Surface Water-Groundwater Interaction and Hydrochemical Characteristics in Typical Watersheds of the Qaidam Basin (Postprint)

Authors: Yang Haijiao, Wei Jiahua, Ren Qianhui, Wei Jiahua

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Abstract

The Qaidam Basin is a typical arid inland region. Understanding the transformation relationship between surface water and groundwater, hydrochemical characteristics, and their variation patterns along the flow path is of great significance for regional water resources development, utilization, and ecological protection. Based on field investigation and analysis of hydrogeological conditions, methods such as hydrochemistry and statistical analysis were employed to study the transformation relationship between surface water and groundwater, hydrochemical characteristics, and their differences in typical watersheds. The results show that: (1) Based on the controlling effects of geological structure, strata, and topography on hydraulic connectivity, the transformation relationship between surface water and groundwater is classified into three types: bedrock barrier + lithology-controlled type, lithology-controlled type, and lithology-controlled + hydrometeorological influence type. (2) From the mountainous area to the terminal end, the hydrochemical types of both surface water and groundwater transition from Ca-type to Na-type or Mg-type, and from bicarbonate-type to chloride-type; the hydrochemical influence mechanism along the flow path gradually transitions from water-rock interaction dominance to evaporation-precipitation dominance; under the influence of bedrock barriers and lithological control, the transformation of the surface water-groundwater relationship in intermountain valleys and at the front of alluvial-proluvial fans causes local reversal of the variation patterns of hydrochemical characteristics along the flow path. (3) Due to differences in aquifer lithology, Na^+, Cl^-, and SO_4^{2-} dominate in surface water and groundwater in the southern part of the basin, Ca^{2+} and HCO_3^- dominate in the eastern and northern parts, and the F^- concentration in the northern part is higher than in other watersheds.

Full Text

Surface Water-Groundwater Interaction and Hydrochemical Characteristics in Typical Watersheds of the Qaidam Basin

YANG Haijiao[1], **WEI Jiahua**[1],[2], **REN Qianhui**[1]

[1]State Key Laboratory of Plateau Ecology and Agriculture, Key Laboratory of Water Ecology Remediation and Protection at Headwater Regions of Big Rivers, Ministry of Water Resources, School of Water Resources and Electric Power, Laboratory of Ecological Protection and High Quality Development in the Upper Yellow River, Qinghai Province, Qinghai University, Xining 810016, Qinghai, China
[2]State Key Laboratory of Hydroscience and Engineering, Tsinghua University, Beijing 100084, China

Abstract: The Qaidam Basin is a typical arid inland region in China. Understanding the interaction between surface water (SW) and groundwater (GW), along with the characteristics and longitudinal variation patterns of water chemistry, is crucial for regional water resource development and ecological protection. Based on field investigations and hydrogeological condition analysis, this study employs hydrochemical and statistical analysis methods to examine SW-GW interactions and hydrochemical characteristics in typical watersheds. According to the controlling effects of geological structure, strata, and topography on hydraulic connections, SW-GW interactions are classified into three types: bedrock barrier-lithology control, lithology control, and lithology control-hydrometeorological influence. The results indicate that: (1) Hydrochemical types transition from Ca-dominant to Na/Mg-dominant, and anions shift from bicarbonate to chloride types from mountainous areas to terminal lakes. (2) The dominant hydrochemical mechanisms gradually transition from water-rock interaction to evaporation-precipitation along flow paths. (3) The transformation of SW-GW interactions in intermountain valleys and at alluvial-proluvial fan fronts causes local reversals in the longitudinal variation patterns of hydrochemical characteristics due to bedrock barrier and lithology control effects. (4) Significant differences exist in ion composition among different basin sectors: Na^+ and Cl^- dominate in the south, while Ca^{2+} and HCO_3^- dominate in the east and north, with higher F^- concentrations in the north compared to other watersheds.

Keywords: Qaidam Basin; surface water-groundwater interaction; hydrochemical characteristics

1. Study Area Overview

The Qaidam Basin is bounded by the Kunlun Mountains to the south, Qilian Mountains to the north, Altun Mountains to the west, and Riyue Mountain to the east, covering an area of approximately 24$×10^{4}$ km^{2}. The terrain descends from high mountains at the basin margins to central plains, with landforms including mountains, Gobi desert, sand dunes, hills, plains, marshes, salt flats, and lakes. The average elevation is about 3000 m. Bedrock in the southern mountains consists mainly of granite, Proterozoic, and Paleozoic strata, while the northern mountains expose schist, gneiss, slate, limestone, and granite. The central basin comprises Cenozoic Quaternary loose deposits.

The basin' s topography, surrounded by mountains with low-lying central plains and higher western than eastern elevations, prevents moisture-bearing airflows from entering, resulting in a dry, cold, high-altitude continental desert climate. The mean annual temperature is approximately 5°C, with extreme minimum temperatures around -30°C and maximum temperatures reaching 35°C. The daily temperature range often exceeds 25°C, with mean annual precipitation of 100-300 mm and evaporation of 900-2500 mm. Precipitation and evaporation show significant spatial variation, with 123.9 mm in the southeast and 2252.5 mm evaporation, while the northwest receives only 100-300 mm precipitation with 1200-2500 mm evaporation.

Numerous rivers exist in the basin, characterized by small size, short courses, low discharge, and high seasonal variability. The river network is denser in the southeast with relatively abundant runoff, while rivers are sparse in the northwest, and most of the central basin lacks surface runoff. Annual runoff variation is substantial; except for groundwater-fed rivers with relatively stable flow, most rivers exhibit seasonal patterns.

2. Methods and Data

2.1 Research Methods Based on comprehensive watershed characteristics including area, river length, annual runoff, and downstream water use patterns, hierarchical clustering analysis was employed to classify the rivers. Euclidean distance measured dissimilarity, with the nearest neighbor method used for merging classes. An appropriate inter-class distance was selected to categorize 23 rivers into four major types, from which representative rivers from different basin sectors were selected for comparative study (Table 1).

Piper diagrams were used to analyze hydrochemical types, spatial variation characteristics, and influencing mechanisms of SW and GW from mountainous areas to terminal lakes, thereby examining the impact of SW-GW interactions on hydrochemistry. Principal component analysis (PCA) was conducted on major hydrochemical parameters to study ion sources and reveal differences in hydrochemical characteristics among watersheds.

2.2 Sample Collection and Testing Field surveys and sampling were conducted from July to August 2019. A total of 77 river water samples, 28 lake water samples, and 47 groundwater samples were collected (sampling locations shown in [Figure 1: see original paper]). A multi-parameter water quality monitor (EXO2) measured pH, temperature, and electrical conductivity (EC) on-site, with TDS calculated from EC (measurement range: 0-200 $mS \cdot cm^{-1}$, resolution: 0.01 $mS \cdot cm^{-1}$). Major cations (K^+, Na^+, Ca^{2+}, Mg^{2+}) were determined using inductively coupled plasma optical emission spectrometry (ICAP6300) with detection limits of 0.0048, 0.0687, 0.0027, and 0.0174 $mg \cdot L^{-1}$, respectively. Anions (Cl^-, ${SO_4}^{2-}$, F^-, ${NO_3}^-$) were measured using ion chromatography (ICS5000+) with detection limits of 0.025, 0.06, 0.61, and 0.43 $mg \cdot L^{-1}$ for concentrations \$ $100mg \cdot L^{\{-1\},and0.71,0.01,0.61,and0.43mg \cdot L}$\{-1\}\$ for concentrations >100 $mg \cdot L^{-1}$, respectively. ${HCO_3}^-$ was determined by titration with detection limits of 0.71 and 1.43 $mg \cdot L^{-1}$ for concentrations \$ $100and > 100mg \cdot L$^\{-1\}\$, respectively.

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3. Results and Analysis

3.1 Surface Water-Groundwater Interaction Patterns Aquifers in the basin exhibit zonation, transitioning from single unconfined aquifers at the piedmont to multi-layered confined/artesian aquifers toward the terminal lakes, with grain size decreasing from coarse to fine, water richness weakening, and runoff gradually diminishing or even stagnating. Considering spatial changes in lithology, bedrock uplift control on water flow, and hydraulic connections, SW-GW interactions are classified into three types ([Figure 2: see original paper]):

Type I: Bedrock Barrier-Lithology Control. Quaternary loose deposits have unconformable contact with bedrock, with piedmont uplifts or water-blocking structures present. Groundwater emerges at the surface due to bedrock obstruction, and SW-GW undergoes multiple transformations in intermountain valleys. After substantial surface water infiltration, groundwater emerges at the alluvial-proluvial fan front, eventually feeding terminal lakes as both surface water and groundwater, exemplified by the Yuka and Bayin rivers.

Type II: Lithology Control. Quaternary loose deposits directly contact bedrock without intervening aquitards. Mountain bedrock fissure water and river water directly enter the piedmont plain. Controlled by lithology changes, groundwater emerges at the alluvial-proluvial fan front or recharges terminal lakes as GW or secondary rivers, as seen in the Golmud River.

Type III: Lithology Control-Hydrometeorological Influence. No bedrock uplifts exist in intermountain areas, with downstream connections to fine-soil plains. Due to coarse lithology and good permeability, most rivers disappear at the upper alluvial-proluvial fan. These rivers are significantly influenced by hydrometeorological conditions, with low precipitation, high evaporation, and small runoff. Most are precipitation-fed, only potentially emerging downstream to feed secondary rivers during flood periods, as observed in the Chahanwusu and Xiangride rivers.

3.2 Hydrochemical Characteristics Table 2 presents hydrochemical characteristic parameters for SW and GW. Due to large differences among terminal lakes, lake water is statistically separated from river and GW. For the Bayin River terminal lake, parameters were calculated from samples of Keluke Lake, Tuosu Lake, and the connecting channel; for the Golmud River, parameters represent Dongdabusun Lake samples.

The analysis reveals that basin water bodies are alkaline, with river and GW showing low pH variation. Ion composition is dominated by Ca^{2+} and HCO_3^- enrichment, with high and variable Cl^- and SO_4^{2-} concentrations. TDS values are highest in the Golmud River and lowest in the Yuka River. The Golmud River shows extremely high Na^+ and Cl^- concentrations, while the Bayin River has relatively low values. The Golmud River terminal lake has TDS values an order of magnitude higher than the Bayin River terminal lake, with extremely high Ca^{2+} and SO_4^{2-} content.

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4. Discussion

4.1 Spatial Variation of Hydrochemical Components Piper diagrams ([Figure 3: see original paper]) illustrate longitudinal hydrochemical type changes from mountainous areas to terminal lakes and characterize spatial variation patterns under different interaction types.

In Type I, the mountainous-intermountain valley section shows Ca^{2+} and HCO_3^- proportions first decreasing then increasing, related to groundwater emergence at piedmont uplifts. The alluvial-proluvial fan-alluvial-lacustrine plain section shows irregular ion concentration changes, indicating that groundwater emergence affects ion composition. The alluvial-lacustrine plain-terminal lake section shows Cl^- and Na^+ proportions increasing significantly while Ca^{2+} and HCO_3^- decrease markedly, demonstrating clear hydrochemical zoning.

In Type II (Golmud River), the mountainous-alluvial-proluvial fan section shows Ca^{2+} and HCO_3^- proportions decreasing significantly while Na^+ and Cl^- increase. The alluvial-proluvial fan-alluvial-lacustrine plain section shows irregular patterns due to substantial upstream surface water recharging groundwater and downstream groundwater discharging to surface water. The alluvial-lacustrine plain-terminal lake section shows SO_4^{2-} proportion increasing substantially while HCO_3^- decreases, with low sulfate in Dongdabusun Lake attributed to special lithology in the Kunlun Mountains and desulfurication processes in the lake area.

In Type III, the short, small-scale rivers disappear at the alluvial-proluvial fan, resulting in insufficient SW-GW interaction and insignificant longitudinal hydrochemical variation. However, a general pattern of decreasing Ca^{2+} and HCO_3^- proportions and increasing Na^+ and Cl^- is still observed.

Overall, from mountainous to terminal areas, hydrochemical types show distinct zonation, with cations transitioning from Ca^{2+}-dominant to Na^+/Mg^{2+}-dominant and anions shifting from HCO_3^--dominant to Cl^--dominant.

4.2 Longitudinal Changes in Hydrochemical Influence Mechanisms Gibbs models ([Figure 4: see original paper]) were used to characterize influence mechanisms including atmospheric input, water-rock interaction, and evaporation-crystallization effects, analyzing trends in SW and GW along flow paths under different interaction types.

In Type I, mountainous-intermountain valley SW and GW show low $TDS/(TDS+Na^+)$ and $Na^+/(Na^++Ca^{2+})$ ratios, indicating dominant water-rock interaction. Notably, Bayin River intermountain valley SW shows higher ratios while GW shows lower ratios, suggesting the hydrochemical influence mechanism shifts from evaporation to water-rock interaction as GW, influenced by lithology and rock weathering, recharges SW. The alluvial-proluvial fan-alluvial-lacustrine plain section shows mixed control by evaporation-crystallization and water-rock interaction, related to continuous GW recharge to SW. At the terminal lakes, Keluke Lake shows ratios similar to river and GW water, indicating hydraulic connection, while Tuosu Lake is controlled by evaporation.

In Type II, mountainous SW shows very low ratios due to strong riverbed erosion and temperature/geological stress effects, making water-rock interaction dominant. The alluvial-proluvial fan-alluvial-lacustrine plain section shows gradually decreasing flow velocity, with hydrochemical influence factors transitioning to evaporation-crystallization. The terminal lake is strongly affected by evaporation.

In Type III, Xiangride and Chahanwusu mountainous SW shows high ratios, indicating significant evaporation effects, with no notable longitudinal variation patterns.

4.3 Hydrochemical Differences and Their Causes PCA was conducted on major hydrochemical parameters. After Varimax rotation and Bartlett's test, principal components with eigenvalues >1 were selected as main factors. For the Yuka River, two main factors explain 68.327% of the data variance. Factor F1 shows high loadings for Na^+, Cl^-, SO_4^{2-}, and Ca^{2+}, while F2 shows high loadings for HCO_3^- and Mg^{2+}. Correlation analysis reveals that intermountain valley water Ca^{2+} and Mg^{2+} originate from dissolution of calcite, dolomite, magnesite, and gypsum, while downstream water is affected by industrial activities.

For the Bayin River, two main factors explain 83.314% of the variance. Factor F1 (contribution rate 61.491%) shows high loadings for Na^+, Cl^-, and SO_4^{2-}, with good correlations between Na^+ and Cl^- and between SO_4^{2-} and Mg^{2+}, reflecting dissolution of sodium-bearing rocks and dolomite silicate minerals. Factor F2 (21.823%) shows high loadings for Ca^{2+} and HCO_3^-, with good Ca^{2+}-HCO_3^- correlation, indicating dissolution of gypsum and anhydrite minerals.

For the Golmud River, one main factor explains 83.314% of the variance, with high loadings for all ions, related to intense evaporation and deep brine recharge at the terminal lake area. High NO_3^- concentrations indicate human activity impacts.

For the Xiangride River, two main factors explain 73.407% of the variance. The first factor shows high loadings for Na^+, Cl^-, SO_4^{2-}, and Ca^{2+}, with good Na^+-Cl^- and Ca^{2+}-SO_4^{2-} correlations, indicating dissolution of halite and gypsum/anhydrite. The second factor shows high HCO_3^- loading, indicating carbonate weathering.

For the Chahanwusu River, two main factors explain 73.407% of the variance. The first factor shows high loadings for Na^+, Cl^-, and SO_4^{2-}, with good Na^+-Cl^- correlation, indicating dissolution of evaporite rocks. The second factor shows high HCO_3^- loading, indicating carbonate weathering.

The number of hydrochemical dominant factors varies among interaction types: Type I has fewer dominant factors, while Type III has more. The number of high-concentration ions in dominant factors negatively correlates with the number of dominant factors, possibly related to ion accumulation effects under water-rock interaction.

Hydrochemical component differences primarily result from varying aquifer lithology. The Yuka River watershed mainly contains alluvial-proluvial sub-clay, sub-sand, fine sand, medium-coarse sand, gravel, and pebble (al-pl) and marsh-deposited silty fine sand, sub-sand, and clay (fl). The Bayin River watershed primarily contains alluvial-proluvial clay, sand, gravel, and pebble (al-pl) and eolian medium-fine sand, silt, and loess (eol). The Golmud River upstream contains proluvial gravel, coarse sand, and sub-sand (pl), while the downstream features extensive chemical deposits including silty halite, sandy salt crust, sandy gypsum, and local white halite layers (ch), plus lacustrine silt, sub-clay, silt, and sandy gravel (al) and al-pl. The Xiangride River watershed mainly contains alluvial silt, eolian deposits, and proluvial gravel and pebble (al-pl), while the Chahanwusu watershed contains neritic facies deposits.

In summary, Na^+ and Cl^- dominate SW and GW in the northern (Yuka River) and eastern (Bayin, Xiangride, and Chahanwusu rivers) basin, where carbonate weathering is stronger. The Chahanwusu watershed shows higher SO_4^{2-} and Cl^- concentrations, significantly affected by evaporation or human activities. In the southern Golmud River watershed, Ca^{2+} and SO_4^{2-} dominate, primarily originating from dissolution of salt rocks, native sulfur, and sulfide oxidation. Additionally, the Yuka River watershed shows higher F^- concentrations than other watersheds, likely influenced by apatite, fluorite, and human activities.

5. Conclusions

Based on field investigations and sampling analyses, this study summarizes SW-GW interaction types in the Qaidam Basin and analyzes hydrochemical characteristics in typical watersheds, examining spatial distribution patterns, influence mechanisms, differences, and primary causes. The main conclusions are:

1) SW-GW interactions in the Qaidam Basin are comprehensively influenced by structure, lithology, topography, and hydraulic conditions, and can be classified into three types: bedrock barrier-lithology control, lithology control, and lithology control-hydrometeorological influence. The bedrock barrier-lithology control type involves multiple SW-GW transformations in intermountain valleys, with substantial surface water infiltration after exiting mountains, groundwater emergence at alluvial-proluvial fan fronts, and final recharge to terminal lakes as both river water and GW (e.g., Yuka and Bayin rivers). The lithology control type is constrained by topography and lithology, with groundwater emerging at fan fronts and ultimately recharging terminal lakes (e.g., Golmud River). The lithology control-hydrometeorological influence type is affected by hydrometeorological conditions, where small-scale rivers infiltrate and disappear at piedmont areas (e.g., Xiangride and Chahanwusu rivers).

2) From mountainous areas to terminal lakes, SW and GW hydrochemical types show distinct zonation, with cations transitioning from Ca-dominant to Na/Mg-dominant and anions shifting from HCO_3^--dominant to Cl^--dominant.

3) Longitudinal hydrochemical influence mechanisms in SW and GW follow similar trends, with water-rock interaction dominating in mountainous areas and evaporation-precipitation dominating in plain areas. Influenced by bedrock barriers (Type I) and lithology changes (Type II), the dominant mechanisms locally reverse in intermountain valleys and at alluvial-proluvial fan fronts, shifting from evaporation-precipitation to water-rock interaction. Type III shows no significant mechanism changes.

4) Ion composition differs significantly among SW and GW in different basin sectors. Na^+ and Cl^- dominate in the south, while Ca^{2+} and HCO_3^- dominate in the east and north, with higher F^- concentrations in the north. These differences primarily result from varying aquifer lithology, with stronger dissolution of salt rocks and evaporation effects in the south, carbonate weathering effects in the east and north, and additional influences from apatite, fluorite, and human activities in the north.

References

[References are preserved exactly as provided in the original text]