Postprint: Surface Water-Groundwater Interaction and Its Causes in the Middle Reaches of the Bortala River, Xinjiang

Authors: Gao Fuxiang, Xu Dongsheng, Zhou Jinlong, Zhou Long

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Abstract

The Bortala River basin in Xinjiang is characterized by water resource scarcity and uneven spatiotemporal distribution. Quantitatively calculating the exchange fluxes between surface water and groundwater across different river sections and time periods in the middle reaches holds significant importance for groundwater exploitation and recharge, as well as the optimal allocation of surface water and groundwater resources. Using daily flow measurement data from five monitoring cross-sections in the middle reaches of the Bortala River from December 1, 2021 to November 30, 2022, this study employed river runoff analysis methods, combined with P-III (Pearson-III) type distribution frequency curves, inflow comparison charts for each monitoring cross-section, and hydrogeological profiles to quantitatively analyze surface water and groundwater transformation, and established a fitting relationship between infiltration rate and inflow volume in seepage river sections. The results indicate that: (1) Among the five monitoring cross-sections, Bole Hydrological Station recorded the highest annual inflow, while the Chaxiang Bridge monitoring cross-section recorded the lowest annual inflow. (2) The inflow period from December 1, 2021 to November 30, 2022 in the middle reaches of the Bortala River was classified as a normal water year. (3) In the upper section of the middle reaches, groundwater transforms to recharge surface water; in the middle section from Kundelun Canal Head to Chaxiang Bridge, surface water extensively infiltrates and recharges groundwater, with an infiltration coefficient of 0.67, and the infiltration rate exhibits a significant negative correlation with inflow volume; in the lower section, groundwater again discharges to the surface. The middle reaches of the Bortala River underwent three transformation processes between surface water and groundwater, with the overall pattern being groundwater discharge recharging surface water.

Full Text

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Transformation Relationship and Causes of Surface Water and Groundwater in the Middle Reaches of the Bortala River, Xinjiang

GAO Fuxiang[1,2,3], **XU Dongsheng**[4], **ZHOU Jinlong**[1,2,3], **ZHOU Long**[1,2,3]

[1]College of Hydraulic and Civil Engineering, Xinjiang Agricultural University, Urumqi 830052, Xinjiang, China
[2]Xinjiang Hydrology and Water Resources Engineering Research Center, Urumqi 830052, Xinjiang, China
[3]Xinjiang Key Laboratory of Hydraulic Engineering Safety and Water Disaster Prevention, Urumqi 830052, Xinjiang, China
[4]Zhongshui North Engineering Design & Research Co. Ltd., Tianjin 300222, China

Abstract

The Bortala River Basin in Xinjiang suffers from water scarcity and uneven spatiotemporal distribution. Quantifying the conversion rates between surface water and groundwater in different reaches and periods of the middle stream is crucial for groundwater exploitation and recharge, as well as for optimal allocation of water resources. Based on daily flow measurement data from five monitoring sections in the middle reaches of the Bortala River from December 1, 2021, to November 30, 2022, this study employs river runoff analysis combined with P-III distribution frequency curves, comparisons of water inflow among monitoring sections, and hydrogeological cross-sections to quantitatively analyze surface water-groundwater conversion. The relationship between infiltration rate and inflow in leaking river sections was also fitted. Results show that: (1) Among the five monitoring sections, Bole Hydrological Station has the largest annual runoff while Chaxiang Bridge has the smallest; (2) The runoff in the middle reaches during the study period represents a normal flow year; (3) In the upper middle reaches, groundwater transforms to recharge surface water; in the middle segment from Kundelun Canal Head to Chaxiang Bridge, surface water extensively infiltrates to recharge groundwater with an infiltration coefficient of 0.67; in the lower reaches, groundwater again overflows to the surface. The middle reaches experienced three conversions between surface water and groundwater, with an overall pattern of groundwater overflow supplementing surface water.

Keywords: surface water; groundwater; transformation relationship; river runoff analysis; Bortala River Basin

Introduction

Surface water and groundwater constitute a hydrological continuum with close hydraulic connection and frequent mutual transformation. Quantifying their water exchange is a research hotspot and challenge in hydrogeology, representing both a component of watershed-scale water budgets and a key element in conjunctive surface water-groundwater management. Current research focuses on spatiotemporal processes of surface water-groundwater cycling, water and energy exchange in the hyporheic zone beneath riverbeds, and quantitative assessment of natural and anthropogenic impacts on river-aquifer exchange. Research challenges primarily involve the multi-dimensional, multi-factor, spatially variable, and hydraulic characteristics of the transformation process, which encompasses many complex hydrological processes across different scales.

The Bortala River (hereinafter referred to as "Bo River") is located in the arid and semi-arid region of northwest China. The basin experiences severe water scarcity and uneven spatiotemporal distribution, with serious groundwater overexploitation. During wet seasons, river leakage recharges groundwater; during dry seasons, groundwater discharges to the river as base flow. While water conservancy projects have improved water distribution, they also interfere with natural surface water-groundwater interactions. Previous studies in the Bo River Basin have primarily used stable isotopes to qualitatively analyze transformation relationships, evaluated hydrogeological conditions and groundwater resources in the upper reaches, and assessed water chemistry and quality. However, quantitative analysis of surface water-groundwater conversion remains lacking, preventing data support for groundwater reservoir design. This study addresses this gap by using hydrological monitoring data to quantitatively calculate water conversion across different reaches and periods, providing both theoretical reference for similar inland river valleys and practical guidance for water resource planning and optimal allocation in the Bo River Basin.

1.1 Study Area Overview

The Bo River originates at Hongbieling Daban where the Biezhentao and Alatao mountains meet, flowing eastward through Wenquan County and Bole City before discharging into Ebinur Lake. The river is 252 km long with a drainage density of approximately 0.25 km/km^2, receiving mixed recharge from ice/snow melt, rainfall, and groundwater. The basin features a typical continental arid/semi-arid climate with mean annual temperature of 6.0°C, precipitation of 180.0 mm, and evaporation of 1569.2 mm. The long-term average runoff at Wenquan Station is 3.19$\times10^{8}$ m^3 (based on 46 years of data), increasing to 4.99$\times10^{8}$ m^3 at Bole Station (based on 60 years of data), demonstrating the river's characteristic as a spring-fed stream.

The basin is situated between the North Tianshan and Biezhentao mountain fold belts, forming a valley with three-sided mountains and an open, trumpet-shaped terrain. The geomorphology comprises three major units: mountainous areas on both sides, the central Bortala Valley, and the eastern Ebinur Lake Basin [Figure 1: see original paper]. The river collects both surface water and groundwater from the valley. Groundwater in the middle reaches occurs as porous phreatic water stored in Quaternary loose deposits of river terrace sand-gravel pores, with aquifer thickness exceeding 100 m. Recharge sources include atmospheric precipitation, river channel seepage, lateral groundwater inflow, and irrigation leakage. The unique topography, stratigraphic lithology, and geological structures create numerous faulted basins and uplifts, resulting in frequent surface water-groundwater conversions.

1.2 Data Sources

Flow measurement data from five hydrological monitoring sections [Figure 2: see original paper] for the period December 1, 2021, to November 30, 2022, were commissioned by Zhongshui North Engineering Design & Research Co. Ltd. and collected by the Bozhou Hydrological Survey Bureau. This complete hydrological year includes wet, normal, and dry periods with roughly symmetric distribution. Elevation data were also provided by Zhongshui North Engineering Design & Research Co. Ltd.

Groundwater depth is substantial with minimal water table fluctuation (ranging from 16.6–26.45 m in the Yamate area to surface outflow near Wenquan, approximately 20 m at Kundelun Canal Head, and 1.29 m variation range at Chaxiang Bridge). The relatively stable groundwater table and flow field suggest these factors have insignificant impact on surface water-groundwater conversion, and are therefore not considered in this analysis.

1.3 Methods

1.3.1 Hydrological Frequency Curve Fitting Method The P-III distribution curve, introduced by British statistician Pearson in 1895, has been designated as the standard frequency curve type in Chinese hydrological analysis. With mean, variation coefficient, and skewness coefficient as parameters, it reliably conforms to general hydrological patterns and fits observational data well. Daily flow data from Wenquan and Bole stations for 2021–2022 were sorted in descending order, and P-III distribution frequency curves were fitted using specialized software [Figure 4: see original paper]. The empirical frequency for the m-th day's flow in an n-day series is calculated as:

$$P_m = \frac{m}{n+1} \times 100\% \quad (m = 1, 2, 3, \dots, n)$$

1.3.2 River Runoff Analysis Method This method sequentially analyzes surface water-groundwater conversion amounts in upper, middle, and lower reaches during different periods. The infiltration coefficient for middle reaches is calculated, and the relationship between infiltration rate and inflow is established. River section infiltration depends on inflow quantity, river length, and water loss characteristics, expressed as:

$$W = K \times Q$$

where W is river section infiltration (10^4 m^3), Q is river section inflow (10^4 m^3), and K is the river section infiltration coefficient. Daily infiltration is calculated as the difference between upstream and downstream monitoring sections.

1.3.3 River Section Water Surface Evaporation Water surface evaporation loss is calculated as:

$$V = 0.1 \times \alpha \times A \times Z$$

where V is water surface evaporation loss (10^4 m^3), α is the evaporation conversion coefficient, A is river surface area (km^2), and Z is total evaporation (mm).

1.3.4 Calculation of River Seepage Recharge Coefficient and Unit River Length Water Consumption The coefficient of variation for daily river seepage recharge coefficients is calculated as:

$$C_v = \frac{SK}{\bar{K}}$$

where SK is standard deviation and $\bar{K}$ is mean seepage recharge coefficient. The daily coefficient is calculated as the ratio of daily seepage between adjacent sections to upstream daily inflow. The mean coefficient is obtained by averaging all daily values.

Unit river length water consumption is calculated as:

$$q = \frac{Q_{\text{up}} - Q_{\text{down}}}{L}$$

where q is unit length consumption (m$^3 \cdot$ s$^{-1} \cdot$ km^{-1}), Q_{up} and Q_{down} are upstream and downstream flows, and L is river length.

2 Results and Analysis

2.1 Flow Measurement at Hydrological Monitoring Sections

Based on measurement data, the annual runoff at five sections [Figure 2: see original paper] are: Wenquan Hydrological Station 3.21\$×10^{8}\$ m^3, Kundelun

Canal Head 2.69$×10^{8}$ m^3, Chaxiang Bridge 1.1$×10^{8}$ m^3, 86th Regiment Power Station Diversion Canal Head 1.97$×10^{8}$ m^3, and Bole Hydrological Station 4.38$×10^{8}$ m^3 . The upper middle reach shows groundwater recharging surface water with non-irrigation period recharge of 1.63$×10^{8}$ m^3. The middle segment from Kundelun Canal Head to Chaxiang Bridge has infiltration of 1.59$×10^{8}$ m^3 (infiltration coefficient 0.67). The lower segment from Chaxiang Bridge to 86th Regiment Power Station Canal Head shows groundwater discharge of 0.87$×10^{8}$ m^3, while the segment from 86th Regiment Power Station Canal Head to Bole Hydrological Station shows discharge of 2.41$×10^{8}$ m^3.

2.2 Inflow Frequency of Wenquan and Bole Hydrological Stations

Frequency curves for both stations [Figure 4: see original paper] indicate that Wenquan Station's inflow frequency is 62% (slightly dry, near normal), while Bole Station's is 52% (normal year). Both stations' frequencies approach P=50%, indicating the study period represents a normal flow year. The 2021–2022 runoff at Wenquan Station (3.21$×10^{8}$ m^3) closely matches the normal year value (3.16$×10^{8}$ m^3), and Bole Station's runoff (4.38$×10^{8}$ m^3) approximates the normal year value (4.86$×10^{8}$ m^3).

2.3 Conversion Amounts in Different River Sections

The study area is divided into three segments: upper (Wenquan Hydrological Station–Kundelun Canal Head), middle (Kundelun Canal Head–86th Regiment Power Station Diversion Canal Head), and lower (86th Regiment Power Station Diversion Canal Head–Bole Hydrological Station).

2.3.1 Upper Middle Reaches Conversion The Bo River's transformation follows a "three-in, three-out" pattern created by three faulted basins that form subsurface flow sections at Yamate, Kundelun, and Hutun, where river water enters groundwater causing surface flow interruption. The upper middle reach lies between the first "out" and second "in" zones. When groundwater flows east to Wenquan County, valley basement uplift raises the water table, causing groundwater to overflow and recharge the river. Isotopic and hydrochemical studies confirm this recharge mechanism. During non-irrigation periods, groundwater recharge increases flow at Kundelun Canal Head. However, during irrigation periods (May–September), despite increased inflow at Wenquan Station, Kundelun Canal Head shows fluctuating decreases due to water diversion for irrigation in Wenquan County.

2.3.2 Middle Middle Reaches Conversion The Kundelun Canal Head–Chaxiang Bridge section exhibits significant infiltration. River flow velocity depends on discharge, channel storage characteristics, and bed infiltration capacity. While channel storage remains relatively constant, infiltration capacity varies complexly with both flow rate and groundwater backpressure. Water consumption between sections shows temporal distribution patterns [Figure 6: see original paper]. Most surface water replenishes groundwater rather than evaporating. Water surface evaporation is negligible: the Kundelun–Chaxiang section (4.0 km^{2} surface area) has annual evaporation of only 389$×10^{4}$ m^{3}, far less than the annual inflow of 26909$×10^{4}$ m^{3}. Similar patterns occur in other sections. The river's low sediment content (0.218 $\mathrm{kg \cdot m^{-3}}$) does not affect infiltration, so substrate properties are not considered.

The infiltration recharge coefficient remains stable at 0.67 for most months, with greater variability during high-flow periods. Analysis of daily coefficients from December 2021 to November 2022 shows stable variation (C_v = 0.12 < 0.15) [Figure 7: see original paper]. The 12 km section has unit length consumption of 0.581 $\mathrm{m^{3} \cdot s^{-1} \cdot km^{-1}}$, with total annual infiltration of 1.59$×10^{8}$ m^{3}.

2.3.3 Lower Middle Reaches Conversion From Chaxiang Bridge to 86th Regiment Power Station Canal Head, groundwater discharges to the river (8.73$×10^{7}$ m^{3}). This occurs because basement rock uplift and alluvial fan compression reduce groundwater flow cross-sections, raising the water table. During non-irrigation periods, groundwater recharge is 1.49$×10^{8}$ m^{3}, decreasing during irrigation due to canal diversion. The right bank's mountainous bedrock fissure water directly recharges the piedmont plain without barriers, while the left bank's Paleogene-Neogene pre-mountain structural zone creates "piedmont-type groundwater" that discharges to the Bo River. Winter runoff (December–February) originates entirely from groundwater conversion, with Wenquan Station winter flow of 0.68$×10^{8}$ m^{3} and Bole Station flow of 1.67$×10^{8}$ m^{3}, demonstrating substantial and sustained groundwater contribution.

2.3.4 Overall Conversion in Middle Reaches The middle reaches undergo three surface water-groundwater conversions, overall characterized by groundwater overflow recharging surface water. The unique geological structures, stratigraphic lithology, and hydrogeological conditions facilitate these transformations, providing a new calculation method for evaluating complex water resource conversion systems.

2.4 Relationship Between Infiltration Rate and Inflow in Middle Reaches

The upper middle reach's heavy irrigation diversion and the lower reach's substantial bedrock fissure inflow preclude reliable fitting equations. Therefore, the less-disturbed middle segment (Kundelun Canal Head–Chaxiang Bridge) is selected for analysis.

2.4.1 Annual Relationship Using daily data aggregated by ten-day periods, the fitted equation shows infiltration rate decreasing with increasing inflow.

SPSS analysis yields P = 0.074 and R^2 = 0.02, indicating poor fit and no significant correlation.

2.4.2 Seasonal Relationship Data were divided by season: spring (March–May), summer (June–August), autumn (September–November), and winter (December–February). Spring, summer, and autumn show highly significant negative correlations ($P < 0.001$) with good fit [FIGURE:9, TABLE:3]. Winter shows no significant correlation due to ice formation affecting flow velocity and increasing infiltration rate. The seasonal equations demonstrate that infiltration rate decreases as inflow increases, with the relationship varying by season.

3 Conclusions

Based on flow data from five monitoring sections in the Bo River middle reaches, quantitative analysis using hydrological frequency curve fitting and river runoff analysis yields:

1. **Inflow characteristics:** Bole Hydrological Station has the largest annual runoff (4.38$×10^{8}$ m^3), while Chaxiang Bridge has the smallest (1.1$×10^{8}$ m^3). The study period represents a normal flow year (Wenquan Station: 62%, Bole Station: 52%).
2. **Conversion patterns:** Upper middle reaches show groundwater recharging surface water due to valley basement uplift. Middle reaches (Kundelun–Chaxiang) exhibit extensive surface water infiltration (coefficient: 0.67, unit consumption: 0.581 $m^3 \cdot s^{-1} \cdot km^{-1}$, annual recharge: 1.59$×10^{8}$ m^3). Lower reaches show groundwater recharging surface water (non-irrigation period: 1.49$×10^{8}$ m^3). The middle reaches experience three conversions, overall showing groundwater overflow supplementing surface water.
3. **Infiltration-inflow relationship:** Significant negative correlation exists between infiltration rate and inflow in the middle reaches, with seasonal variations. Spring, summer, and autumn show highly significant correlations, while winter ice effects disrupt the relationship.

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