Assessment of Spatiotemporal Variations in Groundwater Discharge to the Lower Malian River Based on Hydrochemistry and Isotopes: Postprint

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Abstract

Accurate evaluation of groundwater recharge to river water is fundamental for watershed water resource management and rational utilization. In the lower reaches of the Malian River basin, 7s groups of surface water and groundwater samples were collected across different seasons, and combined multi-method evaluation using C1 —, electrical conductivity (EC), and D80 isotopes was employed to identify the locations, quantities, and seasonal variations of groundwater recharge to river water. The results indicate that EC and C1 — mass concentration of Malian River water both exhibit decreasing trends along the flow direction, and 8D and 8' 80 values decrease along the flow direction. During the rainy season, EC and C1 — mass concentrations are lowest, and 8D and 8' 8 0 values are highest. Groundwater component concentrations are all lower than river water, with no significant temporal or spatial variation. Groundwater discharge per unit width exhibits temporal and spatial variation, with the upper and lower reaches being strong groundwater discharge zones and the middle reach having weaker groundwater discharge; groundwater discharge accounts for 72. 20%9s.07% of total discharge across different seasons. During the rainy season, groundwater discharge per unit width decreases significantly, and the baseflow proportion in river water decreases from 68. 89% in the pre-rainy season to 29.43%; overall, groundwater recharge to river water shows obvious seasonal variation, while spatial variation patterns are relatively stable. The research findings are beneficial for deepening understanding of the interaction mechanisms between river water and groundwater, and provide a foundational basis for local water resource utilization.

Full Text

2. Data and Methods

2.1 Sample Collection

To investigate the spatial and temporal variations in groundwater discharge, we collected 75 surface water and groundwater samples from the Malian River downstream section during three hydrological periods: pre-monsoon (4 weeks), monsoon (8 weeks), and post-monsoon (11 weeks). The sampling sites were distributed along a 100 km river reach at intervals of 5–10 km. River water samples were collected at 0.3 m depth below the water surface, while groundwater samples were obtained from monitoring wells located within 100 m of the riverbank.

2.2 Analytical Methods

Electrical conductivity (EC) and chloride ion concentration (Cl) were measured using a HACH HQ40D portable multi-parameter meter and ion chromatography, respectively. The oxygen and hydrogen isotopic compositions (¹ O and D) were analyzed using a stable isotope ratio mass spectrometer. The precision of the isotopic measurements was ±0.1‰ for ¹ O and ±1.0‰ for D.

3. Results

3.1 Characteristics of EC, Cl , and Isotopes

The mass balance equation for quantifying groundwater discharge to the river is expressed as:

$$Q_2C_2 = Q_1C_1 + IxC_{gw} + Q_pC_p + Q_tC_t \quad (4)$$

where Q_1 and Q_2 represent the river discharge at the upstream and downstream sections ($m^3 \cdot d$ ¹), respectively; C_1 and C_2 denote the solute concentrations or isotopic compositions at the corresponding sections; I is the groundwater inflow per unit length ($m^2 \cdot d$ ¹); x is the length of the river reach (m); C_{gw} is the solute concentration or isotopic composition of groundwater; and Q_p and Q_t represent discharge from precipitation and tributaries, respectively.

The uncertainty of the groundwater inflow rate $U(I)$ was calculated using:

$$U(I) = \sum (C_i - \bar{C})^2$$

where C_i represents individual measurement values and $\bar{C}$ is the mean concentration.

The measured values of EC, Cl , ¹ O, and D showed distinct spatial and temporal patterns. During the pre-monsoon period, river water EC ranged from

1705.40 to 3123.60 S · cm ^{1}, with a mean of 2329.41 S · cm ^{1}, while Cl concentrations varied from 401.30 to 639.39 mg · L ^{1} (mean: 485.23 mg · L ^{1}). The isotopic compositions ranged from -10.41‰ to -7.45‰ for ^{1} O and -78.25‰ to -61.96‰ for D. During the monsoon period, EC decreased significantly to 1705.40–2642.00 S · cm ^{1} (mean: 2244.47 S · cm ^{1}), and Cl concentrations showed a slight increase in variability (387.20–531.38 mg · L ^{1}). The isotopic values became more enriched, with ^{1} O ranging from -7.45‰ to -6.30‰ and D from -61.96‰ to -54.88‰. In the post-monsoon period, EC and Cl concentrations increased again to 1806.12–3123.60 S · cm ^{1} and 435.80–707.42 mg · L ^{1}, respectively, while isotopic values became more depleted.

Groundwater samples exhibited significantly lower values than river water throughout all periods: EC ranged from 409.58 to 1696.84 S · cm ^{1}, Cl from 115.92 to 255.96 mg · L ^{1}, ^{1} O from -11.19‰ to -9.11‰, and D from -79.80‰ to -68.28‰. No significant spatial or temporal variations were observed in groundwater tracers, indicating relatively stable groundwater quality. All groundwater samples plotted close to the Local Meteoric Water Line, suggesting precipitation recharge with limited evaporation. In contrast, river water showed more enriched isotopic signatures, likely due to evaporation effects.

Table 1. Average Cl , EC, and hydrogen and oxygen isotopes of river water and groundwater during three periods

Period	Location	EC (S · cm ^{1})	Cl (mg · L ^{1})	^{1} O (‰)	D (‰)
Pre-monsoon	River water	2329.41	485.23	-9.37	-71.55
	Groundwater	410.90	130.52	-10.93	-80.80
Monsoon	River water	2244.47	469.29	-6.83	-58.40
	Groundwater	409.58	122.31	-10.54	-78.91
Post-monsoon	River water	2444.87	536.81	-9.78	-73.55
	Groundwater	415.23	115.92	-11.19	-79.80

The groundwater discharge rates exhibited significant spatial and temporal variations. In the upper reach (R01–R04), the groundwater inflow rates ranged from 6.1 to 10.6 m² · d ^{1} during the pre-monsoon period, accounting for 39% of the total discharge. During the monsoon period, these rates decreased to 1.5–5.3 m² · d ^{1} (23.8% of total discharge), and increased again to 3.9–12.9 m² · d ^{1} (35.3%) in the post-monsoon period. The middle reach (R04–R11) showed lower contributions, with groundwater discharge representing less than 5% of total flow. In contrast, the lower reach (R11–R14) exhibited higher groundwater inflow, contributing 7.49% and 1.85% during pre-monsoon and monsoon periods, respectively.

The mass balance calculations revealed that the uncertainty ranges for Cl and EC measurements were 0.02%–5.46% and 0.05%–7.35%, respectively. The isotopic measurements showed uncertainties of 0.06%–2.63% for ^{1} O and 0.20%–

3.80% for D. The spatial variation in groundwater discharge was primarily controlled by geological and hydrogeological conditions, including aquifer thickness, hydraulic gradient, and riverbed permeability. Temporal variations were more pronounced than spatial variations, with baseflow contributing 68.89% of total discharge during the pre-monsoon period, decreasing sharply to 29.43% during the monsoon period, and recovering to 71.19% post-monsoon.

The multi-tracer approach demonstrated that while uncertainties remain inherent in the mass balance model, it can provide detailed information on the spatial distribution of groundwater discharge, particularly in gaining rivers. The method is valuable for understanding river–groundwater interactions and supporting sustainable water resource management and ecological protection in arid and semi-arid regions.

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