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Dams extend the surface water renewal time in inland river basins: A comparative study based on stable isotope data from two different basin

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Abstract

The dramatic increase in the number of dams on rivers in recent years have led to a more complicated water circulation mechanism in arid regions. Capturing the impact of dams on water circulation processes is an ongoing challenge in the hydrology field. By utilizing observational isotopic data from water bodies, we conducted a comparative study on the Fyw and MTT in two inland river basins within the arid zone of Central Asia. Research findings suggest that dams amplify the damping effect and phase shift of seasonal fluctuations in river water, which in turn

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extends the water circulation period within inland river basins. The cascading interception of river water by dams has substantially reduced the proportion of young water (Fyw) in the river and has nearly tripled the mean transit time (MTT) of river water. This work confirms the fact that dams are profoundly influencing the water circulation processes in inland river basins from an isotopic kinetic perspective, and is useful for understanding the mechanisms driving water circulation times arid areas.

Key Words: Inland river basin; Arid areas; Dams; Water renewal time; Climate change

1. Introduction

Sustainable development, whether at the regional or global scale, depends on effective water resource management (Garrick et al., 2017; Chiang et al., 2021). Over the past 50 years, most ~~researches~~ have been devoted to using water transit times to reveal basin-scale water circulation times, functions and the sensitivity of basin hydrological systems to environmental variables (McGuire and McDonnell, 2006; Gudmundsson et al., 2021; Gies, 2022). This is important for improving the efficiency of water resources management in basins, especially given the impact of the unknown variable of human activities (Cooley et al., 2021). As an essential component of the water circulation in a basin, the water transit time can reveal the time scale of the renewal of a water body (Hrachowitz et al., 2009). It not only reflects the transformation of water bodies between input (precipitation) and output (runoff) in the study basin, but also allows assessing the impact of anthropogenic interventions on the natural processes of basin hydrology (Hrachowitz et al., 2010). Due to the complex hydrological mechanism and insufficient observation conditions, the research on water transit time in arid regions is currently imperfect (Zhu et al., 2021; Rosa et al., 2020; Yao et al., 2023). Therefore, it is necessary to get an in-depth knowledge of the water transit time and the water circulation mechanism in arid regions, so as to improve our understanding of the water transit times and dominant factors affecting the hydrologic response at the watershed scale.

As effective tracers of the environment, hydrogen and oxygen stable isotopes in water can identify runoff sources and hydrologic flow path through the coupling with basin climatic and hydrological properties and explain the spatial and temporal variability of basin hydrological processes (Kim et al., 2016; Kirchner, 2016). Water transit times are usually described by metrics such as the F_{yw} and mean transit times (MTTs), etc. (W. Kirchner, 2015; Stockinger et al., 2016). The F_{yw} and MTTs are basic metrics that describe the hydrological function of a catchment and provide important clues for guiding regional water resources management (Hu et al., 2020). A study in 2016 calculated the F_{yw} in hundreds of catchments around the world and found that nearly a third of the world's rivers are less than three months old (Jasechko et al., 2016). Catchment characteristics profoundly influence the changes in F_{yw} (Campbell et al., 2020). It has been noted that the natural features of a catchment, such as vegetation cover and drainage area, can cause changes in F_{yw} (Ceperley et al., 2020). In addition, arid and semi-arid catchments typically respond slowly to precipitation events and show low F_{yw} in the direct hydrological response (Kingsbury et al., 2017). There are a number of factors influencing the water transit times

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(Cartwright et al., 2020). At high altitudes with seasonally cold climates, precipitation is temporarily stored in the snow during the winter, resulting in longer water transit times (Lyon et al., 2010). In addition to the natural factors mentioned above, dams also profoundly influence the water transit times (Weiler et al., 2003). The observation systems established in previous studies often failed to take control of the entire basin and failed to provide insights into the interference of dams on hydrological processes in the basin (Seeger and Weiler, 2014; Zhang et al., 2012). Therefore, this study also introduces a highly accurate, full-coverage, all-factor monitoring system and explores the possible impact of dams on the water transit time of the basin.

Here we compared water transit times in two basins in the central arid zone of Asia to (a) analyse water transit times in different inland river basins and their driving mechanisms; (b) identify the main factors influencing water transit times; and (c) gain an accurate understanding of hydrological processes in arid zones and their response mechanisms to dams. Our study can help identify the impact of dams on the hydrological processes in specific regions or watersheds, thereby enhancing our understanding of human-induced disruptions to river systems in arid zones.

2. Study area

The Shiyang River Basin (101°22'-104°04'E, 37°07'-39°27'N) is an inland river basin in the Central Asian arid zone, with intensive human activity and complex hydrological characteristics in the region, and facing serious challenges in water resources management and development (Zhu et al., 2018). Two sub-basins (Fig. 1), the Xiying River Basin and the Binggou River Basin, located in its upper reaches,

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were selected as comparative study areas. The Xiying River basin (37°28'-38°02'N or 101°40'-102°23'E) is at an elevation of 1873-4911m and a basin area of 1727.5 km^2, which is characterised by strong solar radiation, abundant sunshine, vigorous evaporation and large temperature differences between day and night (Sang et al., 2022). The average annual precipitation in the basin is 281.2 mm and the average annual evaporation is as high as 1133.4 mm. The river's average annual water output is 3.18×10^8 m^3, accounting for about 22.3% of the average annual runoff of the Shiyang River. By 2021, there are 13 dams built in the basin, including multi-stage dams and large and medium-sized reservoir dams (Zhu et al., 2021).

The Binggou River basin (102°107'-102°31'52'E, 37°34'-37°47'N) has a temperate continental climate, with an average basin temperature of 3.5 °C, annual precipitation of 400-600 mm and annual evaporation of 800 mm. The river is 45 km long, with an area of 335 km^2. The river has an average annual runoff of 1.47×10^8 m^3, accounting for 10.3% of the average annual runoff of the Shiyang River. By 2021, only one reservoir dam has been constructed in the basin, the Nanying Reservoir (Zhu et al., 2018).

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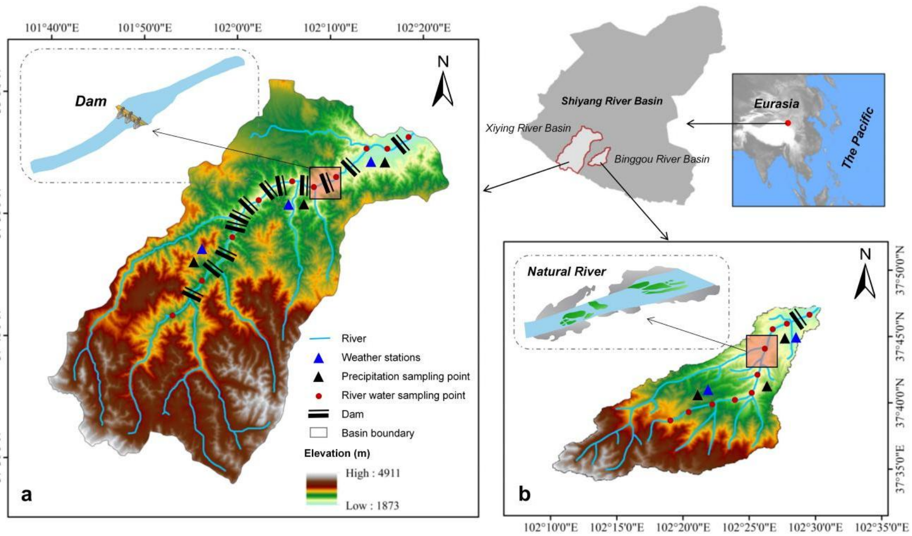

Fig. 1 Overview of the study area. (a) Xiying River basin and distribution of sampling sites. (b) Binggou River basin and distribution of sampling sites.

3. Materials and methods

3.1 Sampling and laboratory analysis

From April 2015 to October 2020, we collected 405 surface water samples in the Xiying River and 277 surface water samples in the Binggou River. Three precipitation sampling sites were established in Xiyong River and Binggou River respectively, and we collected a total of 784 precipitation samples. Automatic weather stations are used to record meteorological parameters such as temperature and relative humidity (Table 1).

Table 1 Basic data for sampling sites

Types of sampling points	Abbreviations	Numbers	Sampling frequency	Acquisition methods
Precipitation	P_1, P_2, P_3, P_4, P_5, P_6	784	Precipitation events	Rain gauge collection
River water	X_1, X_2, X_3, X_4, X_5, X_6, X_7, X_8, X_9, X_{10}, B_1, B_2, B_3, B_4, B_5, B_6,	682	Weekly	Surface water sampling

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	B_7, B_8, B_9, B_{10},

Surface water samples were stored in high-density polyethylene (HDPE) bottles. Precipitation samples were collected with standard funnels at meteorological stations. In order to prevent evaporation and leakage of samples during transport and storage, all bottle openings were sealed with plastic tape and then frozen. All the water samples collected were tested by a liquid water isotope analyzer (dlt-100, Los Gatos Research, USA) in the Stable Isotope Laboratory of Northwest Normal University. In order to ensure the accuracy of the measurements, a duplicate sample was collected for each sample, and the average value of the two was taken as the final value. The isotope analysis results are expressed with the notation "*δ*" and relative to Vienna Standard Mean Ocean Water (V-SMOW):

$$\delta_{\text{sample}}(‰)=\left[\left(\frac{R_{\text{sample}}}{R_{\text{v-smow}}}\right)-1\right]\times 1000 \quad (1)$$

where R_{sample} is the ratio of $^{18}O/^{16}O$ or $^{2}H/^{1}H$ in the samples and $R_{standard}$ is the ratio of $^{18}O/^{16}O$ or $^{2}H/^{1}H$ in V-SMOW. The precision was ± 0.6‰ for $\delta^{2}H$ and ± 0.2‰ for $\delta^{18}O$.

3.2 Methods

3.2.1 Young water fractions (F_{yw})

The variation of the isotopic composition of precipitation is seasonal (Campbell et al., 2020). The damping and phase shift of this seasonal cycle as it is transmitted through catchments can be used to infer timescales of catchment storage and transport. Using this principle, Kirchner (2016) developed a method to calculate the F_{yw} in heterogeneous and nonstationary catchments, and we calculated F_{yw} for each

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catchment using this method ~~(Kirchner, 2016)~~. First, we performed Fourier curve fitting on the δ[18]O (‰) time series to determine the cosine and sine coefficients of the precipitation and river water:

$$C_p(t) = a_p \cos(2\pi ft) + b_p \sin(2\pi ft) + K_P \tag{2}$$

$$C_S(t) = a_s \cos(2\pi ft) + b_s \sin(2\pi ft) + K_s \tag{3}$$

where $C_P(t)$ is the $\delta^{18}O$ (‰) compositions of the precipitation and $C_S(t)$ is the $\delta^{18}O$ (‰) compositions of the streamflow. k_p and k_s are the vertical shifts of the fitted sine waves, f is the frequency of the annual fluctuations (set to 1/365 days), t is the time in days after the start of the sampling period, and a_p, b_p, a_s, and b_s are coefficients for determining the amplitude and phase shift of the seasonal $\delta^{18}O$ cycles (Hu et al., 2020):

$$A_P = \sqrt{a_p^{\,2} + b_p^{\,2}},\ A_S = \sqrt{a_s^{\,2} + b_s^{\,2}} \tag{4}$$

$$\varphi_P = \arctan(b_p / a_p),\ \varphi_S = \arctan(b_s / a_s) \tag{5}$$

where A_P and A_S are the amplitudes of the precipitation and streamflow, respectively, and φ_P and φ_S are the phase shifts of the precipitation and streamflow, respectively. Then F_{yw} equals the amplitude ratio A_S/A_P, and the threshold age for F_{yw} is 0.189 years (69 days) .

3.2.2 Mean transit times (MTT)

After the quality control of the data, we quantified the MTT for the two basins. We used the MTT to describe the average water transit times and analyzed the effect of dams on the water transit times.

Assuming that the distribution of water transit time in the basin conforms to the

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gamma distribution function, the transit time distribution (TTD) in the basin can be computationally expressed as (Hrachowitz et al., 2011) :

$$g(\tau)=\frac{\tau^{\alpha-1}}{\beta^{\alpha}\Gamma(\alpha)}\exp^{-\tau/\beta}=\frac{\tau^{\alpha-1}}{(\bar{\tau}/\alpha)^{\alpha}\Gamma(\alpha)}e^{-\alpha\tau/\bar{\tau}} \quad (6)$$

Where τ is the transit time, and τ = αβ is the mean transit time.

$$\alpha\beta=\tau \quad (7)$$

Where α and β are a shape factor and scale factor[43], respectively.

3.2.3 Uncertainty analysis of model

A 4-year warm-up period was set for the model. Uncertainty was estimated using generalized likelihood uncertainty estimation (GLUE) (Heidbüchel et al., 2012). The Nash–Sutcliffe Efficiency (NSE) ensured that temporal stream isotope dynamics were adequately captured (Harman, 2015).

4. Results

4.1 The isotopic characteristics of the precipitation and the river water

Throughout the sampling period, precipitation stable hydrogen and oxygen isotope values showed significant seasonal variation, being most enriched in summer and most depleted in winter. However, the seasonal variation of precipitation isotope values in the Binggou River basin showed greater variability than in the Xiying River basin (Fig. 2). The local meteoric water line (LMWL) in the Xiying River basin is: $\delta D = 7.51\delta^{18}O + 10.04$ ($R^2 = 0.96$, $P < 0.01$), and the LMWL in the Binggou River basin is: $\delta D = 7.75\delta^{18}O + 10.98$ ($R^2 = 0.91$, $P < 0.01$). The slope of the LMWL in the two basins is lower than the global meteoric water line (Table 2), indicating that this region is in the arid zone, which is less disturbed by precipitation and strongly differentiated by evapotranspiration. Specifically, the slope and intercept of the LMWL in the Xiying River basin are lower than those of the Binggou River, showing a greater evaporative enrichment effect than the Binggou River.

In contrast, the slope of the fitted H-O isotope curve for river water is much lower than that of the LMWL, suggesting that the region experienced intense evaporation, resulting in a higher enrichment of stable hydrogen-oxygen isotopes in river water (Fig. 2). This indirectly confirms the climatic characteristics of intense evaporation in inland river basins. Also, the variability of stable hydrogen-oxygen isotope values in river water is smaller than that of precipitation, but inherits well the variability characteristics of precipitation isotopes (Fig. 2). The isotopic values of river water in the Xiying River basin showed a trend of gradual enrichment from upstream to downstream. The isotopic values of the river water near the dams are particularly enriched (Fig. S1). In contrast, there is no clear phenomenon of gradual enrichment from upstream to downstream in the isotopic values of river water in the Binggou River basin (Fig. S1).

Table 2 Isotopic values of different water bodies in different spatial zones of the Shiyang River.

Sampling Type	Values of $\delta^{18}O$ (‰)			Water line equation
	Min.	Max.	Mean.	
Precipitation in the Xiying River	-9.0	15.2	-31.1	$\delta D = 7.51\ \delta^{18}O + 10.04$
Surface water of the Xiying River	-8.1	-5.6	-8.6	$\delta D = 6.59\ \delta^{18}O + 4.95$
Precipitation in the Binggou River	-9.3	7.3	-28.9	$\delta D = 7.75\ \delta^{18}O + 10.98$
Surface water of the Binggou River	-8.6	-4.6	-10.7	$\delta D = 6.68\ \delta^{18}O + 6.10$

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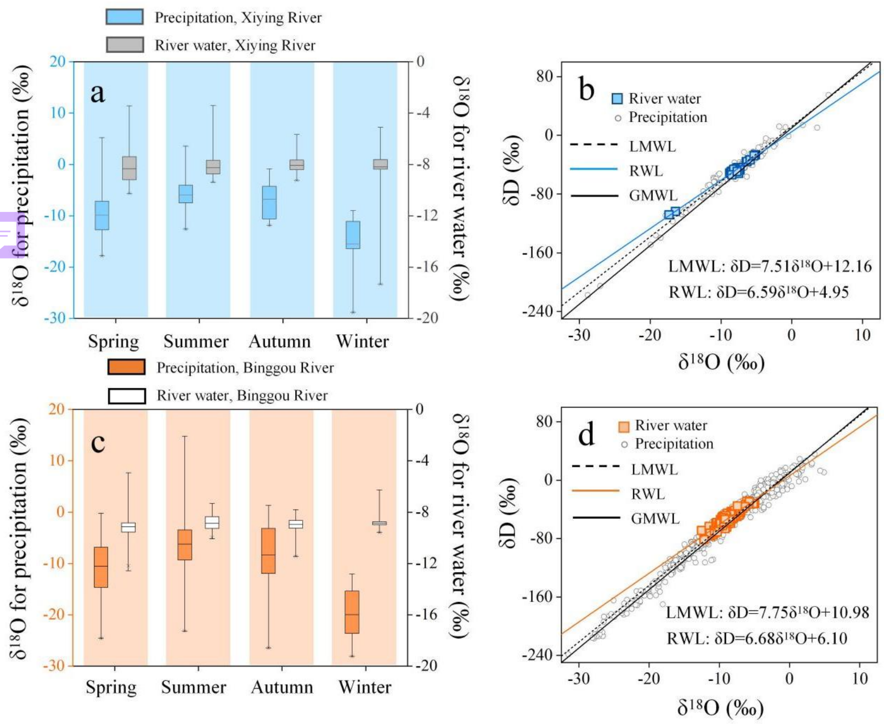

Fig. 2 Isotopic value characteristics and the relationship between δD and δ18O for the precipitation and the river water. (a) for the Xiying River basin and (b) for the Binggou River basin. RWL is an abbreviation for river water line and LMWL is an abbreviation for local meteoric water line

4.2 Variation of $\delta^{18}O$ in the precipitation and the river water

We compared the time series variation of the isotopic composition of precipitation and the isotopic composition of river water in these two basins. The time-series variation in the isotopic composition of precipitation is large for the two basins (Fig. 3). Precipitation isotope values in the Xiying River basin varied between -31.1‰ and 15.2‰, while precipitation isotope values in the Binggou River basin

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varied between -28.9‰ and 7.3‰ (Table 2). Precipitation isotope values in the Xiying River basin showed greater variability than those in the Binggou River basin. In contrast, the amplitude of river water isotopes in both basins has experienced greater damping. The isotopic values of river water in the Xiying River basin varied between -8.6‰ and -5.6‰, while the isotopic values of river water in the Binggou River basin varied between -10.7‰ and -4.6‰.

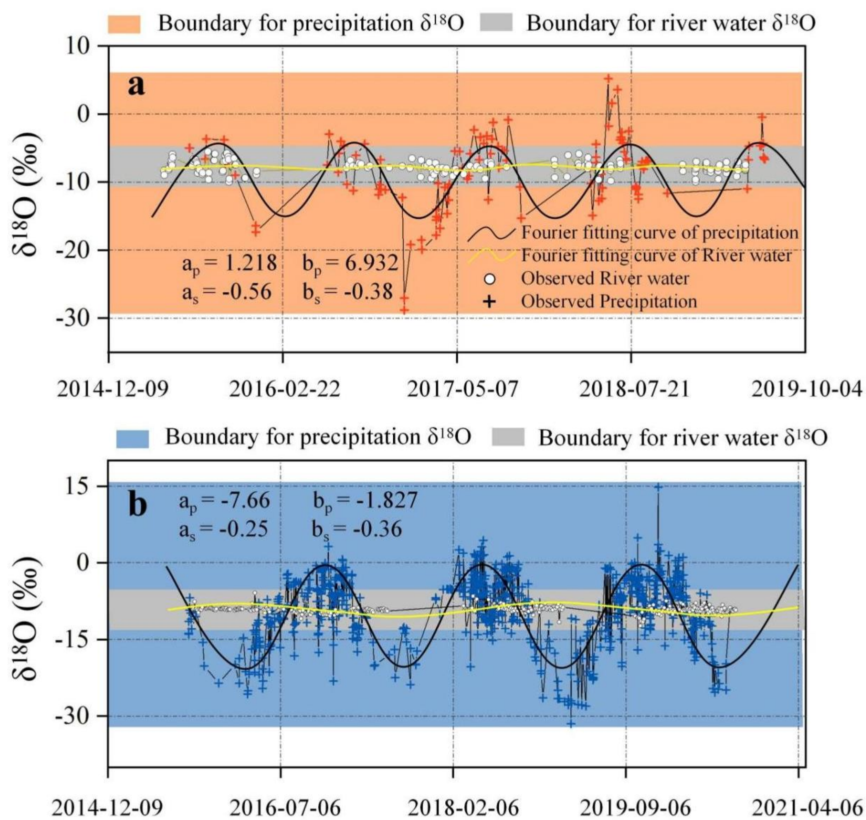

Fig. 3 Time series variation and Fourier curve fitting of precipitation and the river water in two comparison basins, a_p and b_p are the coefficients for determining the amplitude of the for precipitation, a_s and b_s are the coefficients for determining the amplitude for the river water. *a* for the Binggou River, *b* for the Xiying River.

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We performed a Fourier curve fitting analysis. The Fourier curve fitting models for precipitation and streamflow were statistically significant ($p < 0.01$). Changes in river isotopic values were dampened at both sites compared to precipitation (Fig. 3). Specifically, the variation in river isotopic values in the Binggou River well inherited the variation in precipitation, while the seasonal signal of river isotope values in the Xiying River basin had a more significant damping. Stable hydrogen and oxygen isotope values in the precipitation and the river water show significant differences and significant seasonal variation. This finding suggests that in the Xi Ying River Basin, characterized by a dense distribution of dams, the surface water demonstrates a complex interplay of processes including isotope dilution, enrichment, and attenuation.

~~5. Discussions~~

5.1 Dynamics of F_{yw} and MTTs

The MTT for the Xiying River basin is 3390 days, which is significantly longer than the 1170 days for the Binggou River basin (Table 3). As the spatial and temporal heterogeneity of the basin may cause errors in the MTT estimates, we used F_{yw} to constrain the estimated MTT results. This is because F_{yw} is not affected by changes in basin characteristics (Zhang et al., 2020). In general, smaller F_{yw} corresponds to longer water transit times.

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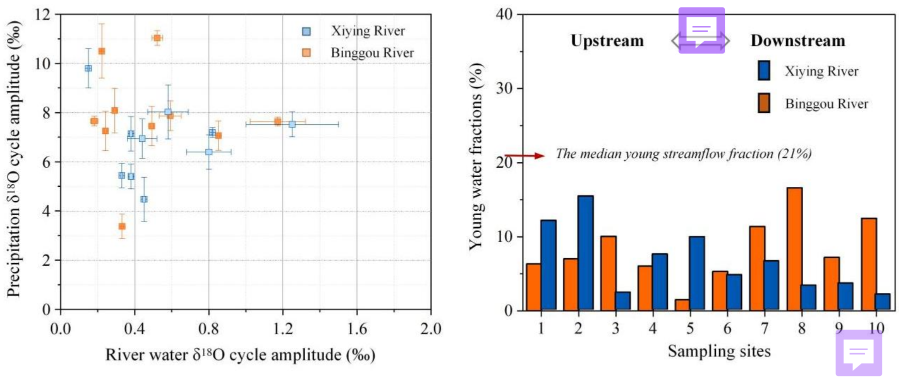

Fig. 4 Amplitude of the seasonal cycle of precipitation and river water $\delta^{18}O$ (left) and riverine variation of the F_{yw} in two compared basins (right).

Table 3 Comparison of amplitude, young water fraction (F_{yw}) and the mean transit time (MTT) in two basins.

Basins	Precipitation Amplitude	River water amplitude	Number of dams	MTT	MTT (95% C.L)	F_{yw}	F_{yw} (95% C.L)	NSE
Xiying River basin	a_p=-7.66 b_p=-1.827	as=-0.25 bs=-0.36	13	3390	2784-3874	6.70%	2.1%-15.3%	0.54
Binggou River basin	a_p=1.218 b_p=6.932	as=-0.56 bs=-0.38	1	1170	1011-1357	8.40%	1.5%-16.6%	0.62

We found that the F_{yw} in the Xiying River basin decreases from upstream to downstream (Fig. 4). Reaching the outlet of the river, the F_{yw} of the river is even less than 3%. However, there is no significant decrease in the variation of the F_{yw} in the Binggou River. We examined the along-river variation of the F_{yw} and river isotope values in the two basins and found a significant negative correlation between river isotope composition and young water in the Xiying River basin (r = -0.15, p < 0.01), while no significant correlation was found in the Binggou River basin (Fig. 5). Thus,

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the along-river enrichment of river water isotopic values caused by the multi-stage dams resulted in a significantly lower proportion of the F_{yw} in the Xiying River river.

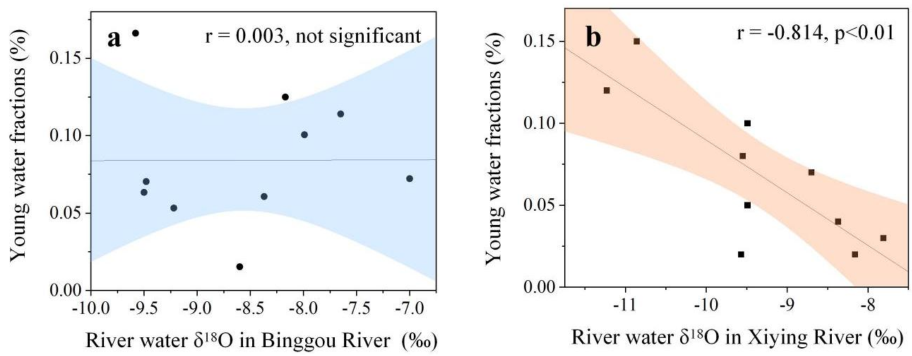

Fig. 5 Correlation between river water $\delta^{18}O$ and the young water fractions. *a* for the Binggou River, *b* for the Xiying River.

5.2 Impact of dams on the catchment water transit times

Many global studies have shown that humans have a significant impact on the land water circulation through the construction and operation of dams (Lehner et al., 2011). Compared with free-flowing rivers, rivers affected by dams have higher evaporation losses, especially in arid and semi-arid regions. All runoff in the entire Xiying River Basin was affected by dams (Wang et al., 2019). Due to abundant water energy, many basins have built multi-stage dams from upstream to midstream. With the gradual interception of these dams, a cumulative effect is generated. This cumulative effect leads to a gradual evaporation and enrichment of hydrogen and oxygen isotopes from the upper reaches to the middle reaches of the river (Fig. 6).

The artificially intercepted runoff may experience a considerable delay from the upstream source area to the estuary, leading to a series of local and downstream water system changes (Vorosmarty et al., 1997). The estuaries of several large rivers show that the continental runoff caused by the reservoirs has aged for more than 3 months (Voeroesmarty et al., 1997). In a free-flowing river, the average residence time of continental runoff may be between 16 days and 26 days(Vörösmarty and Sahagian, 2000). In contrast, at the mouth of the 236 large-scale reservoirs, emissions-weighted global averages have risen by nearly 60 days (Zarfl et al., 2015) . Therefore, after the river water passes through the basin regulated by dams, the time to reach the outlet of the basin will be greatly extended. Fig. 6 shows the change in water transit times under the influence of dams. Under the interference of dams on the river, the river water is continuously blocked, resulting in strong isotope evaporation and enrichment. This evaporation enrichment phenomenon will produce an isotope evaporation non-equilibrium fractionation effect, in which the heavy isotopes stay and the light isotopes continue to flow downstream. As a result, the variability of the seasonal amplitude of the precipitation isotope is weakened, and the seasonal amplitude of the isotope of the river water is reduced, resulting in the damping and phase shift of the river water relative to the seasonal period of the precipitation isotope (Song et al., 2020; Jodar et al., 2016). The Fourier fitting curve amplitudes of the precipitation isotopic values in the Xiying River Basin are -7.661 and -1.827. Under the influence of dams and the evaporative fractionation effect, the amplitude of the isotope of the river water reaching the outlet of the basin are only -0.25 and -0.36 (Fig. 3). The stronger the evaporative enrichment effect caused by dams, the greater this damping and phase shift, resulting in longer MTTs.

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We also used changes in river hydrological data to support this conclusion. Studies have shown that small watersheds are more sensitive to the impact of human activities such as dams. Fig. S2 shows the average daily water discharge variation during the peak flood season (June, July and August) in the Xiying River basin. From 1989 to 2019, the peak flow in the Xiying River basin has shown a yearly decreasing trend in June and July, mainly due to the interception of multi-stage dams reducing the flow rate of the river. As a result, the natural properties of hydrology are strongly influenced by dams, and the multi-stage dams extend the water circulation times by changing links in the hydrological cycle of the basin.

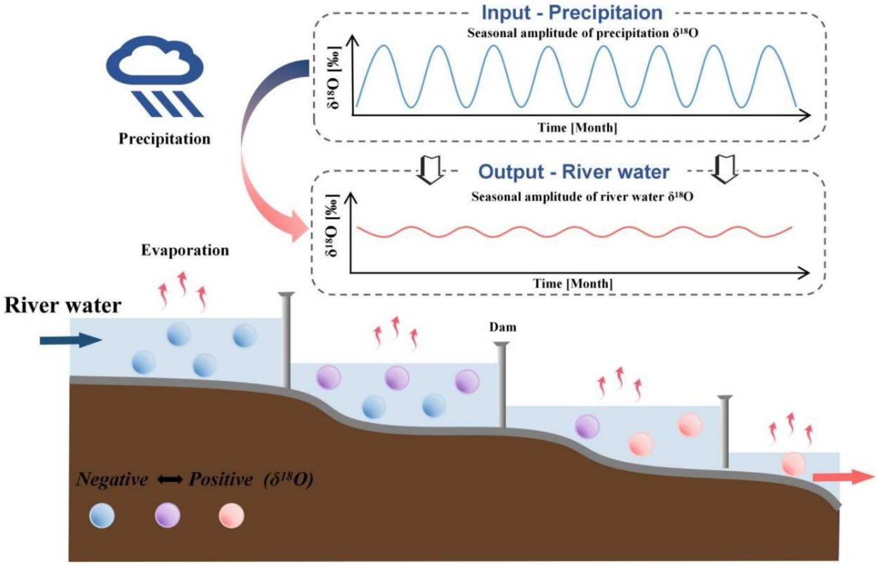

Fig. 6 A conceptual model of the effect of dams on the water circulation processes from the perspective of isotope kinetics. The top right corner shows the seasonal amplitude of the precipitation and the river water.

5.3 Uncertainty analysis of the algorithm

The factors contributing to the uncertainty are manifold. Firstly, the time interval of sampling can seriously affect the uncertainty of the results. Stockinger et al. (2016) noted that a high sampling frequency would improve the accuracy of the F_{yw} calculations (Stockinger et al., 2014). The uncertainty in using weekly sampling method in this study is relatively small. In addition, the choice of the spatial location of sampling points can also have an impact on the accuracy of the results (Jasechko et al., 2016). Data errors can also occur because of mismatches in the spatial location of the chosen sampling types (precipitation, surface water), such as precipitation sampling points being too far away from stream water sampling points. Ice meltwater is another important source of stream water recharge in the Shiyang River basin, and the involvement of glaciers and snow also largely delays the transit time of water, increasing the uncertainty in the model calculations (Timbe et al., 2014).

Uncertainty in MTTs for the two basins were estimated using five years of water isotope data ($\delta^{18}O$) from 2015 to 2019. If the NSE result for a group of data is less than 0.4, the uncertainty in the data is within manageable limits(Hrachowitz et al., 2009). The results show that the NSE in the Xiying River basin being the largest (0.54) and the Binggou River the smallest (0.62). It is undeniable that anthropogenic disturbances may also add to the uncertainty of the results of studies in the Xiying River Basin. As the Xiying River is one of the most abundant rivers in terms of water resources and hydrodynamic energy in the upper Shiyang River Basin, multi-stage dams have been built on the river to regulate the redistribution of water resources. Dams disturb the natural state of hydrological processes in the basin and therefore lead to uncertainty in the model (Matteau et al., 2009) .

6. Conclusions

By utilizing observational isotopic data from water bodies, we conducted a comparative study on the Fyw and MTT in two inland river basins within the arid zone of Central Asia. The objective was to quantitatively assess the impact of dams on water circulation times. Our findings show that the main human factor of long water circulation times in inland river basins in arid regions is dams. The MTT of Xiying River Basin is 3380 days, which is longer than the Binggou River basin (1170 days). The multi-stage dams resulted in a significant decrease in the young water fraction of the river, leading to longer MTT. The analysis shows that dams increasing the damping and phase shift of seasonal amplitude of river water relative to precipitation isotopes. Therefore, it leads to longer water circulation times in inland river basins. This work have used mathematical and computational methods to assess the water circulation times. Although uncertainties exist, we have tried to minimize them by establishing a highly accurate and comprehensive isotope monitoring network and optimizing the location of the precipitation and surface water sampling points, The study confirms the fact that dams are profoundly influencing the water circulation processes in inland river basins from an isotopic kinetic perspective, and is useful for understanding the mechanisms driving water circulation times globally.

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Data Availability Statement

The data that support the findings of this study are openly available in Zhu (2021) at “Data sets of Stable water isotope monitoring network of different water bodies in Shiyang River Basin, a typical arid river in China”, Mendeley Data, V1, doi: 10.17632/t87pm4b5dx.1.

Author contributions statement

Jiangwei Yang and Liyuan Sang: Writing-Original draft preparation; Xiaoyu Qi,Zhijie Zheng and Yingying Jiao: Visualization; Siyu Lu, Wenmin Li and Rui Li: Investigation; Guofeng Zhu: Supervision; Qinqin Wang, Yuxin Miao and Yani Gun: Software.

Declaration of Interest Statement

We undersigned declare that this manuscript entitled “Dams extend the surface water renewal time in inland river basins: A comparative study based on stable isotope data from two different basin” is original, and has not been published before and is not currently being considered for publication elsewhere.

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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