniques, and the use of climate-resilient infrastructure. This study underscores the importance of qanat systems in arid and semi-arid regions and provides practical recommendations for sustainable land and water resource management, enhancing the socio-economic well-being of local communities.

Keywords: Qanat systems, agricultural impact, Karabakh region, soil and water management.

Introduction

The ancient qanat (kehriz) systems of the Karabakh region in Azerbaijan offer a fascinating insight into historical water management techniques and their relevance to contemporary water quality and soil health. These underground channels, engineered to transport water from aquifers to the surface, have been instrumental in sustaining agriculture and supporting local communities in arid and semi-arid regions for centuries (Guliyev, 2016; 2021). By providing a dependable water source, qanat systems have played a critical role in maintaining agricultural productivity and the livelihoods of those who depend on it (Nasiri and Mafakheri, 2015; Mansouri Daneshvar et al., 2023).

Water quality from qanat systems is essential for both drinking and irrigation. Studies have shown that water from these systems often remains high in quality due to natural filtration processes occurring as it flows through underground channels (Shams, 2014). Research conducted in Nakhchivan and other parts of

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Azerbaijan supports this, indicating that qanat water is typically free from significant contamination, making it suitable for various uses. Similar observations have been made in other regions utilizing qanat systems, such as Iran, Jordan, Syria, and Oman, where water quality remains high despite challenging arid conditions (Lightfoot, 1996; Abudanh and Twaissi, 2010; Hamidian et al., 2015).Understanding the soil properties near qanat systems is equally important. The continuous supply of clean water from qanat systems can influence soil salinity and fertility, thereby impacting agricultural productivity. Research in various parts of Azerbaijan, including the Karabakh region, has shown that soils near qanat systems tend to have favorable properties for agriculture, with lower salinity levels and better nutrient content compared to other areas. This can be attributed to the regular and controlled irrigation provided by qanat water, which helps maintain soil health and reduces the accumulation of salts (Hamidian et al., 2015; Abadi et al., 2023).

The significance of water quality and soil properties becomes even more pronounced in the context of climate change. As global temperatures rise and precipitation patterns shift, the availability and quality of water resources are becoming critical concerns (Abbass et al., 2022; Telo da Gama, 2023). In Azerbaijan, where much of the freshwater comes from transboundary rivers and underground sources, ensuring the sustainability of qanat systems is vital for mitigating the impacts of climate change. Clean and reliable water sources like qanat systems are essential for adapting to changing environmental conditions and ensuring the long-term viability of agricultural practices (Guliyev, 2016; Guliyev, 2021; Pasha et al., 2023).

The agricultural activities supported by qanat systems in the Karabakh region are of particular socio-economic importance. The reliable water supply from these systems supports a variety of crops, contributing significantly to the livelihoods of local communities (Babayeva et al., 2024). The historical and cultural significance of qanat systems also adds to the heritage value of the region, making it important to preserve and study these ancient technologies (Koren and Bisesi, 2003).

This study represents a pioneering scientific investigation into the qanat systems of the Karabakh region. By evaluating the water quality and soil properties associated with these systems, this research aims to provide valuable insights into the sustainable management of water and soil resources in arid and semi-arid regions. The findings will contribute to a better understanding of how traditional water systems can be integrated with modern agricultural practices to enhance environmental conservation and sustainability efforts.

The objectives of this study are:

- To assess the physicochemical quality of water from qanat systems in the Cebrail district, Karabakh region of Azerbaijan, focusing on key parameters such as pH, electrical conductivity, hardness, mineralization, and the presence of various minerals and heavy metals.
- To evaluate the soil properties in areas adjacent to qanat systems, including pH, organic matter content, texture, and nutrient levels.
- To determine the relationship between water quality and soil characteristics, providing recommendations for sustainable land and water resource management in the face of climate change.

This research marks the first scientific study conducted in the Cebrail district, Karabakh region on this topic, underscoring its significance in the field of environmental and agricultural sciences. By filling existing knowledge gaps and providing practical recommendations, this study aspires to support sustainable development goals and enhance the livelihoods of communities dependent on these vital resources.

Material and Methods

Sample Collection

This study was conducted on 7 qanat systems in the Cebrail district, Karabakh region of Azerbaijan. Water and soil samples were collected from these qanat systems and their surrounding areas. The specific locations of the qanat systems were recorded using GPS coordinates to ensure precise documentation and repeatability of the study.

Water Sample Collection and Analysis

Water samples were collected directly from the qanat outlets using sterilized polyethylene bottles. Approximately 1 liter of water was collected from each qanat. The samples were immediately stored in cool, dark conditions to prevent any changes in water quality during transport to the laboratory.

In the laboratory, various water quality parameters were analyzed. The smell at 20°C was assessed by sensory evaluation, while colorfulness was measured using a colorimeter. Turbidity was determined with a nephelometer. The hydrogen ion concentration (pH) and electrical resistance at 25°C were measured using pH and EC meters. Water hardness was assessed through EDTA titration, and mineralization was calculated from the sum of all dissolved minerals. Dry residue was measured by evaporating the water sample and weighing the remaining solids. Calcium (Ca^{2+}) and magnesium (Mg^{2+}) concentrations were analyzed using atomic absorption spectrophotometry (AAS), and sodium (Na^{+}) and potassium (K^{+}) were measured by flame photometry. Hydrocarbonate (HCO_3^-) levels were determined by titration with hydrochloric acid, while sulfate (SO_4^{2-}) was measured using a turbidimetric method. Chlorides (Cl^-) were assessed via the argentometric method, and ammonium nitrogen (NH_4^+-N) was measured using the Nesslerization method. Nitrates (NO_3^-) and nitrites (NO_2^-) were determined using a UV spectrophotometer and colorimetric method, respectively. Phosphates (PO_4^{3-}) were determined using a colorimetric method, fluorides (F^-) using an ion-selective electrode, and cyanides (CN^-) via a colorimetric method. All analyses were performed in triplicate to ensure accuracy and reliability (Rice and Bridgewater, 2012; Chambers, 2019).

Soil Sample Collection and Analysis

Soil samples were collected from the surface layer (0-20 cm) at multiple points surrounding each qanat system to obtain a representative sample. The samples were air-dried, ground, and passed through a 2 mm sieve to remove debris and large particles.

Various soil properties were analyzed to assess their quality. Soil pH was measured in a soil-to-water suspension using a pH meter, and electrical conductivity (EC) was determined using a conductometer. Humus content was assessed by the Walkley-Black method, and salinization degree was evaluated by measuring the EC of the soil extract. Sulfate (SO_4^{2-}) and nitrate (NO_3^-) ions were analyzed using turbidimetric and UV spectrophotometer methods, respectively. Carbonate (CO_3^{2-}) and hydrocarbonate (HCO_3^-) ions were measured by titration with hydrochloric acid. Calcium (Ca^{2+}) and magnesium (Mg^{2+}) ions were quantified using AAS. Mechanical composition, including physically sand (>0,01 mm) and physically clay (<0,01 mm) fractions, was determined using the hydrometer method. All analyses were conducted in triplicate to ensure data reliability (Page et al., 1982; Carter and Gregorich, 2008).

Results and Discussion

Characteristics of Qanat Systems

The qanat systems studied in the Cebrail district of the Karabakh region exhibit a variety of characteristics, as detailed in Table 1. These systems, which range in length from 200 meters to 1500 meters, provide crucial water sources for both drinking and irrigation. The depth of the main wells and exit wells varies significantly, impacting the water extraction efficiency and overall sustainability of each system. Water consumption rates also differ, with some qanat systems delivering up to 275 liters per minute, demonstrating their significant capacity to support local agricultural activities.

Table 1. Characteristics of qanat Systems in the Cebrail District, Karabakh Region, Azerbaijan

Qanat No	Location	Name	Coordinates	Elevation (m)	Length (m)	No. of Wells	Depth of Main Well (m)	Depth of Exit Well (m)	Water Consumption (L/min)
1	Horovlu wilage	Asger kəhrizi	N 39.402079 E 47.095482	435	500	13	16	2,5	6
2	Horovlu wilage	Orta Kehriz	N 39.398508 E 47.096434	439	450	10	12	2,0	15
3	Center of Cebrail	Cinar Kehrizi	N 39.402266 E 47.025902	601	1500	20	30	2,5	1
4	Chereken willage	Taveka kəhrizi	N 39.415907 E 47.080623	532	1000	32	20	3,5	2
5	Horovlu kəndi	Şıxı kəhrizi	N 39.415849 E 47.080600	416	450	14	13	1,5	4
6	Horovlu willage	Xəlifə Kəhrizi	N 39.393335 E047.096304	433	850	16	17	2,5	11
7	Quycaq willage	Kuzey Kəhrizi	N 39.405364 E 47.145355	373	200	42	25	2,75	8

Water Quality of Qanat Systems

The analysis of water samples from the seven qanat systems reveals important insights into the physicochemical properties of the water. As shown in Table 2, the absence of odor at 20°C across all samples indicates the lack of organic contaminants that typically cause unpleasant smells. The colorfulness parameter was zero in most samples, except for Qanat No. 5, which exhibited minimal color, suggesting clear water with low turbidity in general.

The turbidity values, which range from 0.21 mg/L to 1.29 mg/L, show variations in suspended particles among the qanat systems. According to the World Health Organization (WHO, 2017) guidelines, turbidity should be below 5 NTU (Nephelometric Turbidity Units) for drinking water. All the qanat water samples meet this criterion, indicating that they are suitable for consumption in terms of clarity.

The pH levels, ranging from 6.83 to 7.70, are within the neutral to slightly alkaline range, which is considered ideal for both drinking and irrigation. The WHO (2017) recommends a pH range of 6.5 to 8.5 for drinking water, and all the qanat samples fall within this range, confirming their suitability for consumption.

Electrical conductivity (EC) values, ranging from 4040 µS/cm to 8280 µS/cm, indicate varying salinity levels. According to the Food and Agriculture Organization (FAO, 1985) standards, water with EC values below 700 µS/cm is considered good for irrigation, while values above 3000 µS/cm indicate potential salinity problems for sensitive crops. Most qanat systems exceed 3000 µS/cm, suggesting that while the water is generally usable, it requires careful management to avoid soil salinization.

Hardness levels ranged from 1.85 mmol/L to 3.60 mmol/L. The WHO (2017) classifies water with hardness above 1.5 mmol/L as moderately hard, and above 3.0 mmol/L as hard. Thus, some qanat samples can be considered hard, which may necessitate treatment for specific uses to prevent scaling in pipes and negative effects on crops.

Mineralization levels, indicating total dissolved solids (TDS), varied from 3404 mg/L to 7136 mg/L. The WHO guideline (WHO, 2017) for TDS in drinking water is 1000 mg/L. All the qanat water samples exceed this guideline, suggesting that while they may be suitable for irrigation, they might not be ideal for direct human consumption without treatment.

Table 2. Chemical properties of water samples from qanat systems

Water chemical properties	Qanat No						
	1	2	3	4	5	6	7
Smell at 20⁰C	0	0	0	0	0	0	0
Colorfulness	0	0	0	0	5	0	0
The blur, mg/lt	0,26	0,30	0,45	1,29	0,21	0,77	0,44
pH	7,07	6,83	6,90	7,70	7,64	7,00	7,40
Electrical Conductivity, µS/cm	650,0	732,0	404,0	556,0	828,0	802,0	792,0
The hardness, mmol/l	295,0	350,0	185,0	230,0	360,0	300,0	300,0
Mineralization, mg/lt	537,9	640,5	340,4	440,1	713,6	669,6	617,6
Dry residue, mg/lt	416,0	488,0	225,0	324,0	537,0	524,0	483,0
Ca^{2+}, mg/lt	86,20	100,20	56,10	72,10	108,20	88,20	96,20
Mg^{2+}, mg/lt	19,50	24,30	10,90	12,20	21,90	19,50	14,60
$Na^+ + K^+$, mg/lt	30,60	36,60	14,50	27,80	54,00	69,50	54,30
HCO_3^-, mg/lt	244,0	305,0	231,8	231,8	353,8	292,8	268,4
SO_4^{2-}, mg/lt	147,0	165,0	18,0	76,0	159,0	174,0	153,0
Cl^-, mg/lt	1,40	1,40	1,40	8,90	14,50	17,40	23,00
NH_4^+-N, mg/lt	0,16	0,12	0,17	0,16	0,15	0,25	0,18
NO_3^--N, mg/lt	8,20	7,00	6,90	11,00	1,90	6,00	7,40
NO_2^--N, mg/lt	0,02	0,02	0,01	0,01	0.019	0.041	0.022
PO_4^{2-}, mg/lt	0,11	0,13	0,12	0,15	0,10	2,18	0,05
F^-, mg/lt	0,43	0,32	0,22	0,00	0,01	0.02	0,43
CN, mg/lt	0,007	0,002	0,001	0,002	0,000	0.002	0,003

In terms of individual ions, calcium (Ca^{2+}) and magnesium (Mg^{2+}) concentrations ranged significantly. Calcium ranged from 5610 mg/L to 10820 mg/L, and magnesium ranged from 1090 mg/L to 2430 mg/L. According to WHO guidelines (WHO (2017), the recommended maximum levels for calcium and magnesium in drinking water are 75 mg/L and 50 mg/L, respectively. All samples exceed these limits, suggesting potential issues for direct consumption but remaining suitable for irrigation with proper management.

Sodium (Na^+) and potassium (K^+) levels also varied, with sodium and potassium combined concentrations ranging from 1450 mg/L to 6950 mg/L. High sodium levels can adversely affect soil structure and permeability when used for irrigation. WHO (2017) suggests a maximum sodium concentration of 200 mg/L for drinking water. Therefore, while the levels are high for direct human consumption, careful water management practices can mitigate adverse effects on agricultural soils.

The concentrations of bicarbonate (HCO_3^-), sulfate (SO_4^{2-}), and chloride (Cl^-) were measured. Bicarbonate levels ranged from 2318 mg/L to 3538 mg/L, sulfate from 180 mg/L to 1740 mg/L, and chloride from 140 mg/L to 2300 mg/L. WHO guidelines (WHO (2017) recommend maximum concentrations of 250 mg/L for sulfate and 250 mg/L for chloride in drinking water. Some qanat systems exceed these limits, indicating the necessity for treatment before human consumption.

Ammonium nitrogen (NH_4^+-N) levels were found to be low across all samples, within the acceptable limits for drinking water. Nitrate (NO_3^-) and nitrite (NO_2^-) concentrations varied but remained within WHO guidelines (WHO (2017) of 50 mg/L and 3 mg/L, respectively, for drinking water.

Phosphate (PO_4^{3-}) levels were generally low, except for Qanat No. 6, which showed an elevated level of 2.18 mg/L. Fluoride (F^-) concentrations were within safe limits for all samples, and cyanide (CN^-) levels were negligible.

Soil Quality Around Qanat Systems

The soil samples collected from the vicinity of the qanat systems reveal a range of physicochemical properties, as shown in Table 3. The pH levels, which ranged from 7.10 to 7.90, indicate slightly alkaline conditions that are conducive to most agricultural activities. Electrical conductivity (EC) values, which measure soil salinity, were relatively low across all samples, ranging from 0.078 dS/m to 0.096 dS/m, indicating minimal salinity issues.

Organic matter content in the soils was found to be between 4.40% and 4.90%, reflecting good soil fertility and structure, which is beneficial for crop growth. The degree of salinization was low, with values ranging from 0.02% to 0.09%, indicating that there is minimal risk of salt accumulation in the soil, which is crucial for maintaining soil health and agricultural productivity.

Sulfate concentrations in the soil varied between 8500 mg/kg and 10100 mg/kg. These levels are generally acceptable but require monitoring to prevent potential negative impacts on soil and plant health. Nitrate concentrations ranged from 2000 mg/kg to 5800 mg/kg, indicating adequate levels of available nitrogen for plant growth.

Table 3. Physicochemical properties of soil samples around qanat systems

Soil Physicochemical Properties	Qanat No						
	1	2	3	4	5	6	7
pH	7,70	7,10	7,60	7,20	7,90	7,60	7,60
EC, dS/m	0,89	0,87	0,79	0,96	0,84	0,88	0,78
Organic matter, %	4,90	4,80	4,60	4,40	4,70	4,70	4,80
Salinization degree, %	0,09	0,02	0,08	0,07	0,09	0,08	0,09
SO_4^{2-}, mg/kg	100,00	85,00	90,00	87,00	89,00	101,00	89,00
NO_3^-, mg/kg	54,00	20,00	44,00	58,00	56,00	54,00	44,00
CO_3^-, mg/kg	0	0	0	0	0	0	0
HCO_3^-, mg/kg	427,00	323,80	327,00	389,00	357,00	427,00	421,00
Ca^{2+}, mg/kg	300,60	200,40	306,60	308,60	298,50	300,60	290,60
Mg^{2+}, mg/kg	182,30	121,50	180,00	169,30	179,60	182,30	187,30
Physically clay, %	47,00	45,00	49,00	48,00	49,00	45,00	48,00
Physically sand, %	53,00	55,00	55,00	58,00	54,00	56,00	52,00

The levels of carbonate (CO_3^{2-}) were negligible across all samples, while bicarbonate (HCO_3^-) levels ranged from 32380 mg/kg to 42700 mg/kg. These high bicarbonate levels can influence soil pH and nutrient availability. Calcium (Ca^{2+}) concentrations ranged from 20040 mg/kg to 30860 mg/kg, and magnesium (Mg^{2+}) concentrations ranged from 12150 mg/kg to 18730 mg/kg, indicating good soil structure and fertility.

The mechanical composition of the soil, which includes the proportion of sand, silt, and clay, revealed that the soils are predominantly sandy loam. Sand content ranged from 52% to 58%, and clay content ranged from 45% to 49%. This texture is favorable for agricultural practices as it ensures good drainage and root penetration while retaining sufficient moisture and nutrients.

The soil samples collected from around the qanat systems indicate favorable conditions for agriculture. The slightly alkaline pH levels and low salinity, as indicated by electrical conductivity, suggest that these soils are well-suited for a variety of crops. The high organic matter content reflects good soil fertility, which is essential for healthy plant growth and productivity.

Sulfate and nitrate levels are within acceptable ranges for agricultural soils, although continued monitoring is necessary to ensure that these levels do not rise to harmful concentrations. The negligible carbonate levels and high bicarbonate levels highlight the influence of qanat water on soil chemistry, potentially affecting soil pH and nutrient availability.

The mechanical composition of the soils, predominantly sandy loam, is ideal for agriculture as it provides good drainage, root penetration, and moisture retention capabilities. This balance of physical properties supports robust plant growth and helps prevent issues such as waterlogging and soil compaction (Glinski, 1990).

Implications for Agricultural Practices and Water Management

The analysis of water and soil samples from the qanat systems in the Cebrail district provides valuable insights into the suitability of these resources for sustainable agricultural practices. The generally high-quality water, with minimal contamination, supports the use of qanat systems for both drinking and irrigation purposes. However, the variations in mineral content and salinity among different qanat systems highlight the need for site-specific management practices to ensure optimal soil health and crop productivity.

The soil analysis indicates favorable conditions for agriculture, with good pH levels, organic matter content, and low salinization risk. The high bicarbonate levels and variations in sulfate and nitrate concentrations necessitate regular monitoring and potential amendments to maintain soil health and fertility.

The results of this study align with previous findings on qanat water quality. Studies in other regions of Azerbaijan, such as Nakhchivan, and in countries like Iran and Oman, have shown that qanat water often maintains high quality due to natural filtration through underground channels (Lightfoot, 1996; Hamidian et al., 2015). The slight variations in some parameters, such as higher mineral content in certain qanat systems, are consistent with the findings of Somaratne and Frizenschaf (2013), Baba and Gündüz (2017), and Abanyie et al. (2023) that local geology and aquifer composition can influence water quality.

The generally low levels of turbidity and absence of odor confirm the natural filtration efficiency of the qanat systems. The pH levels being within the ideal range for drinking and irrigation align with global observations of qanat water properties. The higher electrical conductivity and mineralization levels in some qanat systems indicate the need for careful water management, especially for irrigation purposes. This finding is supported by FAO guidelines (FAO, 1985) which emphasize monitoring and managing irrigation water with high EC to prevent soil salinization.

The calcium and magnesium concentrations, although high, are not uncommon in groundwater sources in arid and semi-arid regions. Effective treatment methods such as lime softening or ion exchange can make this water suitable for drinking. Sodium levels, while high for direct consumption, can be managed through blending with lower sodium water or using gypsum to ameliorate the effects on soil structure when used for irrigation. The variations in sulfate and chloride concentrations also necessitate monitoring, especially since they can affect soil and plant health over time. The low levels of ammonium, nitrate, nitrite, phosphate, fluoride, and cyanide in the water samples further confirm the suitability of qanat water for agricultural use, provided that appropriate management practices are employed.

Overall, the study underscores the importance of qanat systems in providing reliable water sources in arid and semi-arid regions. By integrating traditional water management practices with modern agricultural techniques, the sustainability and productivity of these systems can be enhanced, contributing to the socio-economic well-being of local communities. This comprehensive analysis of water and soil quality around qanat systems provides a solid foundation for sustainable agricultural practices and effective water resource management in the Karabakh region.

Relationship Between Water Quality and Soil Characteristics

The findings of this study highlight significant interactions between water quality and soil characteristics in the Cebrail district of the Karabakh region. The qanat systems, which provide a reliable source of water, directly influence the physicochemical properties of the surrounding soils. This relationship is crucial for understanding how to manage both water and soil resources sustainably, especially in the context of climate change.

The high mineralization levels and electrical conductivity (EC) of the water samples from certain qanat systems suggest that irrigation with this water can contribute to soil salinization if not managed properly. The elevated levels of calcium (Ca^{2+}), magnesium (Mg^{2+}), and sodium (Na^{+}) in the water are likely to affect soil structure and fertility. For instance, high sodium levels can lead to soil dispersion, reducing permeability and aeration, which negatively impacts plant growth.

Conversely, the relatively low levels of contaminants such as ammonium nitrogen (NH_4^{+}-N), nitrates (NO_3^{-}), and phosphates (PO_4^{3-}) in the water indicate that it can be beneficial for maintaining soil fertility without contributing significantly to nutrient runoff or groundwater pollution. The presence of essential nutrients in the water can enhance soil nutrient content, supporting sustainable agricultural productivity.

Recommendations for Sustainable Land and Water Resource Management

To mitigate the potential negative impacts of high mineral content in irrigation water, several management practices can be recommended:

- Regular Monitoring: Continuous monitoring of both water and soil quality is essential. This includes tracking salinity levels, pH, and concentrations of key ions in both water and soil to detect any adverse changes promptly.
- Blending Water Sources: Blending qanat water with lower salinity water can help reduce overall salinity levels, making it safer for both drinking and irrigation purposes. This approach can also balance out the mineral content.
- Soil Amendments: Applying soil amendments such as gypsum can help displace sodium ions from soil particles, improving soil structure and reducing the risk of sodicity. Organic matter additions can also enhance soil structure and nutrient-holding capacity.
- Irrigation Management: Implementing efficient irrigation techniques, such as drip irrigation, can minimize water usage and reduce the risk of soil salinization. Additionally, scheduling irrigation based on soil moisture content and crop needs can prevent over-irrigation and leaching of nutrients.
- Crop Selection: Choosing salt-tolerant crop varieties can help sustain agricultural productivity in areas with higher soil salinity. These crops can better withstand the stress caused by saline conditions.
- Integrated Water Resource Management: Developing a comprehensive water resource management plan that considers the variability of water quality across different qanat systems is crucial. This plan should integrate traditional knowledge with modern practices to enhance water use efficiency and sustainability.

Adaptation to Climate Change

As global temperatures rise and precipitation patterns become more unpredictable, the reliance on qanat systems as a sustainable water source becomes increasingly important. Ensuring the sustainability of these systems involves not only maintaining the quality of water but also protecting the surrounding soil environment.

- Climate-Resilient Infrastructure: Investing in the maintenance and restoration of qanat infrastructure to withstand extreme weather events is vital. This includes reinforcing tunnels and wells to prevent collapse and ensuring that water channels remain unblocked.
- Water Conservation Practices: Promoting water conservation techniques among local communities can help manage limited water resources more effectively. This includes rainwater harvesting and efficient water storage methods.
- Community Engagement: Engaging local communities in water management decisions ensures that traditional practices and local knowledge are incorporated into modern water management strategies. This participatory approach can enhance the resilience of the qanat systems to climate change.
- Research and Innovation: Encouraging ongoing research into the effects of climate change on water and soil resources in the Karabakh region can provide valuable insights. Innovations in water management and soil conservation techniques can be developed and adapted to local conditions.

By understanding and managing the relationship between water quality and soil characteristics, and by implementing adaptive strategies to address the impacts of climate change, the sustainability of qanat systems can be ensured. These efforts will support the long-term viability of agricultural practices and the socio-economic well-being of communities in the Karabakh region.

Conclusion

This study provides a detailed assessment of the water quality and soil characteristics associated with qanat systems in the Cebrail district of the Karabakh region, Azerbaijan. The analysis of water samples from seven qanat systems revealed generally high-quality water with minimal contamination, suitable for both drinking and irrigation purposes. However, certain qanat systems exhibited higher mineral content and salinity, indicating the need for careful management to prevent soil salinization and ensure sustainable use.

The soil samples collected from the vicinity of the qanat systems demonstrated favorable conditions for agriculture, including good pH levels, low salinity, and high organic matter content. The mechanical composition of the soils, predominantly sandy loam, supports robust agricultural productivity by providing good drainage, root penetration, and moisture retention.

Key findings from the study include:

- The water from qanat systems generally meets WHO guidelines (WHO (2017) for turbidity and pH, making it suitable for consumption and irrigation.
- Electrical conductivity and mineralization levels in some qanat systems exceed recommended limits for drinking water, necessitating treatment or blending with lower salinity water.
- The high levels of calcium, magnesium, and sodium in certain qanat systems require management practices such as soil amendments and efficient irrigation techniques to mitigate potential negative impacts on soil structure and crop health.
- The low levels of contaminants such as ammonium, nitrate, nitrite, phosphate, fluoride, and cyanide in the water samples confirm the suitability of qanat water for agricultural use.

The relationship between water quality and soil characteristics highlights the need for integrated water and soil management strategies to ensure sustainable agricultural practices. Regular monitoring of both water and soil quality, along with the implementation of site-specific management practices, can help maintain soil health and crop productivity.

In the context of climate change, the sustainability of qanat systems becomes increasingly important. Adaptive strategies, including climate-resilient infrastructure, water conservation practices, community engagement, and ongoing research, are essential to enhance the resilience of these traditional water management systems.

By integrating traditional qanat systems with modern agricultural practices, the sustainability and productivity of these systems can be enhanced, contributing to the socio-economic well-being of local communities in the Karabakh region. This study not only fills existing knowledge gaps but also provides practical recommendations for sustainable land and water resource management, supporting long-term environmental conservation and agricultural development goals.

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