Hydrochemical Characteristics of Surface Water and Groundwater in the Plain Area of the Che'erchen River Basin, Northern Slope of the Kunlun Mountains (Postprint)

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Abstract

The Cherchen River basin exhibits an excessively high proportion of agricultural water use, with prominent contradictions between water supply and demand. Clarifying the hydrochemical characteristics of farmland irrigation water and groundwater is of great significance for basin water resources allocation and oasis water ecological security. Using field investigation, mathematical statistics, and hydrochemical analysis methods, this study analyzed the hydrochemical and stable hydrogen-oxygen isotopic characteristics of groundwater, canal water, and river water in the plain area of the Cherchen River basin, and explored the interaction relationship between farmland irrigation water and groundwater. The results show that: (1) River water, canal water, and groundwater are all weakly alkaline, with F- content exceeding standard limits. The main hydrochemical type is SO4 · Cl-Na for all three, with sulfate and sodium as the dominant anions and cations. Both canal water and groundwater show a trend of salinization, while river water has relatively better overall quality. (2) Groundwater, river water, and canal water share similar hydrochemical characteristics, with their ion sources controlled by rock weathering. The ion sources of groundwater are additionally influenced by evaporation concentration. (3) The slopes of the water lines for river water, canal water, and groundwater are 3.70, 0.61, and 1.42, respectively, all lower than the slope of the local meteoric water line (5.62). Sample points from all water bodies are concentrated below the meteoric water line, indicating that both river water and canal water have very close hydraulic connections with groundwater and serve as important recharge sources for shallow groundwater, with recharge proportions of 56.48% and 43.52%, respectively. The research results can provide a scientific basis for the efficient utilization and rational allocation of water resources in the plain

irrigation area of the Cherchen River basin.

Full Text

Preamble

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Title

Hydrochemical Characteristics of Surface Water and Groundwater in the Plain Area of the Qargan River Basin on the Northern Slope of the Kunlun Mountains

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Abstract

Agricultural water consumption accounts for an excessively high proportion of total water use in the Qargan River Basin, creating a prominent conflict between water supply and demand. Clarifying the hydrochemical characteristics of irrigation water and groundwater is essential for optimizing water resource allocation and ensuring oasis water ecological security. This study investigates the hydrochemical parameters and stable hydrogen-oxygen isotopic compositions of groundwater, channel water, and river water in the plain areas of the Qargan River Basin using field surveys, statistical analysis, and hydrochemical methods. The results reveal that: (1) River water, channel water, and groundwater are all weakly alkaline, with elevated fluoride concentrations in each. The predominant hydrochemical type for all water bodies is $SO_4 \cdot$ Cl-Na, characterized by

SO_4^{2-} and Na^+ as the dominant anion and cation, respectively. While river water maintains relatively good quality, both channel water and groundwater exhibit salinization trends, with groundwater showing more severe degradation. (2) The three water bodies display similar hydrochemical characteristics. Ion sources in river water and channel water are primarily controlled by rock weathering processes, whereas groundwater is influenced by both rock weathering and evaporative concentration. (3) The slopes of the local water lines for river water, channel water, and groundwater are 3.70, 0.61, and 1.42, respectively, all lower than the slope of the local meteoric water line (5.62). Sampling points for all water bodies are concentrated below the meteoric water line, indicating that river water and channel water are closely connected to groundwater hydraulically and serve as important recharge sources for shallow groundwater, contributing 43.52% and 56.48%, respectively. These findings provide a scientific basis for the efficient utilization and rational allocation of water resources in the plain irrigation areas of the Qargan River Basin.

Keywords: Qargan River Basin; hydrochemical characteristics; stable hydrogen and oxygen isotopes; irrigation water; groundwater

Introduction

The Qargan River is a major inland river on the northern slope of the Kunlun Mountains. The oases within its basin primarily rely on surface water resources, with groundwater serving as a supplementary source. Agricultural water use dominates water consumption in the Qargan River Basin, accounting for 76.23%–98.20% of total water use (approximately 89.17%). Previous research has identified farmland irrigation water as another important source of groundwater recharge in arid inland river basins, second only to rivers themselves. During irrigation, substantial application of chemical fertilizers and pesticides occurs, raising concerns about potential groundwater contamination. The Kunlun Mountains' northern slope region features poorly developed soils with extremely low water retention capacity. Despite this, irrigation practices remain dominated by extensive flood irrigation, with water-efficient irrigation covering less than 10% of cultivated land, indicating an urgent need to improve irrigation efficiency. Additionally, water conservancy infrastructure is relatively weak, with canal seepage prevention rates at only 47.8%. Consequently, many channels experience significant water loss, and whether this causes groundwater pollution in the Qargan River Basin represents an important ecological concern. Given the critical importance of food security and ecological protection, investigating the connectivity between irrigation water and groundwater and characterizing water quality changes is essential for the green, high-quality development and sustainable water resource utilization in the Qargan River Basin.

The transformation between surface water and groundwater constitutes a crucial component of the hydrological cycle, directly affecting water quantity and the spatiotemporal distribution of hydrochemical components. Natural water chemistry composition records water formation and movement processes, while stable hydrogen-oxygen isotopes directly participate in the water cycle. Combining hydrochemical and isotopic methods is widely recognized as an effective approach for accurately analyzing surface water-groundwater interactions and transformation relationships. Scholars have successfully applied this method to investigate how human activities, temporal and spatial variations, environmental and geological conditions, and atmospheric precipitation affect water chemistry and interconversion mechanisms. Similar studies in the Pishan River oasis on the Kunlun Mountains' northern slope revealed close connections between surface water and shallow groundwater, though human activities have complicated their transformation relationship. Whether the Qargan River Basin exhibits comparable trends remains understudied. Previous research has documented continuous salt accumulation in Qargan River Basin groundwater, particularly pronounced salinization in alluvial plain areas, and declining water quality in the Qargan River itself. However, few studies have examined irrigation water quality and its relationship with groundwater in the basin' s plain areas. Analyzing the hydrochemical and isotopic characteristics of surface water and groundwater in the Qargan River Basin' s plain oasis zone can provide scientific support for optimizing water resource allocation and improving water quality.

1. Materials and Methods

1.1 Study Area Overview

This study focuses on the plain irrigation zone of the Qargan River Basin, located within Ruoqiang and Qiemo counties in southern Xinjiang (83.75°–89.67°E, 36.19°–39.81°N). The region belongs to a typical mid-latitude, extremely arid climate zone, with an average annual temperature of approximately 10°C, mean annual precipitation of 19.0 mm, and mean annual potential evaporation of 2507 mm. Major rivers with substantial runoff and development potential include the Qargan River, Tashsay River, Washixia River, and Ruoqiang River, with a combined multi-year average runoff of $9.07 \times 10^8\ m^3$. The Qargan River alone contributes approximately $9.0 \times 10^8\ m^3$, primarily recharged by glacier meltwater and mountain precipitation. Runoff varies significantly throughout the year, with over 70% concentrated in summer. After entering the oasis zone, river water is diverted through water conservancy projects into canal systems for agricultural irrigation. Field investigations indicate that in recent years, agricultural irrigation in Qiemo County has accounted for about 90% of annual total water use, with approximately 85% of irrigation water derived from surface water sources. Irrigation water primarily originates from river diversion, supplemented by reservoir storage and groundwater, entering irrigation districts through main, branch, and lateral canals, mainly via flood irrigation. The irrigated oasis area primarily features irrigation-silt soils and alluvial plains with salinized soils.

1.2 Data Sources

In July 2022, we collected 15 river water samples, 15 channel water samples, and 28 groundwater samples from the Qargan River Basin plain area. River water sampling sites were located in the middle and lower reaches of the developed Qargan River, Tashsay River, and Washixia River, and the upper reaches of the Ruoqiang River. Due to a large storage reservoir in the Ruoqiang River' s upper mountain area, the middle and lower river channels remain dry most of the time, so sampling was conducted near the mountainous area. Channel water and groundwater sampling points were distributed across oasis irrigation districts of the four rivers, with channel water primarily sourced from river water, reservoir storage, and agricultural wells. Groundwater sampling points were established at irrigation wells near farmland, representing shallow groundwater. Before sampling, bottles were rinsed at least three times with the water to be collected, then filled and sealed. All samples were sealed with film to prevent evaporation and stored in ice boxes.

All samples were analyzed at the Central Laboratory of the Xinjiang Institute of Ecology and Geography, Chinese Academy of Sciences, for total dissolved solids (TDS), pH, K^+, Na^+, Ca^{2+}, Mg^{2+}, $SO_4{}^{2-}$, Cl^-, $HCO_3{}^-$, $NO_3{}^-$, F^-, and stable hydrogen-oxygen isotopes. TDS was measured gravimetrically, pH was determined using a Mettler Toledo pH meter, K^+ and Na^+ by flame emission spectrometry, Ca^{2+} and Mg^{2+} by flame atomic absorption spectrophotometry, $SO_4{}^{2-}$ and Cl^- by ion chromatography, and $HCO_3{}^-$ by titration. Stable hydrogen-oxygen isotopes (δD and δ^{18}O) were measured using a Gatos Research TLWIA-912 liquid water isotope analyzer, with results expressed as per mil deviation (‰) relative to Vienna Standard Mean Ocean Water (V-SMOW). Measurement precision was $±$1‰ for δD and $±$0.1‰ for δ^{18}O.

1.3 Research Methods

We employed Piper trilinear diagrams to compare the chemical characteristics of different water sources and Gibbs diagrams to assess water chemistry formation mechanisms and evolution. Ion ratio coefficient analysis was used to identify water genesis and potential mineral sources of chemical components. ArcGIS 10.8 was used for mapping and data analysis. Due to minimal rainfall in the oasis plain area and absence of precipitation during the sampling period, we used a binary mixing model to calculate the contribution ratios of river water and irrigation channel water as groundwater recharge sources. The model formula is:

$$\delta_{\text{mix}} = f_A \times \delta_A + (1 - f_A) \times \delta_B$$

where δ_{mix} is the isotopic value of the mixed water; δ_A and δ_B are the isotopic values of water bodies A and B, respectively; and f_A is the proportion from water body A, calculated by:

$$f_A = \frac{\delta_{\text{mix}} - \delta_B}{\delta_A - \delta_B}$$

2. Results

2.1 Basic Physicochemical Properties

Statistical characteristics of hydrochemical parameters for river water, channel water, and groundwater are presented in . The average pH values of river water and channel water are similar (8.31 and 8.30, respectively), slightly higher than groundwater (8.07), with low coefficients of variation, indicating that surface water and groundwater in the region are weakly alkaline overall. According to the TDS classification standard for freshwater (TDS < 1000 mg $\cdot$ L^{-1}), brackish water ($1000 \leq$ TDS < 3000 mg $\cdot$ L^{-1}), and saline water ($3000 \leq$ TDS < 10000 mg $\cdot$ L^{-1}), 46.7% of river water samples are freshwater, while 53.3% are brackish, primarily located in the lower Qargan River. For channel water, 16.7% are freshwater and 83.3% are brackish, mainly in the middle-lower Qargan River and Ruoqiang River irrigation districts. For groundwater, 21.4% are freshwater, 67.9% are brackish (primarily in the Ruoqiang, Washixia, Tashsay, and middle-lower Qargan Rivers), and 10.7% are saline, mainly in the Tashsay Development Zone of Qiemo County. Overall, the average TDS values for river water, channel water, and groundwater are 929.28 mg $\cdot$ L^{-1}, 1004.33 mg $\cdot$ L^{-1}, and 1649.49 mg $\cdot$ L^{-1}, respectively, with large coefficients of variation (all > 0.5). This confirms that groundwater in the Qargan River Basin plain area exhibits a salinization trend. Strong evaporation, dissolution of soluble salts, and agricultural activities can increase SO_4^{2-} and Cl^- concentrations in middle-lower reaches of inland rivers, likely explaining the brackish trend in lower Qargan River water and middle-lower channel water. Additionally, irrigation with salinized surface and groundwater may be a major contributor to shallow groundwater salinization in oasis irrigation districts.

Fluoride concentrations exceed standards in all water bodies: 78.57% of river water samples, 100% of channel water samples, and 83.33% of groundwater samples exceed the 1.0 mg $\cdot$ L^{-1} limit for drinking water quality (GB 5749-2022). The average F^- concentrations in river water, channel water, and groundwater are 2.65 mg $\cdot$ L^{-1}, 3.16 mg $\cdot$ L^{-1}, and 2.72 mg $\cdot$ L^{-1}, respectively. Previous studies have attributed fluoride enrichment in Qargan River Basin water to Quaternary aeolian deposits, shallow groundwater depth, alkaline water environments, and mineral dissolution—conditions consistent with our sampling sites. Long-term high-fluoride environments adversely affect plant growth and can cause human organ damage, warranting serious attention.

2.2 Hydrochemical Types and Controlling Factors

Piper trilinear diagrams reveal that most sampling points cluster in the $SO_4 \cdot$ Cl-Na region, indicating this hydrochemical type dominates all water bodies. A few points fall in the mixed zone, suggesting similar formation processes and frequent interconversion between surface water and groundwater. According to the Gibbs diagram classification based on $\gamma(Na^+)/(Na^+ + Ca^{2+})$ and TDS, river water and channel water chemistry is primarily controlled by rock weathering, while groundwater is influenced by both rock weathering and evaporative concentration. Some groundwater points plot outside the Gibbs zones due to excessively high TDS values ($> 800\ mg \cdot L^{-1}$) causing migration beyond the defined regions.

2.3 Hydrochemical Ion Source Analysis

Ion ratio diagrams reveal relationships between ionic variables and identify mineral sources. The $\gamma(Na^+)/\gamma(Cl^-)$ ratio indicates that when Na^+ originates primarily from halite dissolution, a 1:1 linear relationship with Cl^- is expected. If the slope is less than 1, additional sources exist. Our samples plot near but slightly below the 1:1 line, indicating halite dissolution is the main Na^+ source, though some Na^+ originates from silicate weathering or cation exchange, consistent with local stratigraphy.

The $\gamma(Ca^{2+} + Mg^{2+})/\gamma(HCO_3^-)$ ratio distinguishes carbonate versus silicate and evaporite dissolution sources. When the ratio exceeds 1, Ca^{2+} and Mg^{2+} mainly derive from calc-magnesium silicate or evaporite weathering; when less than 1, carbonate dissolution dominates. Most river and channel water samples plot near the $y = x$ line, indicating mixed carbonate and silicate sources. Groundwater samples mostly plot near $y = x$, with some above, suggesting carbonate and silicate dissolution as the primary Ca^{2+} and Mg^{2+} sources. The $\gamma(SO_4^{2-})/\gamma(HCO_3^-)$ ratio further confirms that evaporite dissolution is the main SO_4^{2-} source, as most samples plot above the $y = x$ line.

2.4 Stable Hydrogen-Oxygen Isotope Characteristics

The $\delta^{18}O$ values for river water range from -8.38‰ to -6.05‰ (mean -7.16‰), and δD ranges from -47.40‰ to -38.10‰ (mean -42.45‰). For channel water, $\delta^{18}O$ ranges from -8.53‰ to -6.28‰ (mean -7.42‰), and δD ranges from -54.00‰ to -38.10‰ (mean -45.73‰). Groundwater $\delta^{18}O$ ranges from -8.53‰ to -6.28‰ (mean -7.42‰), and δD ranges from -54.00‰ to -38.10‰ (mean -45.73‰). Groundwater isotopic values are similar to channel water and overlap with river water ranges, indicating that oasis groundwater is primarily recharged by irrigation channel water, with river water also contributing.

Compared with previous studies on the same water bodies, both river water and channel water show isotopic depletion trends, while groundwater $\delta^{18}O$ values have also decreased slightly. The Qargan River originates from Muztag Peak on the Kunlun Mountains' northern slope, where most glaciers are retreating and mountain precipitation is increasing. The depletion trend may relate to increased contributions from isotopically depleted glacier meltwater and high-elevation precipitation. Channel water shows slightly more depleted isotopic values than river water, likely due to reservoir storage prolonging residence time and causing isotopic fractionation.

Without local precipitation isotope data, we used the local meteoric water line (LMWL) from the nearby Cele River Basin ($\delta D = 5.62\delta^{18}O + 19.53$, $R^2 = 0.72$), whose slope is less than the global meteoric water line ($\delta D = 8\delta^{18}O + 10$), reflecting typical arid region precipitation characteristics with significant secondary evaporation. The isotopic regression lines for river water, channel water, and groundwater have slopes of 3.70, 0.61, and 1.42, respectively—significantly lower than the LMWL slope and the summer surface water slope in the eastern Kunlun Mountains. This indicates weak precipitation recharge and strong evaporation effects. The compact distribution of sampling points below the LMWL demonstrates close hydraulic connections among all water bodies. The similar slopes of channel water and groundwater lines suggest stronger hydraulic connectivity between them than between river water and groundwater.

In northwest inland basins, large volumes of river water diverted through canals play crucial roles in groundwater formation. Recent land use changes in the Qargan River Basin oasis, particularly significant increases in cultivated land, have dramatically increased agricultural water demand. The aging irrigation system with low seepage prevention rates and concentration in valley plain oasis zones suggests that groundwater receives substantial recharge from irrigation water infiltration. Using $\delta^{18}O$ as a conservative tracer, the binary mixing model quantifies contributions to shallow groundwater: river water contributes 43.52% and channel water contributes 56.48%. This confirms that irrigation channel water, though primarily derived from river diversion, plays a more significant role in groundwater recharge than direct river water. The identical hydrochemical types among all water bodies further demonstrate their close hydraulic exchange.

3. Conclusions

(1) River water, channel water, and shallow groundwater in the Qargan River Basin plain area are all weakly alkaline. Channel water and groundwater exhibit salinization trends, with groundwater showing more severe degradation. Except for the lower Qargan River where river water shows some salinization, other irrigation districts have low-mineralization freshwater. Salinization is primarily caused by SO_4^{2-} and Cl^- accumulation. While NO_3^- concentrations exceed standards in about 78% of river water and groundwater samples from some districts, all channel water samples exceed NO_3^- standards. Overall, river water quality is superior to channel water and groundwater.

(2) The three water bodies share similar hydrochemical characteristics, with $SO_4 \cdot Cl$-Na as the dominant type and SO_4^{2-} and Na^+ as the principal ions. River water and channel water chemistry is mainly controlled by rock weathering, whereas groundwater is influenced by both rock weathering

and evaporative concentration.

(3) The water lines for river water, channel water, and groundwater all have slopes lower than the local meteoric water line, with sampling points concentrated below the precipitation line, indicating close hydraulic connections and weak precipitation recharge. Groundwater δ^{18}O values fall within the channel water range and overlap with river water values, suggesting channel water contributes more strongly to groundwater recharge than river water—consistent with binary mixing model results showing contributions of 56.48% from channel water and 43.52% from river water. Given the close relationship between channel water and groundwater, along with salinization trends and fluoride enrichment, targeted in-depth research is urgently needed to assess potential ecological consequences.

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Note: Figure translations are in progress. See original paper for figures.