Postprint: Study on the Interaction between Surface Water and Groundwater in the Ningxia Kushui River Basin

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Abstract

Investigating the conversion relationship between surface water and groundwater in brackish water regions suffering from freshwater resource shortages is of great significance for revealing regional hydrological cycle mechanisms and promoting the rational utilization of brackish water resources. Taking the Kushui River basin in Ningxia as the study area, this research employs hydrogen and oxygen stable isotope technology, combined with field investigation, statistical analysis, and hydrochemical analysis methods, to analyze the spatiotemporal distribution characteristics of hydrochemistry and hydrogen-oxygen stable isotopes in surface water and groundwater, and systematically reveals the spatiotemporal variation patterns of the conversion relationship between surface water and groundwater within the basin. The results indicate that: (1) The hydrochemical types of surface water and groundwater in the upstream and midstream sections of the Kushui River basin are predominantly SO4 · Cl-Na · Mg, with the hydrochemical formation process of surface water being evaporation concentration. The hydrochemical type of downstream groundwater transforms into a mixed type, and the hydrochemical formation process shifts to being controlled by rock weathering. (2) Atmospheric precipitation plays a significant role in recharging surface water and groundwater during the wet season, while its recharge effect is limited during the dry season. Controlled by climate, topography, and hydrogeological conditions, the conversion relationship between surface water and groundwater in the upstream and midstream sections exhibits significant variability and complexity across different periods and river reaches. The downstream area is notably influenced by Yellow River water irrigation. (3) Regions with close hydraulic connection between surface water and groundwater during the dry season are distributed in the midstream and downstream sections, where the water cycle pattern is groundwater recharging surface water, with recharge

proportions of 51.8% and 57.8%, respectively. During the wet season, the hydraulic connection between mainstream surface water and upstream/midstream groundwater is weak, while downstream surface water recharges groundwater with a proportion of 38.8%. Simultaneously, canal water in the downstream area provides certain recharge to surface water, with a recharge proportion of 29.8%.

Full Text

Study on the Transformation Relationship between Surface Water and Groundwater in the Kushui River Basin, Ningxia

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Abstract

In brackish water regions where freshwater resources are scarce, identifying the transformation relationship between surface water and groundwater is crucial for revealing regional hydrological cycle mechanisms and promoting rational utilization of brackish water resources. This study investigates the Kushui River Basin in Ningxia, employing hydrogen-oxygen stable isotope technology combined with field surveys, statistical analysis, and hydrochemical methods to analyze the spatiotemporal distribution characteristics of hydrochemistry and hydrogen-oxygen stable isotopes in surface water and groundwater. The research systematically reveals the spatiotemporal variation patterns of the transformation relationship between surface water and groundwater within the basin. Results show that: (1) The hydrochemical type of surface water and upstream/midstream groundwater in the Kushui River Basin is primarily $SO_4 \cdot Cl\text{-}Na \cdot Mg$, with evaporation concentration as the dominant hydrochemical formation process. Downstream groundwater exhibits a mixed hydrochemical type, and the hydrochemical formation process shifts to rock weathering control. (2) Atmospheric precipitation significantly recharges surface water and groundwater during the wet season, while its effect is limited during the dry season. Controlled by climate, topography, and hydrogeological conditions, the transformation relationship between surface water and groundwater in the upstream and midstream sections shows significant differences and complexity across different periods and river reaches. The downstream area is notably influenced by Yellow River irrigation. (3) During the dry season, areas with close hydraulic connection between surface water and groundwater are distributed in the midstream and downstream sections, with a groundwater-to-surface water recharge pattern and recharge ratios of 51.8% and 57.8%, respectively. During the wet season, the hydraulic connection between mainstream surface water and upstream/midstream groundwater is weak, with downstream surface water recharging groundwater at a ratio of 38.8%. Simultaneously, downstream canal water supplies surface water with a recharge ratio of 29.8%.

Key words: brackish water; hydrogen-oxygen stable isotopes; water chemistry; transformation relationship; Kushui River Basin

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Water resources in the arid and semi-arid regions of northwest China are characterized by scarcity, uneven distribution, and widespread brackish water. Brackish water constitutes an important component of unconventional water resources. While no unified definition currently exists, based on relevant research, this study defines brackish water as water with mineralization greater than 2 $g \cdot L^{-1}$ or sulfate content exceeding 350 $mg \cdot L^{-1}$. In recent years, research on unconventional water resources has gained increasing attention. Investigating the transformation relationship between surface water and groundwater facilitates understanding of basin hydrological cycles and provides a scientific basis for sustainable brackish water resource development. The transformation between surface water and groundwater represents a crucial hydrological process influenced by climate, coupling of different hydrogeological units, hydrochemical processes, and human activities, resulting in changes in water quantity, chemical composition, temperature, and energy. Analyzing these spatiotemporal variations enables the reconstruction of water cycle processes.

Previous studies on surface water-groundwater interactions in northwest China's arid and semi-arid regions have primarily focused on freshwater basins such as the Heihe River, Bayin River, and Bortala River, while research on brackish water basins remains limited. The Kushui River, the second largest tributary of the Yellow River in Ningxia, represents a major brackish water distribution area. Previous research on this region has emphasized surface water hydrological processes, water quality assessment, and brackish water resource evaluation, yet the transformation relationship between surface water and groundwater has not been investigated. This study analyzes the hydrochemical and hydrogen-oxygen stable isotope spatiotemporal evolution patterns of different water bodies in the Ningxia Kushui River Basin to explore regional water cycle characteristics and provide scientific support for sustainable brackish water resource development in arid and semi-arid regions of northwest China.

1. Study Area Overview

The Kushui River originates from Shapozigou Gounao in Tianshuibao Town, Huan County, Gansu Province, flowing through Huan County in Gansu and Wuzhong City and Lingwu City in Ningxia, with a total basin area of 5,447 km^2. This study focuses on the Ningxia portion of the Kushui River Basin (106°03 09 –107°05 59 E, 36°54 00 –38°03 57 N), covering an area of 5,171 km^2. The region experiences a continental arid/semi-arid climate with annual temperatures of 7.3–9.8°C and average annual precipitation of 188.8–264.6 mm. Precipitation distribution is uneven, with 57%–61% concentrated in specific periods. The Tianshui River serves as the main tributary. For this study, the area south of Quanziwan is designated as upstream, the section from Quanziwan to Biandangou Town as midstream, and the area from Biandangou Town to the Yellow River confluence as downstream.

The basin exhibits complex topography and diverse landforms, generally sloping from high in the south and west to low in the north and east. The upstream eastern area comprises eroded loess hills, while the western area consists of alluvial-proluvial intermontane plains. The midstream eastern area features denudation platforms, and the western area comprises eroded red-rock hills. The downstream area is a flat, open alluvial-lacustrine extensional plain.

Groundwater in the basin can be classified into four types: Quaternary porous water, clastic rock fissure water, carbonate karst water, and bedrock fissure water. Quaternary porous water is primarily distributed in the Kushui River valley plain, alluvial-proluvial fans east and north of Luoshan Mountain, and the downstream alluvial-lacustrine plain. Clastic rock fissure water is distributed in the southern Xiamaguan Town area and the western eroded red-rock hills and denudation platforms of the midstream section, with poor water quality. The upper portions of clastic rock fissure aquifers often develop Quaternary porous water. Bedrock fissure water is mainly distributed in the Luoshan area in the southwestern part of the basin, while carbonate karst water occurs in small areas of the Qinglongshan region in the south-central basin [Figure 1: see original paper].

2.1 Sample Collection and Testing

Sampling points were established along the Kushui River mainstream and its Tianshui River tributary. Groundwater samples (n=30) and surface water samples (n=15) were collected during the dry season (November 2021), while groundwater samples (n=30) and surface water samples (n=15) were collected during the wet season (July 2022). Groundwater sampling points were primarily located in private wells within 10–20 m of surface water sampling points, with well depths of 10–20 m, mainly tapping Quaternary porous water. Before sampling, bottles were rinsed 3–5 times with the water sample, sealed with parafilm, and stored in a 保温箱 (incubator).

Hydrochemical testing was conducted by the Yinchuan Mineral Resources Supervision and Monitoring Center Laboratory of the Ministry of Land and Resources. Total dissolved solids (TDS) were measured using the gravimetric method, Na^+ and K^+ 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. Hydrogen-oxygen stable isotope testing was performed by the Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, using a Liquid Water Isotope Analyzer (DLT-100). Results are expressed as per mil (‰) deviations relative to Vienna Standard Mean Ocean Water, with analytical precisions of $\delta D <$ \$±\$1‰ and $\delta^{18}O <$ \$±\$0.1‰.

[Figure 1: see original paper] Distribution of sampling points in study area

2.2 Calculation Method for Surface Water and Groundwater Conversion Ratio

Based on the law of mass conservation, the mixing ratio of different water bodies can be quantitatively analyzed using hydrogen-oxygen stable isotopes (or other stable hydrochemical parameters). The formula is expressed as:

$\delta_{mix} = \Sigma(f_i \times \delta_i)$

where δ_{mix} represents the isotopic value of the mixed water body, δ_i represents the isotopic value of water body i in the mixture, and f_i represents the proportion of water body i in the mixture. From this equation, the mixing ratios of different water bodies can be calculated. For a two-component mixing system, the equation can be derived to calculate the conversion proportions between surface water and groundwater.

3.1.1 Spatiotemporal Variation Characteristics of Ion Composition

The cation concentration relationship in surface water of the Kushui River Basin is $Na^+ > Mg^{2+} > Ca^{2+} > K^+$, with Na^+ as the dominant cation. The anion concentration relationship is ${SO_4}^{2-} > Cl^- > {HCO_3}^-$, with ${SO_4}^{2-}$ as the dominant anion . The ion composition characteristics of groundwater are generally consistent with surface water. However, significant runoff zonation features are observed in different river reaches. In the upstream and midstream sections, groundwater ion composition matches surface water. In the downstream section, groundwater cation concentrations shift to $Na^+ > Ca^{2+} > Mg^{2+}$, while anion concentrations become ${HCO_3}^- > {SO_4}^{2-} > Cl^-$, with significantly elevated ${HCO_3}^-$ concentrations.

The hydrochemical type of surface water is primarily $SO_4 \cdot Cl\text{-}Na \cdot Mg$, with some $SO_4 \cdot Cl\text{-}Na$ types. Upstream and midstream groundwater shares the same hydrochemical types as surface water, indicating similar hydrochemical formation processes or frequent transformation relationships [Figure 2: see original paper]. Downstream groundwater exhibits mixed hydrochemical types, mainly $HCO_3 \cdot SO_4\text{-}Na \cdot Mg$, $HCO_3 \cdot SO_4\text{-}Na \cdot Ca \cdot Mg$, $HCO_3 \cdot SO_4 \cdot Cl\text{-}Na$, and $SO_4 \cdot Cl\text{-}Na \cdot$

Mg types. This transformation indicates changes in water circulation patterns and hydrochemical formation processes in the downstream area. Surface water and groundwater in the upstream and midstream sections, hosted in clastic rock media, undergo dissolution of soluble carbonate rocks and gypsum through leaching processes, combined with evaporation concentration, gradually increasing mineralization and ultimately forming brackish water.

Characteristics of hydrochemical parameters of surface water and groundwater in different periods

[Figure 2: see original paper] Piper diagram of surface water and groundwater in different periods

3.1.2 Spatiotemporal Variation Characteristics of Total Dissolved Solids (TDS)

During the dry season, surface water TDS ranges from 1.87 to 7.54 $g \cdot L^{-1}$ (mean: 4.18 $g \cdot L^{-1}$), while groundwater TDS ranges from 1.12 to 6.11 $g \cdot L^{-1}$ (mean: 3.91 $g \cdot L^{-1}$). During the wet season, surface water TDS (1.03–4.52 $g \cdot L^{-1}$, mean: 2.45 $g \cdot L^{-1}$) is significantly lower than in the dry season, while groundwater TDS (0.72–5.83 $g \cdot L^{-1}$, mean: 3.14 $g \cdot L^{-1}$) shows smaller temporal variation. The TDS variation amplitude of surface water far exceeds that of groundwater across different periods and runoff zones.

During the dry season, mainstream surface water and upstream/midstream groundwater TDS show a trend of initial increase, then decrease, followed by another increase. Midstream surface water TDS increases due to lateral runoff recharge from relatively water-rich Paleogene-Neogene clastic rock fissure water and continuous dissolution of carbonate rocks and gypsum from clastic rock layers. Groundwater TDS variation trends in the upstream and midstream sections are basically consistent with surface water, indicating obvious recharge-discharge relationships. In the downstream section, both surface water and groundwater TDS show slowly decreasing trends, though groundwater TDS shows local fluctuations at livestock watering points where large-volume, long-duration pumping creates local depression cones, causing surface water infiltration and significant TDS elevation.

During the wet season, surface water TDS decreases significantly compared to the dry season, indicating that atmospheric precipitation is a major recharge source. Midstream surface water TDS shows a decreasing trend with local fluctuations, while both surface water and groundwater TDS in the downstream section show slowly decreasing trends, indicating weak hydraulic connection between surface water and groundwater in the midstream section. Comparison of TDS variation trends reveals that wet season surface water TDS in the downstream section is significantly lower than in the dry season. Tianshui River tributary surface water and groundwater TDS both show trends of initial slow decrease followed by gradual increase, with upstream and midstream groundwater TDS showing fluctuating increases, indicating that the tributary is primarily recharged by groundwater [Figure 3: see original paper].

[Figure 3: see original paper] TDS variation trend of surface water and groundwater in different periods

3.2 Hydrochemical Control Factors

Gibbs diagrams reveal that surface water TDS/(TDS+Na^+) values are primarily located between 0.7 and 1.0, mainly within the evaporation concentration range. Groundwater TDS/(TDS+Na^+) values are primarily between 0.6 and 1.0, with most points in the evaporation concentration zone and a few shifting toward rock weathering control, indicating that ion formation in surface water is dominated by evaporation concentration with minor rock weathering.

Upstream and midstream groundwater TDS/(TDS+Na^+) values range between 0.8 and 1.0, while $Cl^-/(Cl^-+HCO_3{}^-)$ values range between 0.5 and 1.0, indicating that hydrochemical formation processes in both upstream and midstream sections are controlled by evaporation concentration. The hydrochemical formation processes of upstream groundwater and surface water are consistent between wet and dry seasons, suggesting close transformation relationships. Downstream groundwater shows a clear shift from evaporation concentration to rock weathering control, with cation values primarily between 0.4 and 0.7 (still mainly controlled by evaporation) and anion values mostly between 0.1 and 0.3, indicating complete transition to rock weathering control. A few points fall outside the control lines, likely due to human activity impacts [Figure 4: see original paper].

[Figure 4: see original paper] Gibbs diagram of surface water and groundwater in different periods

3.3 Isotopic Characteristics

During the dry season, surface water δD values range from -56.88‰ to -43.70‰ (mean: -52.52‰) and δ^{18}O values range from -8.02‰ to -4.35‰ (mean: -7.49‰). During the wet season, δD values range from -53.93‰ to -43.70‰ (mean: -49.88‰) and δ^{18}O values range from -7.60‰ to -5.47‰ (mean: -6.60‰). Compared to the wet season, dry season isotopes show depletion due to more significant isotopic fractionation at lower temperatures. Dry season groundwater δD values range from -56.88‰ to -43.70‰ (mean: -52.52‰) and δ^{18}O values range from -8.02‰ to -4.35‰ (mean: -7.49‰). Wet season groundwater δD values range from -53.93‰ to -43.70‰ (mean: -49.88‰) and δ^{18}O values range from -7.60‰ to -5.47‰ (mean: -6.60‰). The similarity between dry season surface water and groundwater isotopes reflects limited atmospheric precipitation and dominant two-way transformation between surface water and groundwater as the main hydrological cycle process. Wet season groundwater isotopes are significantly more depleted than surface water, indicating mixed recharge from multiple sources.

The local meteoric water line was derived from monthly precipitation isotope data at the Yinchuan Station of the International Atomic Energy Agency (50 km from the study area): $\delta D = 7.21\delta^{18}O + 5.5$. Dry season groundwater and surface water samples plot below the meteoric water line, with surface water-groundwater isotopic regression slopes of 3.5 and 4.2, respectively, both lower than the meteoric water line slope (7.21), indicating limited atmospheric precipitation recharge and significant evaporation effects across different runoff zones. Upstream mainstream surface water and groundwater samples are scattered, indicating weak hydraulic connection. Midstream and downstream surface water and groundwater samples cluster together, indicating close hydraulic connection [Figure 5: see original paper].

Wet season surface water-groundwater isotopic regression slopes are 2.8 and 3.1, respectively, lower than dry season slopes. Wet season groundwater samples plot on both sides of the meteoric water line, while surface water samples show increasing deviation from the meteoric water line from downstream to upstream, with varying degrees of deviation across runoff zones, indicating enhanced evaporation effects from downstream to upstream. Upstream and midstream mainstream surface water and groundwater samples are scattered, indicating no obvious transformation relationship, while upstream Tianshui River tributary samples cluster closely, indicating strong hydraulic connection. Some downstream groundwater samples show significant $\delta^{18}O$ depletion due to recharge from the strongly water-bearing Quaternary porous aquifer, Yellow River irrigation water, and canal leakage [Figure 5: see original paper].

[Figure 5: see original paper] Relationship between δD and $\delta^{18}O$ of surface water and groundwater in different periods

4. Discussion

Stable isotopes serve as effective tracers for investigating water source recharge and discharge mechanisms. This study examines surface water-groundwater transformation relationships by combining isotopic variation patterns with hydrochemical and hydrogeological conditions.

During the dry season, upstream mainstream groundwater $\delta^{18}O$ values (-7.60‰ to -6.83‰) are enriched compared to surface water (-7.49‰ to -5.47‰). With sharply reduced river discharge and significant ice cover in winter upstream, limited exposed water surface and scarce precipitation indicate that surface water receives minimal lateral runoff recharge from the poorly water-bearing clastic rock fissure aquifers on both banks. Midstream mainstream surface water $\delta^{18}O$ values (-7.49‰ to -6.83‰) are similar to groundwater (-7.60‰ to -6.60‰), with parallel variation trends, indicating midstream surface water is recharged by groundwater at a ratio of 51.8%. Downstream surface water $\delta^{18}O$ shows gradual depletion from Biandangou Town (-6.60‰) to the northern Jinyintan Town (-7.60‰), while groundwater $\delta^{18}O$ shows abrupt depletion, indicating recharge from more isotopically depleted water sources.

The Kushui River downstream is located in the Yellow River alluvial-lacustrine plain irrigation area, where the river channel connects with multiple drainage canals. During the wet season, surface water receives canal water recharge. Although canal water samples were not collected in this study, isotopic data from Fan Guangqun's research on Yinchuan Plain summer canal water (δD = -62.5‰, δ^{18}O = -8.7‰) indicates a canal water recharge ratio of 29.8%. Downstream groundwater samples near Jinyintan Town show significant depletion, suggesting mixing with more depleted isotopes from the Yinchuan Plain peripheral area. Using dry season Yinchua Plain groundwater isotopic data (δD = -72‰, δ^{18}O = -9.8‰) from Fan Guangqun's study, the recharge ratio from peripheral groundwater is calculated at 38.8%.

Tianshui River tributary surface water δ^{18}O shows gradual enrichment during the dry season due to evaporation, while groundwater heavy isotopes show fluctuating variations, indicating weak hydraulic connection. During the wet season, upstream mainstream surface water δ^{18}O values (-5.47‰ to -4.35‰) show enrichment trends, while upstream groundwater δ^{18}O (-7.60‰ to -6.83‰) is significantly different, indicating evaporation-controlled isotopic enrichment and weak hydraulic connection. Upstream mainstream surface water δ^{18}O abruptly depletes from -4.35‰ to -7.60‰ upon receiving Tianshui River tributary inflow, then gradually enriches due to evaporation along the flow path. Midstream groundwater δ^{18}O shows opposite trends to surface water due to lateral recharge from western clastic rock fissure water, indicating no significant transformation relationship between midstream surface water and groundwater [Figure 6: see original paper].

[Figure 6: see original paper] Trend of δ^{18}O in surface and groundwater in different periods

Research on brackish water has primarily focused on formation mechanisms and distribution characteristics. However, brackish water basins are predominantly located in ecologically fragile arid and semi-arid regions of northwest China, where protection of native water environments during resource development requires attention. This study, based on geological background, hydrogeological conditions, and sampling data from the Ningxia Kushui River Basin, discusses the transformation relationship between surface water and groundwater in different river sections and periods, reflecting the complexity of water cycle mechanisms and susceptibility to human activities. This underscores the importance of scientific development approaches for ecological protection and effective water resource utilization in brackish water basins.

Due to the complex geological background, local-scale water cycle mechanisms in the Kushui River Basin remain unclear, with several limitations requiring improvement: (1) The meteoric water line uses outdated data from the Yinchuan IAEA station. Given significant spatiotemporal variation in precipitation isotopes and climate change impacts, long-term precipitation isotope data collection across river sections is needed to ensure accuracy. (2) This study uses only one-year sampling data to represent wet and dry season characteristics, which may limit representativeness; multi-year sampling should enhance data reliability. (3) In human activity-intensive downstream areas, hydrochemical and isotopic compositions show irregular variations, indicating altered regional water cycle patterns that require further investigation of impact mechanisms and intensity.

5. Conclusions

(1) The hydrochemical type of surface water in the Kushui River Basin is primarily $SO_4 \cdot Cl\text{-}Na \cdot Mg$, with minor $SO_4 \cdot Cl\text{-}Na$ types. Upstream and midstream groundwater shares similar hydrochemical types with surface water, while downstream groundwater exhibits mixed types. The hydrochemical formation process in upstream and midstream sections is dominated by evaporation, whereas downstream groundwater is controlled by rock weathering. TDS variation patterns along the flow path show significant differences across periods and runoff zones.

(2) The isotopic distribution characteristics of surface water and groundwater show obvious variations across different periods and runoff zones. During the dry season, temperature effects cause significant isotopic depletion in both surface water and groundwater. During the wet season, atmospheric precipitation recharge and evaporation effects are stronger than in the dry season. Downstream groundwater receives strong recharge from Yellow River alluvial plain groundwater and irrigation water, resulting in significant isotopic depletion.

(3) Influenced by climate, hydrogeological conditions, topography, and human activities, the transformation relationship between surface water and groundwater in the Kushui River Basin shows significant spatiotemporal variation characteristics. During the dry season, upstream surface water receives limited groundwater recharge, while midstream and downstream sections exhibit surface water recharging groundwater at ratios of 51.8% and 57.8%, respectively. During the wet season, upstream and midstream surface water and groundwater show no significant transformation relationship, while downstream surface water recharges groundwater at 38.8% and receives canal water recharge at 29.8%.

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