

## Analysis of Hydrochemical Characteristics and Groundwater Recharge Sources in the Hotan River Basin (Postprint)

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### Abstract

To investigate the hydrochemical characteristics and groundwater recharge features of the Hetian River Basin, SPSS statistical analysis, Piper diagrams, Gibbs diagrams, and hydrogen-oxygen and  $^{14}\text{C}$  isotope tracing were employed to analyze the hydrochemical composition, recharge sources, and transformation relationships of water bodies (well water, pond water, and river water) across different geomorphological units. The results indicate: (1) All water bodies primarily originate from meltwater from ice and snow and atmospheric precipitation in the middle-high mountain areas above 2000 m in the southern region. From the mountainous area to the desert area, groundwater hydrochemical types exhibit distinct zonation characteristics. The pH values of different water bodies are all weakly alkaline, with significant differences in ion composition and TDS values, generally following the pattern of pond water > well water > river water.  $\text{NO}_3^-$  content is significantly anomalous in a few groundwater sampling points. (2) In the gravel plain area, groundwater receives substantial vertical disconnected recharge from surface river water. Groundwater exhibits low TDS values and rapid renewal rates, and is primarily controlled by water-rock dissolution, with hydrochemical types predominantly being  $\text{SO}_4 \cdot \text{Cl} \cdot \text{Ca} \cdot \text{Mg}$  type. (3) In the fine soil plain area, total dissolved solids (TDS) values of groundwater show large variations, mostly being  $\text{Cl} \cdot \text{SO}_4 \text{--Na}$  type. Within the interfluvial area, groundwater in the upstream section receives recharge from surface water and lateral runoff from adjacent areas, with young  $^{14}\text{C}$  ages; in the middle and lower reaches, the “oxygen shift” phenomenon in hydrogen-oxygen isotopes is widespread. Groundwater at the watershed divide has old  $^{14}\text{C}$  ages, while ages near the riverbank are young, indicating close hydraulic connection between groundwater and river water. Groundwater on both sides of the interfluvial area flows in the northeast and northwest directions, respectively, eventually discharging into the peripheral desert area. The research results can provide a

scientific theoretical basis for rational development, utilization, and protection of water resources and ecological environment in the Hetian River Basin.

## Full Text

### Abstract

To investigate the hydrochemical characteristics and groundwater recharge patterns in the Hotan River Basin, we employed statistical analysis, Piper and Gibbs diagrams, and hydrogen-oxygen isotope tracing to analyze water chemistry, recharge sources, and transformation relationships among different water bodies (well water, pond water, and river water) across various geomorphic units. The results demonstrate that: (1) All water bodies primarily originate from ice-snow meltwater and atmospheric precipitation in the mid-high mountainous areas above 2000 m elevation in the southern region. From the mountainous area to the desert zone, groundwater hydrochemical types exhibit distinct zonal characteristics. All water bodies are weakly alkaline, with significant variations in ion composition and TDS values following the pattern: pond water > well water > river water. A few groundwater samples show notably anomalous  $\text{NO}_3^-$  concentrations. (2) The gravel plain area receives substantial vertical, disconnected recharge from surface river water. Groundwater in this zone has low TDS values, rapid renewal rates, and is dominated by water-rock interaction processes, with hydrochemical types primarily presenting as  $\text{SO}_4 \cdot \text{Cl-Ca} \cdot \text{Mg}$ . (3) Groundwater in the fine-soil plain area is recharged by surface water and lateral runoff from adjacent areas, with large TDS variation ranges, predominantly showing  $\text{Cl} \cdot \text{SO}_4\text{-Na}$  types. Near the riverbanks, groundwater  $^{14}\text{C}$  ages are young, indicating close hydraulic connection with river water. Groundwater on both sides of the inter-river block flows northeastward and northwestward, respectively, eventually discharging into the peripheral desert area. The “oxygen shift” phenomenon in hydrogen-oxygen isotopes is widespread in middle and lower reach groundwater. Groundwater at the watershed divide shows large TDS variation, mostly of the  $\text{Cl} \cdot \text{SO}_4\text{-Na}$  type. Within the inter-river block, groundwater near the upper reaches receives recharge from surface water and lateral runoff, with young  $^{14}\text{C}$  ages. These findings provide a scientific basis for rational water resource development and ecological environmental protection in the Hotan River Basin.

**Keywords:** hydrochemistry; groundwater; recharge source; isotope; Hotan River Basin

### 1.1 Study Area Overview

The Hotan region is located in southern Xinjiang, with terrain sloping from high in the south to low in the north, with elevations ranging from 1102 to 7282 m. The southern region comprises the Kunlun Mountains, the southwest features the Karakoram Mountains, and the northern boundary is the Taklamakan Desert. The Hotan River Basin lies at the center of the Hotan region,

characterized by an arid climate with scarce rainfall. The annual average water surface evaporation exceeds 2000 mm, while the multi-year average precipitation is only about 35 mm, making the aridity index greater than 25. Based on natural geography and runoff conditions, the basin can be divided into mountainous, plain, and desert zones corresponding to upstream, midstream, and downstream sections.

The upstream mountainous area (Fig. 1) provides favorable dynamic conditions and recharge sources for groundwater in the basin, with high elevations and perennial ice-snow meltwater in the mid-high mountain zones. Vegetation is sparse, bedrock is extensively exposed, weathering is intense, and fractures are well-developed. Overall water abundance is poor, with relatively water-rich zones occurring only in fault water-bearing zones. Groundwater primarily discharges as springs and provides lateral recharge to adjacent areas through leakage.

The low mountain and hilly area serves as the basin's convergence zone, with well-developed surface gullies but poor infiltration recharge conditions and water table depths exceeding 50 m. Groundwater occurs as clastic rock fissure-pore water with poor and uneven water abundance, generally less than 500 m<sup>3</sup>/d.

The midstream piedmont alluvial plain is the main occurrence, enrichment, and transformation zone for Quaternary unconsolidated pore water. Based on differences in geomorphic lithofacies zones and aquifer structures, this area is divided into gravel plain and fine-soil plain geomorphic units. The gravel plain consists of multiple alluvial fans of varying sizes that are connected and superimposed at the piedmont. Groundwater recharge conditions are poor, with depths generally between 3–50 m and weak water abundance, mostly within 1000 m<sup>3</sup>/d. The fine-soil plain primarily comprises weakly inclined plains where hydrological networks develop in gravel or silty alluvial layers within the Yurungkash River and Karakash River (hereafter referred to as “Yurungkash River” and “Karakash River”) basins. The strata are loose with well-developed pores, and surface water-groundwater exchange is frequent. Groundwater tables are generally shallow, mostly within 3–18 m, with water abundance between 1000–3000 m<sup>3</sup>/d, locally exceeding 3000 m<sup>3</sup>/d.

The inter-river block is located between the Yurungkash and Karakash Rivers, distributed as a narrow strip in the northeast direction with a width of approximately 8–15 km. The downstream desert area features well-developed dune depressions, with groundwater primarily occurring in the underlying alluvial-proluvial layers beneath the plain zone. The aquifers are mostly fine sand, locally interbedded with silty sand, thin sandy loam, or lens bodies. Groundwater runoff conditions are poor, mainly receiving lateral recharge from upstream groundwater underflow, with temporary flood infiltration during extreme flood events also serving as a groundwater source. Water table depths are mostly 1–3 m, with discharge dominated by vertical evaporation and local vegetation transpiration.

## 1.2 Data Sources and Processing

Between May and June 2021, fieldwork for the “Key Basin Groundwater Flow Field Investigation” project was conducted in the Hotan River Basin, during which 50 full-analysis water samples and hydrogen-oxygen isotope samples were collected, including 33 well water samples (well depths 50–130 m, water table depths 2.17–16.35 m), 9 pond water samples, and 8 river water samples. Additionally,  $^{14}\text{C}$  samples were collected at 6 selected well water sampling points. Throughout the process, water sample collection and preservation strictly followed the Groundwater Quality Standard.

Full-analysis water samples were tested by a unit with Class-A geological experimental testing qualifications and national metrology certification. Test items included conventional ions, dissolved total solids (TDS), hydrogen ion concentration index (pH), total hardness (TH), and other comprehensive indicators. Hydrogen-oxygen isotope samples were determined by mass spectrometry with analytical precision:  $\delta\text{D} < 1\text{‰}$ ,  $\delta^{18}\text{O} < 0.2\text{‰}$ .  $^{14}\text{C}$  isotope samples were tested using ultra-sensitive accelerator mass spectrometry (AMS) technology.

During data processing, SPSS statistical software was used for descriptive statistics of main water sample indicators. Aquachem software generated Piper triangular diagrams for characteristic analysis and classification of major ions. The Gibbs diagram method was used to summarize hydrochemical evolution processes under different controlling factors. Related charts and formulas were processed using Photoshop, MathType, and Visio software.

## 1.3 Research Methods

Based on test results and combined with the geological, geomorphological, and hydrogeological conditions of the study area, hydrochemical components, hydrogen-oxygen isotopes, and  $^{14}\text{C}$  isotopes were used as tracer indicators to analyze hydrochemical characteristics, recharge sources, and water body transformation relationships.

### 2.1.1 Parameter Statistical Characteristics

Statistical results (Table 1) show that all water bodies are weakly alkaline. Groundwater TDS values range from 381.16–3062.20  $\text{mg} \cdot \text{L}^{-1}$ , mostly freshwater or slightly brackish water (1000.00–1500.00  $\text{mg} \cdot \text{L}^{-1}$ ), except for sample point HT-18 east of the desert highway in the hinterland with TDS of 3062.20  $\text{mg} \cdot \text{L}^{-1}$ , likely related to its specific hydrogeological conditions. River water is all freshwater with TDS  $< 500.00 \text{mg} \cdot \text{L}^{-1}$ . Pond water TDS ranges from 1000.00–3028.06  $\text{mg} \cdot \text{L}^{-1}$ , all being slightly brackish or brackish water.

Spatially, from the low mountain and hilly area in the south to the aeolian desert area in the north, TDS values of different water bodies gradually increase, showing a clear zonal evolution pattern. Ion content variation coefficients ( $C_v$ ) for well water samples show  $\text{NO}_3^-$  values larger than other ions, with some samples

significantly exceeding natural background values, likely related to domestic sewage, feces, or agricultural fertilizers from human activities. Major ion indicator values follow the pattern: pond water > well water > river water. Cv values for river water indicators are significantly smaller than those for well and pond water, indicating less dispersion and suggesting that river water's chemical composition is less affected by other water bodies during rapid downstream transport through the fine-soil plain, primarily recharging groundwater through infiltration.

### 2.1.2 Types and Spatial Distribution

As shown in the Piper diagram (Fig. 3), groundwater characteristics are dominated by mixed types. Combined with sample distribution locations, from south to north, hydrochemical types in the gravel plain area are mostly  $\text{SO}_4 \cdot \text{Cl-Ca} \cdot \text{Mg}$ , while those in the fine-soil plain and desert areas are mostly  $\text{Cl} \cdot \text{SO}_4\text{-Na}$ , showing obvious spatial zonation. Only sample point HT-07 on the left bank of the Yurungkash River falls in the  $\text{HCO}_3\text{-Ca} \cdot \text{Mg}$  type, further indicating that the inter-river block watershed affects local groundwater hydrochemical composition. River water samples are extremely concentrated as a single  $\text{SO}_4 \cdot \text{Cl-Ca} \cdot \text{Mg}$  type, with hydrochemical structure essentially identical to that of gravel plain groundwater, indicating that river water and gravel plain groundwater share the same primary recharge sources—likely ice-snow meltwater or precipitation from the southern mid-high mountainous areas.

Gibbs model results show all groundwater samples are far from atmospheric precipitation control areas, falling within water-rock interaction and evaporation-concentration zones. For groundwater, samples from the fine-soil plain and aeolian desert area east of the Karakash River boundary line mainly fall in the evaporation-concentration zone, while samples west of the Karakash River (e.g., HT-01, HT-02, HT-03) are clearly controlled by water-rock interaction. According to water level monitoring data, water table depths at these sample points are significantly greater (mostly >30 m) than in other areas, suggesting that groundwater here is more likely recharged by lateral runoff from the gravel plain area. River water samples are concentrated in the water-rock interaction zone, further confirming that river water originates mainly from ice-snow meltwater or atmospheric precipitation in the southern mid-high mountainous areas. Among pond water samples, except for HT-22 located in the river network system of the fine-soil plain, all other samples fall in the evaporation-concentration zone, again indicating complex hydraulic relationships among water bodies within the inter-river block.

## 2.2 Groundwater Source Analysis

Stable isotope tracing is a relatively new research method that provides crucial insights into groundwater recharge sources, migration, and circulation processes. The concept of deuterium excess (d-excess) can reflect the degree of imbalance in

atmospheric precipitation, evaporation, and condensation processes in a region and better describe and quantify differences in hydrogen-oxygen stable isotope composition among different water bodies.

As seen in parameter statistical characteristics and the  $\delta D$ - $\delta^{18}O$  relationship curve (Fig. 5), all water bodies fall within the variation range of the Hotan local meteoric water line ( $\delta D = 7.8\delta^{18}O + 8.1$ ), indicating that atmospheric precipitation is the main recharge source for water bodies in the region. For well water,  $\delta D$  and  $\delta^{18}O$  values are negative, with d-excess fluctuating between -7.45–9.31‰, significantly smaller than those of pond and river water, indicating weaker evaporation effects. All samples plot near the meteoric water line and are biased toward the upper left side, suggesting that groundwater recharge sources may be mountainous precipitation or mid-high mountain ice-snow meltwater. Additionally, sample HT-09 in the desert oasis area north of Luopu County on the east side of the Yurungkash River shows the most significant heavy isotope depletion, with d-excess > 10‰, indicating that the recharge area is likely in the distant southern mid-high mountainous region.

For river water,  $\delta D$  and  $\delta^{18}O$  values are the most negative and samples are most concentrated, with d-excess of 8.31–9.85‰, significantly smaller than pond water. Combined with previous hydrochemical analysis, this indicates that river water's primary recharge source is ice-snow meltwater or precipitation from mid-high mountainous areas. Pond water samples show the largest range and Cv values, plotting mostly in the lower left near the Karakash River's right bank, especially sample HT-21 near the north of the inter-river block, where the "oxygen shift" phenomenon is more pronounced, indicating that other water bodies experience strong evaporation during recharge to pond water. Additionally, d-excess values for pond water are significantly smaller than those for well and river water, indicating a larger proportion of groundwater recharge with longer transport time in the aquifer, likely originating from the distant southern mid-high mountainous area.

Using the elevation effect of  $\delta^{18}O$ , the recharge source elevation H (m) of atmospheric precipitation infiltrating the groundwater aquifer was calculated using the formula:  $H = h + (\delta g - \delta p)/k$ , where h is the groundwater sampling elevation (m),  $\delta g$  is the groundwater isotope value,  $\delta p$  is the atmospheric precipitation isotope value in the study area (using the weighted average value of Hotan local atmospheric precipitation isotopes), and k is the elevation gradient (using the global average elevation gradient of  $-0.28‰ \cdot (100m)^{-1}$ ). Calculations show that groundwater recharge source elevations range from 1710–3272 m, with an average of 2313 m. Among these, 20 samples have elevations >2000 m, indicating that ice-snow meltwater and atmospheric precipitation from the southern mid-high mountainous areas above 2000 m are the main groundwater recharge sources in the basin (Table 2).

$^{14}C$  dating results show that  $^{14}C$  ages generally increase from south to north (Fig. 6). In terms of distance from the main river channel, groundwater near the Yurungkash River shows young  $^{14}C$  ages (330–320 a.B.P.), indicating sig-

nificant influence from river channel recharge. Relatively distant samples, especially HT-13 at the inter-river block watershed, show a groundwater age of 9780 aB.P., far exceeding the age near the riverbank. Combined with hydrochemical and isotope analysis, this suggests that groundwater at the inter-river block watershed discharges laterally to both riverbanks, with recharge sources in the distant southern low mountain and hilly area or mid-high mountainous area. Sample HT-11 in Wuerqi Township, Moyu County, shows a young  $^{14}\text{C}$  age due to extensive canal systems and active agricultural production, shallow water table depth, high artificial exploitation, and complex mixing and transformation. Sample HT-18, located in the desert hinterland east of the Hotan Desert Highway far from the Yurungkash River main channel with minimal human activity, shows an age of 7290 aB.P., indicating long residence time in the aquifer and confirming that groundwater mainly originates from southern mid-high mountainous ice-snow meltwater and atmospheric precipitation.

### 3 Conclusions

Through hydrogeological investigation and hydrochemical sampling analysis, combined with hydrogen-oxygen stable isotope tracing and  $^{14}\text{C}$  radiometric dating methods, this study examined hydrochemical characteristics, groundwater recharge sources, elevation zone estimation, and water transformation relationships across different geomorphic units. The main conclusions are:

- (1) All water bodies are weakly alkaline. Ion contents ( $\text{K}^+$ ,  $\text{Na}^+$ ,  $\text{Ca}^{2+}$ ,  $\text{Mg}^{2+}$ ,  $\text{Cl}^-$ ,  $\text{SO}_4^{2-}$ ,  $\text{HCO}_3^-$ ) and TDS values follow the pattern: pond water > well water > river water. Pond water has the highest average TDS ( $3028.06 \text{ mg} \cdot \text{L}^{-1}$ ), significantly influenced by evaporation. River water TDS is  $<500.00 \text{ mg} \cdot \text{L}^{-1}$ , dominated by water-rock interaction. The Cv value for  $\text{NO}_3^-$  in some groundwater samples is large, with partial content exceeding standards.
- (2) River water originates from ice-snow meltwater or precipitation in the southern mid-high mountainous areas. The piedmont gravel plain is the main recharge and transformation zone for basin groundwater, receiving substantial vertical, disconnected infiltration recharge from surface river water. Groundwater in this zone has low TDS, large d-excess values, young  $^{14}\text{C}$  ages, rapid renewal rates, and hydrochemical types mostly presenting as  $\text{SO}_4 \cdot \text{Cl-Ca} \cdot \text{Mg}$ .
- (3) Groundwater in the fine-soil plain area is recharged by surface water and lateral runoff, with large TDS variation ranges, predominantly  $\text{Cl} \cdot \text{SO}_4\text{-Na}$  types. Influenced by surface water, lateral runoff, and evaporation, groundwater near the upstream area of the inter-river block shows young  $^{14}\text{C}$  ages, while middle and lower reach groundwater generally exhibits “oxygen shift” phenomena.
- (4) Hydrochemical characteristics within the inter-river block are complex. Groundwater at the watershed divide has old  $^{14}\text{C}$  ages, mainly receiv-

ing lateral runoff recharge from upstream adjacent areas. Near-riverbank groundwater has young ages, indicating close hydraulic connection with river water. Groundwater on the east side of the Yurungkash River and west side of the Karakash River generally flows northeastward and northwestward, respectively, discharging laterally into the peripheral desert area near the fine-soil plain edge overflow zone.

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