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Quantifying groundwater recharge and discharge for the middle reach of Heihe River of China using isotope mass balance method

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Abstract: Quantifying the inflow and outflow of groundwater is essential to understand the interaction between surface water and groundwater. It is difficult to determine these elements in relation to groundwater recharge and discharge to the river, because they cannot be directly measured through site specific study. The methods of isotope mass balance combining with water budget were used to quantify the groundwater recharge from and discharge to the Heihe River, northwest China. The mean isotope ratios of monthly monitoring data for one hydrological year were selected to be the isotope rations of end members in isotope mass balance. The results from the isotope mass balance analysis, incorporating with the 35-year hydrological data, suggest that about 0.464×10^9 m^3/a of runoff flowing out Qilian Mountains is contributed to groundwater recharge (about 28% inflow of the Heihe River), while about 1.163×10^9 m^3/a of runoff is discharged from groundwater in the middle reach of the river, which accounts for about 46% of river runoff in the basin. The analysis offers a unique, broad scale studies and provides valuable insight into surface water-groundwater interaction in arid area.

Keywords: Arid region; Stable isotopes; Water budget; Surface water-ground water interaction

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Introduction

Surface water-groundwater interaction is important in basin water budget in arid and semi-arid areas. The key issue to understand the interaction between surface water and groundwater is to quantify the exchange amount of water between the surface water and groundwater, which requires determining the inflow and outflow of groundwater to the river. The isotope mass balance of river water provides an effective tool to estimate the groundwater, surface water and evaporative fluxes (Bocanegra et al. 2013; Sacks et al. 2013; Gibson et al. 2016). The Zhangye Basin situated in the middle reach of Heihe River is a region of water resources scarcity. Surface runoff from mountain area is the only source of water available for maintaining the ecologic system in the basin. The increase of water demand for agricultural irrigation has resulted in the decrease of runoff of Heihe River to the lower reaches. In the middle reach of the river basin, more than 80% of the total river discharge has been diverted to many irrigation canals for agricultural purposes, resulting in the rise of groundwater level and soil salinization (Wang and Cheng, 1999). Understanding the exchange of groundwater and surface water is hence a prerequisite for managing water resources in the Heihe River Basin, where the flux of groundwater input and river water loss must be quantified.

Previous studies on surface water/groundwater interaction in the Heihe Basin indicate that the groundwater component contributes to river budgets varies widely (Gao, 1991; Chen, 1997; Shi et al. 1999; Zhang et al. 2001; Lan et al. 2002; Chen et al. 2003; Wu et al. 2004; Zhang et al. 2005). These studies provided detailed descriptions of groundwater flow patterns and quantified groundwater exchanges using detailed water budget and groundwater flow models. In order to

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determine the water balance of the Heihe River, all the hydrologic components of the river and its surroundings need to be considered. Among these components, groundwater recharge and discharge to the river are especially difficult to quantify due to the complicated patterns of groundwater flow along the river. In order to satisfactorily determine the components in relation to groundwater, in this study, the stable isotope mass balance method was applied. The isotope study of waters in the Heihe Basin showed that the stable isotope components of the Heihe River are varied significantly along the river (Zhang et al. 2005; Chen et al. 2006), which provides an effective approach to estimate the water exchanges between the groundwater and river water. In the meantime, the present study is to quantify the surface water-groundwater interaction in the middle reach of Heihe River by using isotope mass balance approaches.

1 Study area

The Heihe River is the second largest inland river in China. It originates from the northern foot of Qilian Mountain, and the river basin is located between 96°42'-102°00'E and 37°41'-42°42'N. The basin covers an area of 130 000 km^2 with a total length of 812 km (Fig. 1). The upper reach of the basin above Yingluoxia gorge has a river length of about 303 km. The annual precipitation in this headwater area, with an elevation of 2 000-5 000 m a.s.l in the midst of Qilian Mountain, ranges from 200 mm to 500 mm. The middle reach is located between Yingluoxia gorge and Zhengyixia gorge (Fig. 1), with a river length of about 185 km and an altitude of 1 300-1 700 m a.s.l. The lower reach of the river is about 333 km long, most of which are desert and Gobi with a mean annual precipitation of about 40 mm. The total runoff of 1.58 ×10^9 m^3/a of the river is mainly supplied by the precipitation taking place in the Qilian mountain area, which accounts for 96% of annual runoff, while the other 4% is fed by glacial water. The annual runoff variation is shown in Fig. 2 with data derived from the Yingluoxia and Zhengyixia gauging stations. It is noted that most tributaries of the river are ephemeral, characterised by no flows into the piedmont plain after they extend to the mouths of the mountain valleys. Liyuan River is the perennial tributary which flows into the Heihe River in the middle reach. It is 143 km long with an average annual runoff of 0.21 ×10^9 m^3/a.

In the middle reach, the lands with an elevation ranging from 1 300 m a.s.l. to 1 700 m a.s.l. are the cultivated oasis, dominated by irrigated farmlands which require large amount of water resources. In this area, the mean annual temperature is about 7ºC; the mean annual precipitation ranges from 50 mm to 150 mm and mean potential evaporation rate is about 2 000-2 200 mm/a. As a result, very few rain events are able to generate surface runoff. The surface water and groundwater are mainly used for agricultural and industrial purposes in the middle reaches, where the unconfined aquifer consists of a thick Quaternary deposit layer with coarse-grained gravel and sand in the piedmont plain, and a confined part consists of medium to fine and silty sand with a thickness of 50-200 m in the floodplain (Fig. 3). The depths to the water table range from 50-200 m in the upper alluvial fan to 3-5 m in the lower part of the floodplain. The

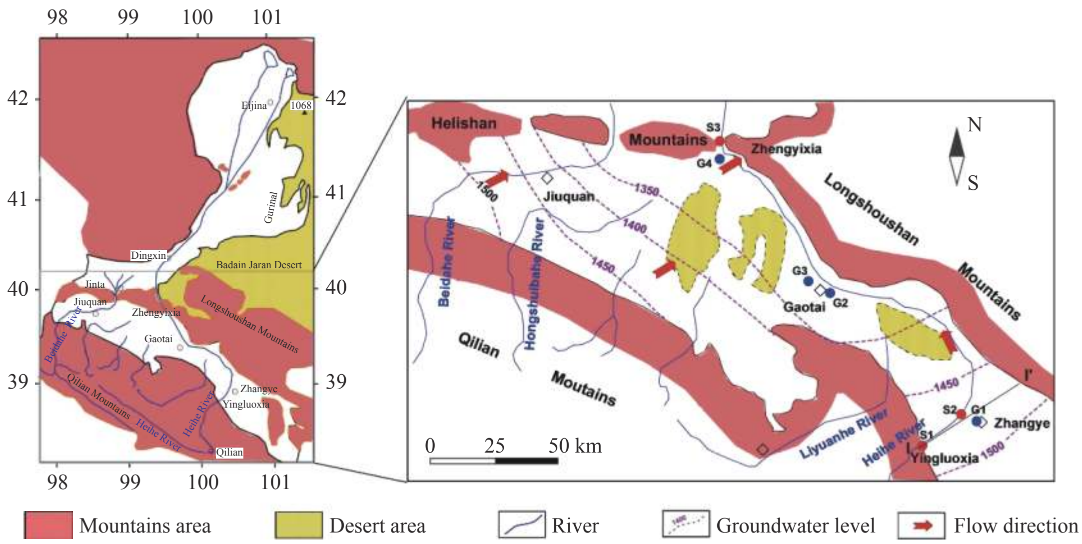

Fig. 1 The Heihe River catchment and study area

Note: S1, S2, S3, are the hydrological gauging site of Yingluoxia, Heihe bridge and Zhengyixia, respectively; G1, G2, G3, G4 are the monthly sampling site for groundwater.

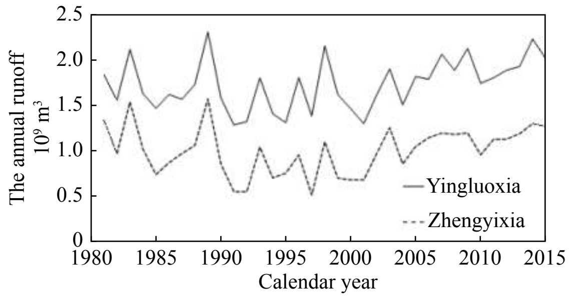

Fig. 2 The annual runoff at the gauging station of Yingluoxia and Zhengyixia (Data from Zhangye hydrological and Water Resources Survey Bureau)

groundwater generally flows from the piedmont towards the farmland area.

Surface water and groundwater exchange frequently in the middle reach. The rivers originating in the Qilian Mountains are the main recharge sources of the aquifers in the low land areas. River water infiltrates into the aquifers through river bed at piedmont Gobi zone after flowing out of the Mountains, and then overflows to surface as springs discharging back to the river (Chen, 1997; Fan, 1991; Gao, 1991) at the alluvial fan-fringe zone. In addition, the Heihe River water is imported to farm lands by the irrigation canal from the mountain reservoir at Yingluoxia, which infiltrates into the aquifer below and finally discharges back into the river through irrigation activity.

2 Methods and theoretical considerations

2.1 Isotope mass balance method (IMBM)

The isotope mass balance approach is used to combine the general water budget equation with the isotope mass balance equation to estimate some unknown components of the water budget. The water budget equation and isotope mass balance equation for $\delta^{18}O$ (δD) are:

$$\sum Q_{in} - \sum Q_{out} = \Delta V \qquad (1)$$

$$\sum \delta_{in} Q_{in} - \sum \delta_{out} Q_{out} = \Delta(\delta_{river}\ V) \qquad (2)$$

Where: $\sum Q_{in}$ and $\sum Q_{out}$ are the volumes of inflow and outflow of river over the specified time period, respectively; ΔV is change in river water over the specified time period; δ_{in}, δ_{out} and δ_{river} are the stable isotope ratio of inflow water, outflow water and river water, respectively. For a long period, the above equations can be simplified further if the river is assumed to be in both isotopic and hydrologic steady state. In this case, both ΔV and $\Delta(\delta_{river}\ V)$ are assumed to be zero.

2.2 Data sources

In this study, the hydrological data were collected from the Zhangye Hydrological and Water Resources Survey Bureau. The runoff data were monitored at Yingluoxia and Zhengyixia gauging stations from 1981 to 2015. The monitoring data of water exported for irrigation from both Yingluoxia and the tributary Liyuan River, and runoff at Heihe bridge were monitored from 1981 to 2002. The data of inflow and outflow used for isotopic mass balance calculation are listed in Table 1.

The isotopic data were collected from Chen et al. (2006) and Su et al. (2019), in which the stable isotope compositions of waters were measured on a monthly basis in one hydrological year (from May 2001 to May 2002) at three sites for river water (S1, S2, S3) and four wells for groundwater (G1, G2, G3, G4) along the river course from the

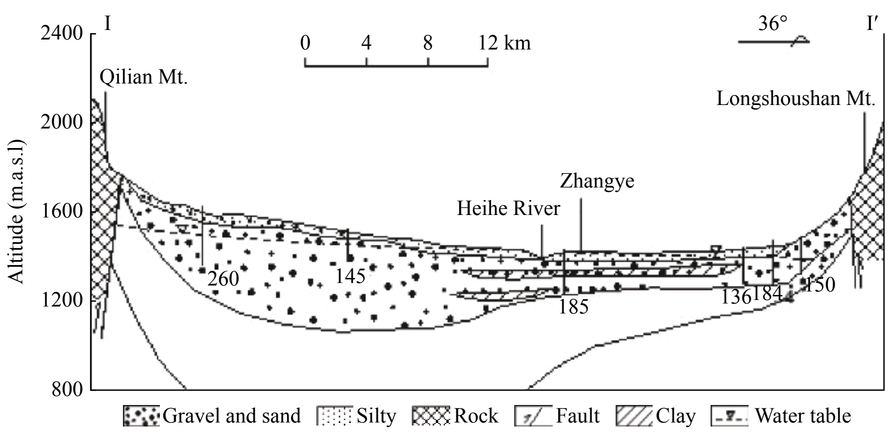

Fig. 3 Hydrogeological cross section along transect I-I' in Fig. 1

Table 1 The mean value of hydrological data of Heihe River

Period	Q_1 (10^9 m^3/a)	Q_2 (10^9 m^3/a)	Q_3 (10^9 m^3/a)	Q_4 (10^9 m^3/a)	Q_{ex1} (10^9 m^3/a)	Q_{ex2} (10^9 m^3/a)
1981−1990 (Wet)	1.744 0	0.600 7	0.025 9	1.094 0	0.660 5	0.736 8
1991−2002 (Dry)	1.540 0	0.449 5	0.017 8	0.766 0	0.669 5	0.647 1
1981−2015	1.733 0	0.568 0	0.021 5	0.999 0	0.665 4	0.687 9

outlet of the mountain valleys to the Zhengyixia (Fig. 1). The mean values of their ratios are still the well representative values for the 35-year isotope mass balance in present study, since the hydrological cycle of this catchment has not been significantly changed over the last 35 years.

3 Results and discussions

3.1 Pattern of surface water-groundwater exchange

Hydrological and isotopic studies suggest that the surface water and groundwater exchange with different patterns along the Heihe River (Fig. 4). The infiltration of river water into the aquifer through the river bed is predominant in the section between the Yingluoxia (gauging station) and Zhangye (Heihe bridge, while in the river section between Zhangye and Zhengyixia (gauging station), the river is basically fed by groundwater. Because of low rainfall to generate the runoff in the middle reach, the river flow from rainwater can be ignored. As for the different patterns of surface water-groundwater exchange along the River, these two sections of river were used to estimate the river water loss through river bed and groundwater discharge into the river, respectively.

3.2 Rate of surface water-groundwater exchange

The water balance between the Yingluoxia and Zhangye bridge (Fig. 4), the inflow of the river is only the runoff from the mountains at Yingluoxia (Q_1), while the outflows consist of river discharge at Zhangye (Q_2), infiltration from river bed (Q_{rg}) (unknown), exported amount for irrigation at the Yingluoxia (Q_{ex1}) and evaporation loss from river surface (E_1). The river water budget equation and the isotope mass balance equation are:

$$\begin{cases} Q_1 = Q_2 + Q_{rg} + Q_{ex1} + E_1 & (3) \\ \delta_1 Q_1 = \delta_2 Q_2 + \delta_{rg} Q_{rg} + \delta_{ex1} Q_{ex1} + \delta_{E1} E_1 & (4) \end{cases}$$

Where: Q_1 is runoff rate at Yingluoxia (10^9 m^3/a);

Q_2 is runoff rate at Zhangye (10^9 m^3/a);

Q_{rg} is water loss from river bed (10^9 m^3/a);

Q_{ex1} is water exported from the river (10^9 m^3/a);

E_1 is evaporation loss from river surface (10^9 m^3/a);

δ_1 is $\delta^{18}O$ (δD) value of river water at Yingluoxia (‰);

δ_2 is $\delta^{18}O$ (δD) value of river water at Zhangye (‰);

δ_{rg} is $\delta^{18}O$ (δD) value of river water infiltrated in to aquifers (‰);

δ_{ex1} is $\delta^{18}O$ (δD) value of water exported from the river (‰);

δ_{E1} is $\delta^{18}O$ (δD) value of evaporating river water (‰).

For the river between Zhangye and Zhengyixia (Fig. 4), the inflows of the river are the runoff (Q_2) at Zhangye, groundwater discharge (G_{out}) (unknown) and the runoff from the tributary (Q_3) of Liyuan River. The outflows are runoff at Zhengyixia (Q_4), export for irrigation from the river (Q_{ex2}) and evaporation loss from river surface (E_2). The water budget equation and the isotope mass balance equation are:

$$\begin{cases} Q_2 + G_{out} + Q_3 = Q_4 + Q_{ex2} + E_2 & (5) \\ \delta_2 Q_2 + \delta_G G_{out} + \delta_3 Q_3 = \delta_4 Q_4 + \delta_{ex2} Q_{ex2} + \delta_{E2} E_2 & (6) \end{cases}$$

Where: G_{out} is groundwater discharge (10^9 m^3/a); Q_3 is input from the tributary (10^9 m^3/a); Q_4 is runoff rate at Zhengyixia (10^9 m^3/a); Q_{ex2} is water exported from the river (10^9 m^3/a); E_2 is evaporation loss from river surface (10^9 m^3/a); δ_G is $\delta^{18}O$ (δD) value of groundwater (‰); δ_3 is $\delta^{18}O$ (δD) value of tributary river water (‰); δ_4 is $\delta^{18}O$ (δD) value of river water at Zhengyixia (‰); δ_{ex2} is $\delta^{18}O$ (δD) value of water exported from the river (‰); δ_{E2} is $\delta^{18}O$ (δD) value of evaporating

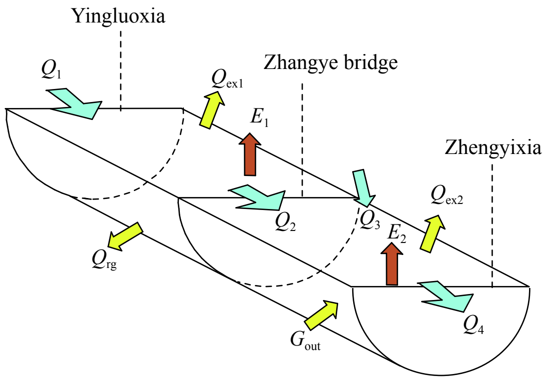

Fig. 4 Elements of water budget in Heihe River

river water (‰).

Considering that the atmospheric circulation pattern of the Heihe River basin has not significantly changed in the past 30 years, the isotopic data of the river (δ_1, δ_2, δ_4) measured on a monthly basis can be used to calculate the mean values for the Yingluoxia, Zhangye and Zhengyixia stations, respectively, and the δ-value of infiltrated river (δ_{rg}) is used as the mean value of monthly river water samples of both Yingluoxia and Zhangye for the interval between the Yingluoxia and Zhangye (Chen et al. 2006). Because the river water was mainly diverted at Yingluoxia by the irrigation channel l, the δ_1 was used as δ-value of the exported water for this interval (δ_{ex1}). In the river section between Zhangye and Zhengyixia, the mean value δ-value based on monthly river water samples is selected to represent the exported water (δ_{ex2}). The δ-value of groundwater inflow (δ_G) is the mean value of monthly groundwater samples at three sites, i.e. Zhangye, Gaotai and Zhengyixia.

The δ-value for river water evaporation was estimated by using the method given by Craig and Gordon (1965):

$$\delta_E = \frac{\dfrac{\delta_L}{\alpha} - h\delta_{atm} - \varepsilon}{1 - h + \Delta\varepsilon} \quad (7)$$

Where: δ_L and δ_a are the $\delta^{18}O$ and δD values of lake water (here, used as river water) and atmospheric moisture, respectively, h is relative humidity, $\Delta\varepsilon$ the kinetic fractionation factor is estimated as (Gonfiantini, 1986):

$$\Delta\varepsilon^{18}O = 12.5(1-h) \quad (8)$$

$$\Delta\varepsilon D = 14.2(1-h) \quad (9)$$

The ε is the total fractionation factor which equals to 1 000 (1−α*) +$\Delta\varepsilon$, α* is the equilibrium isotope fractionation factor at the temperature of the air-water interface, which is equivalent to 1/α defined by Majoube (1971). The equations of the water-vapor fractionation factor α for $\delta^{18}O$ and δD at the temperature of between 0℃ and 100℃ are given by Majoube (1971) as follows:

$$ln\alpha_{18O} = \left(-2.0667 - \frac{415.6}{T} + \frac{1137}{T^2} \times 10^3\right) \Big/ 1000 \quad (10)$$

$$ln\alpha_D = \left(-52.612 - \frac{76278}{T} + \frac{24844}{T^2} \times 10^3\right) \Big/ 1000 \quad (11)$$

Where: T is temperature in Kelvins.

The isotope composition of atmospheric moisture (δ_a) is practically impossible to measure with adequate frequency for a long period. It is estimated from the isotopic composition of local precipitation (δ_p). Assume that δ_a is in isotopic equilibrium with rainwater (Turner et al. 1984; Krabbenhoft et al. 1990; Sacks et al. 1998; Gibson et al. 1999; Sacks, 2002), δ_a is computed as:

$$\delta_a = \delta_p - \varepsilon \quad (12)$$

Where:

$$\varepsilon = 1000(\alpha - 1) \quad (13)$$

To estimate α and δ_a for the two intervals of the Heihe main stream, the mean annual air temperature and mean annual relative humidity at the Zhangye and Gaotai stations are adopted for this calculation. The mean annual air temperatures are 7℃ and 8℃ at the Zhangye and Gaotai, respectively, while the mean annual relative humidities are 52% at the Zhangye and 48% at the Gaotai. The isotopes in precipitation (δ_P) were estimated from the analytical results with the samples collected at Zhangye (coordinates: 100.43°N and 38.93°E, altitude: 1 483 m) by IAEA since 1986, from which the weighted mean values of $\delta^{18}O$ and δD are −6.0‰ and −42‰, respectively (The GNIP Database. http://isohis.iaea.org). All isotopic compositions of waters used in the isotope mass balance method are listed in Table 2.

The unknown terms E_1, Q_{rg}, E_2 and G_{out} shown in Fig. 4 can be estimated by the isotope mass balance Equations 3, 4, 5 and 6 with the data listed in Table 1 and Table 2, with the calculated results are listed in Table 3. The results of water loss through river bed and groundwater discharge into the river estimated from the $\delta^{18}O$ and δD values are very similar. However, the results of water loss by evaporation using δD data are different from those determined from $\delta^{18}O$ data. These may suggest that the δ-value of evaporating river water estimated by Craig-Gordon model has some errors resulted from the uncertainty of selecting calculation parameters.

In the river section between Yingluoxia and

Table 2 The isotopic data used in isotope mass balance method

Isotope ratio	δ_1	δ_2	δ_3	δ_4	δ_{ex1}	δ_{ex2}	δ_{rg}	δ_G	δ_{E1}	δ_{E2}
$\delta^{18}O$ (‰)	−8.2	−7.7	−7.7	−6.1	−8.2	−6.7	−8.0	−7.3	−35	−30
δD (‰)	−61	−58	−58	−56	−61	−57	−60	−61	−162	−152

Table 3 Results of river water loss and groundwater discharge calculated by isotope mass balance method

Period	Method	E_1 (10^9 m^3/a)	Q_{rg} (10^9 m^3/a)	E_2 (10^9 m^3/a)	G_{out} (10^9 m^3/a)
1981-1990(Wet)	$\delta^{18}O$	0.015	0.468	0.085	1.289
	δD	0.022	0.460	0.058	1.286
	mean	0.019	0.464	0.072	1.288
1991-2002(Dry)	$\delta^{18}O$	0.012	0.410	0.063	1.009
	δD	0.017	0.404	0.044	0.999
	mean	0.015	0.407	0.054	1.004
1981-2015	$\delta^{18}O$	0.014	0.485	0.078	1.176
	δD	0.022	0.478	0.053	1.150
	mean	0.018	0.482	0.655	1.163
1981-2002	Water budget	0.014	0.450	0.082	0.144

Zhangye, the mean water losses through river bed infiltration are estimated as 0.464×10^9 m^3/a for wet period (1981−1990) and 0.407×10^9 m^3/a for dry period (1991−2002), respectively (Wang and Meng, 2008). The mean water loss in the 35 years (1981 to 2015) is about 0.482×10^9 m^3/a. In the river section between Zhangye and Zhengyixia, groundwater discharges to the river are estimated as 1.288×10^9 m^3/a for the wet period and 1.004×10^9 m^3/a for the dry period, respectively. The average amount of groundwater inflow in the 35 years (1981 to 2015) is about 1.163×10^9 m^3/a.

The conventional water budget calculations from 1981 to 2002 were done by Li et al. (2011), who estimated the average groundwater recharge from and discharge into the river in the 22 years as 0.45×10^9 m^3/a and 1.144×10^9 m^3/a, respectively. These results are consistent with those from those by the isotope mass balance method, which confirms the use of the steady state approach of the method.

4 Conclusions

(1) The isotope mass balance method can be used to evaluate the surface water-groundwater exchange rate and has a better understanding of surface water/groundwater interaction. The signatures of isotopes in the water are robust tracers, for the isotopic composition of groundwater is relatively uniform and it is distinctly different from that of the surface water. Groundwater inflow computed using isotope signatures is sensitive to the isotopic composition of atmospheric moisture, which may elevate the accuracy of the inflow estimation if the latter is measured. Limitations exist in applying this approach because of the lack of long-term data on the isotopic compositions of river water, atmospheric moisture and rainwater.

(2) A 35-year average amount of river water loss is about 0.464×10^9 m^3/a in the middle reach of Heihe River, which is about 28% runoff of the river flowing out Qilian Mountains and recharges to groundwater, while the amount of groundwater discharges to the Heihe River is about 1.163×10^9 m^3/a between Zhangye and Zhengyixia, about 46% of river runoff at Zhengyixia.

(3) Groundwater inflow and outflow varied significantly in wet and dry periods on a decade scale in the past 35 years. Both values were reduced in the dry period, with about 12% reduction in inflow and about 22% reduction in outflow. More groundwater was pumped from the aquifers in the dry period and therefore reduced the discharge of groundwater into the river. This could help water managers understand the impacts of climatic variability and aquifer pumping on surface water resources.

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