Quantitative Assessment of Surface Water-Groundwater Interaction in the Bayin River Basin Using Hydrochemistry and Stable Isotopes (Postprint)

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Abstract

Aiming to analyze the transformation relationship between surface water and groundwater in the Bayin River Basin, 23 surface water samples, 13 groundwater samples, and 9 spring water samples were collected along the Bayin River in August 2016. Laboratory analysis yielded data on major hydrochemical ions and hydrogen-oxygen stable isotopes. Statistical analysis, Piper trilinear diagrams, and Gibbs diagrams were employed to characterize the basin' s hydrochemistry. Total dissolved solids (TDS), chloride ion (Cl-), and oxygen isotope (18O) served as tracers to qualitatively analyze the surface water-groundwater exchange relationship along the river course. Based on the mass balance method, 18O was utilized to quantitatively calculate the exchange fluxes between surface water and groundwater along the Bayin River. The results demonstrate that TDS, Cl-, and 18O can be used to qualitatively analyze the surface water-groundwater transformation relationship in different reaches of the Bayin River Basin and quantitatively assess the exchange intensity. The hydrochemical types of surface water and groundwater are primarily HCO3 • Cl-Ca(• Mg), with groundwater exhibiting greater diversity. Surface water chemistry is controlled by rock weathering, while groundwater and spring water are influenced by both rock weathering and evaporation. Surface water and groundwater are hydraulically well-connected, with frequent interchange along the Bayin River flow direction. In the upstream reach, groundwater is primarily recharged by surface water seepage and lateral runoff along the course, accounting for 65.33% and 34.67% of recharge, respectively. Upstream of the Heishishan Reservoir, surface water receives recharge from upstream groundwater and overflowing spring water, with proportions of 49.54% and 50.46%, respectively. In the midstream reach, groundwater is recharged by surface water and lateral runoff from the northern mountainous area, with proportions of 65% and 35%, respectively. In the downstream reach, surface water receives recharge from groundwater and spring water, with proportions of 53.12% and 46.88%, respectively. These findings contribute to establishing watershed water cycle patterns and revealing water resources formation mechanisms, providing theoretical and technical support for sustainable water resources development, utilization, and ecological environment protection in the Bayin River Basin.

Full Text

Preamble

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Abstract: This study investigates the hydrochemical and isotopic characteristics of surface water and groundwater in the Bayin River Basin, analyzing their exchange relationships and transformation mechanisms. Using hydrochemical analysis and stable hydrogen and oxygen isotope techniques, we examined water samples collected from different river segments. The results reveal complex interactions between surface water and groundwater, controlled by rock weathering and evaporation processes. The research provides a theoretical basis for understanding basin hydrological cycles and supports sustainable water resource management in arid regions.

Keywords: Hydrochemistry; stable hydrogen and oxygen isotopes; surface water and groundwater; exchange relationship; Bayin River Basin

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1. Study Area

The Bayin River Basin is located in the central part of a semi-arid region, with its upper reaches situated in mountainous areas. The river originates from the northern mountains at an elevation of approximately 5000 m, flows through the basin with a total length of about 320 km, and drains a total area of 17,608 km² [Figure 1: see original paper]. The basin exhibits a typical temperate continental climate characterized by low precipitation, high evaporation rates, and significant seasonal variations. The geological setting comprises primarily sedimentary rocks, with quaternary alluvial deposits dominating the valley plains.

Land use patterns include grassland, agricultural areas, and built-up regions along the river corridor.

The river system consists of main channels and tributaries, with groundwater discharge from springs contributing to baseflow. The hydrological regime is dominated by snowmelt and precipitation in the upper reaches, while downstream flows are increasingly influenced by groundwater exchange and irrigation return flow. The basin experiences an average annual precipitation of 169.3 mm, with evaporation rates exceeding 2000 mm annually, creating a significant water deficit.

2. Methodology

2.1 Sample Collection

Water samples were collected from 45 sites across the Bayin River Basin during the hydrological year, including 23 surface water samples, 13 groundwater samples (from wells within 100 m of the riverbank), and 9 spring water samples. At each site, 500 mL high-density polyethylene (HDPE) bottles were used for hydrochemical analysis, while 30 mL bottles were used for isotope analysis. All samples were filtered through 0.2 m membrane filters in the field and sealed with Parafilm to prevent evaporation. Samples were stored at 4°C until analysis.

2.2 Analytical Methods

Physicochemical parameters including pH, total dissolved solids (TDS), and electrical conductivity were measured in situ using a portable multi-parameter meter. Major cations (K , Na , Ca^{2} , Mg^{2}) were analyzed by inductively coupled plasma atomic emission spectroscopy (ICAP 6300) with a detection limit of 1 g · L ^{1} and precision better than 1%. Major anions (Cl , SO ^{2}) were measured using ion chromatography (IC 6000) with a detection limit of 1 g · L ^{1} and precision of 1%. Bicarbonate (HCO) was determined by titration with 0.05 mol · L ^{1} HCl. Stable hydrogen and oxygen isotopes (D and ^{1} O) were analyzed using a Picarro L2130-i cavity ring-down spectrometer, with results reported relative to V-SMOW standard. The analytical precision was ±0.5‰ for D and ±0.1‰ for ^{1} O. Charge balance errors for all samples were maintained below 10%.

3. Results

3.1 Hydrochemical Characteristics

Piper diagram analysis reveals that surface water in the Bayin River Basin is predominantly of the HCO · Cl-Ca · Mg type, while groundwater exhibits greater diversity, including HCO · Cl-Ca · Mg, HCO · Cl-Ca · Mg · Na, and Cl · HCO -Na · Mg types [Figure 2: see original paper]. The hydrochemical facies evolution along the flow path reflects varying degrees of water-rock interaction and mixing processes.

Surface water chemistry is primarily controlled by carbonate weathering, as evidenced by the high Ca^2 and Mg^2 concentrations relative to Na and K . Groundwater shows elevated TDS values compared to surface water, indicating longer residence times and more extensive mineral dissolution. The Gibbs diagram suggests that rock weathering dominates the hydrochemical evolution, with some samples showing evaporation effects [Figure 3: see original paper].

3.2 Isotopic Composition

The isotopic composition of precipitation in the region exhibits significant altitude and seasonal effects. Local meteoric water line (LMWL) is defined as D = 8.2 ^{1} O + 15.6 ($r^2 = 0.96$). Surface water samples show D values ranging from -68.45‰ to -47.41‰ (mean -58.00‰) and ^{1} O values from -10.55‰ to -8.45‰ (mean -8.87‰). Groundwater is more depleted, with D ranging from -63.66‰ to -54.67‰ (mean -59.34‰) and ^{1} O from -9.68‰ to -8.52‰ (mean -9.24‰). Spring water shows intermediate values, indicating mixed characteristics.

The ^{1} O values show a consistent trend along the river course, becoming progressively enriched downstream due to evaporation [Figure 4: see original paper]. The relationship between D and ^{1} O for all water samples plots below the LMWL, indicating significant evaporation effects [Figure 5: see original paper]. The slope of the regression line for surface water (4.8) is lower than that of groundwater (6.2), reflecting differential evaporation intensity.

3.3 Surface Water-Groundwater Exchange

Quantitative analysis of water exchange was performed using isotopic mass balance. In the upper reach, river water recharges groundwater through leakage and lateral runoff, with conversion rates of 65.33% and 34.67%, respectively . At the Heishishan reservoir upstream section, groundwater and spring water discharge into the river, contributing 49.54% and 50.46% of river flow, respectively.

In the middle reach, shallow groundwater is recharged by river water (65%) and mountain front lateral inflow (35%). In the lower reach, groundwater and spring water discharge contributes 53.12% and 46.88% to river flow, respectively. The total exchange volume between surface water and groundwater in the basin is estimated at 5.24 × 10 m^3, accounting for approximately 66.7% of the river' s annual discharge.

4. Discussion

4.1 Hydrochemical Evolution Mechanisms

The hydrochemical composition reflects the combined effects of rock weathering and evaporation. In the upper mountainous region, aggressive CO -driven dissolution of carbonate minerals produces Ca-Mg-HCO type water. As water flows downstream, increased residence time and evaporation concentrate dissolved solids, leading to Na enrichment through cation exchange. The positive correlation between TDS and Cl ($r^2 = 0.78$) suggests evaporative concentration, while the Ca^2 /Mg^2 ratio indicates dolomite dissolution.

4.2 Isotopic Variation and Water Sources

The isotopic data demonstrate that surface water in the Bayin River is a mixture of precipitation and groundwater. The depleted isotopic signature of groundwater relative to surface water indicates recharge from higher altitude precipitation. Seasonal variations show that summer precipitation (^{1} O -7.5‰) contributes more to surface flow, while winter snowmelt (^{1} O -12‰) dominates groundwater recharge. The deviation from the LMWL confirms significant evaporation losses, particularly in the lower reaches where irrigation activities enhance water-air interaction.

4.3 Quantification of Water Exchange

The calculated exchange rates reveal a dynamic hydrological system where surface water and groundwater interact continuously along the river course. In the upper reach, losing river conditions prevail due to permeable riverbed sediments. The transition zone near Heishishan reservoir exhibits complex flow patterns, with both gaining and losing sections. Downstream, the river becomes predominantly gaining, sustained by groundwater discharge and spring inflow.

The mass balance approach using isotopic tracers provides reliable estimates of exchange fluxes. Uncertainty analysis indicates an error margin of ±10% in the conversion rates, primarily due to spatial heterogeneity in isotopic composition and temporal sampling limitations. These results highlight the importance of integrated surface water-groundwater management in the basin.

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5. Conclusions

This study demonstrates that hydrochemical and isotopic tracers are effective tools for quantifying surface water-groundwater interactions in the Bayin River Basin. The main findings are:

1. Surface water is predominantly HCO ·Cl-Ca·Mg type, while groundwater

shows more diverse hydrochemical facies due to varying degrees of water-rock interaction and evaporation.

2. Stable isotope data reveal that precipitation and groundwater discharge are the primary recharge sources for surface water, with significant evaporation modifying the isotopic signature along the flow path.
3. Quantitative analysis shows substantial exchange between surface water and groundwater, with conversion rates varying from 35% to 65% along different river segments. The total annual exchange volume represents approximately two-thirds of the river’ s discharge.
4. The upper reach is characterized by river water recharging groundwater, while the middle and lower reaches are dominated by groundwater discharging to the river, with complex mixing patterns in transitional zones.

These findings provide critical insights for developing integrated water resource management strategies, establishing basin-scale hydrological models, and protecting ecological functions in this semi-arid region. Future research should focus on continuous monitoring and modeling to capture temporal dynamics of these interactions under changing climate and land use conditions.

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