https://doi.org/10.5194/hess-2022-75
Preprint. Discussion started: 22 April 2022

Hydrology and Earth System Sciences
Open Access
Discussions

Correspondence Authors:

Name: Guofeng Zhu [a, b, *]

Institution:

[a] *College of Geography and Environment Science, Northwest Normal University, Lanzhou 730070, Gansu, China*

[b] *Shiyang River Ecological Environment Observation Station, Northwest Normal University, Lanzhou 730070, Gansu, China*

Address:

College of Geography and Environment Science of Northwest Normal University, 967, East Anning Road, Lanzhou, Gansu, China 730000.

Tel: +86-13909310867

Fax: +86-09317971565

E-mail: zhugf@nwnu.edu.cn

https://doi.org/10.5194/hess-2022-75
Preprint. Discussion started: 22 April 2022

Hydrology and Earth System Sciences
Discussions
Open Access

Evaluation loss estimation of the river-lake continuum of arid inland river: Evidence from stable isotopes

Guofeng Zhu[a,b,*] (zhugf@nwnu.edu.cn), Zhigang Sun[a,b] (zachsuen@163.com), Yuanxiao Xu[a,b] (Xyxange@163.com), Yuwei Liu[a,b] (liuyuweinwnu@163.com), Zhuanxia Zhang[a,b] (zzx_nwnu@163.com), Liyuan Sang[a,b] (nwnusly@163.com), Lei Wang[a,b] (wlxbsd02468@163.com)

[a] *College of Geography and Environment Science, Northwest Normal University, Lanzhou 730070, Gansu, China*

[b] *Shiyang River Ecological Environment Observation Station, Northwest Normal University, Lanzhou 730070, Gansu, China*

[*] *Corresponding author*

Abstract: Stable isotopes could be used as tracers to estimate the evaporation loss of surface water, which provides a new perspective for the research of hydrological processes. A systematic observation station has been built in the Shiyang River Basin, one of the most important inland river basins in Northwest China. This work conducted systematic observations on the river water, precipitation and hydrometeorology of the Shiyang River from 2017 to 2019. The evaporation loss of the Shiyang River is estimated to be 1.30% in the mountainous rivers, 2.28% in the mountainous reservoir (Xiying Reservoir), 2.87% in the oasis rivers, 7.97% in the oasis reservoir (Hongyashan Reservoir), and 41.37% in the terminal lake (Qingtu

https://doi.org/10.5194/hess-2022-75
Preprint. Discussion started: 22 April 2022

Hydrology and Earth System Sciences
Discussions

Lake). No matter in mountain or oasis, the evaporation loss of reservoir is much higher than that of the river, and the evaporation loss of the terminal lake is the largest. The evaporation loss of the river-lake continuum accounts for 14.66% of the total water volume of rivers and lakes (reservoirs). This work enriches the study of stable isotopes in the field of evaporation loss in the river-lake continuum, expands our understanding of the hydrological cycle in arid regions.

Keywords: Stable isotopes, *Hydrocalculator*, Evaporation loss, River-lake continuum

1. Introduction

Rivers are an important path of the global water cycle and play an important role in transporting materials and energy worldwide (Christophe et al., 2020). River water is the most important freshwater resource that humans can be directly utilized, and it plays a vital role in human life and the development of industry and agriculture (Diamond and Jack, 2018). Especially for arid and semi-arid regions, river water provides most of the production and domestic water for local residents. However, the limitation of global warming on the efficient use of water resources by humans is increasingly large. Limited water resources have gradually become obstacles to local economic development, especially in arid and semi-arid areas. Therefore, alleviating the restriction of limited water resources on social and economic growth has become a hot topic.

Evaporation and transpiration play an essential role in the global hydrological cycle (Brutsaert, 1986; Dogramaci et al., 2012), while evaporation tends to be the

https://doi.org/10.5194/hess-2022-75
Preprint. Discussion started: 22 April 2022

largest contributor to continental water flux in arid and semi-arid areas due to the sparse vegetation (Jasechko et al., 2013). Evaporation is the primary water losses for surface water in arid and semi-arid areas (Dogramaci et al., 2012; Wang et al., 2016), in which a significant fraction of lakes' storage (30%-50%) has evaporated (Maestre-Valero et al., 2013; Majidi et al., 2015). Evaporation losses amounted to 40%-60% of the reservoir output and 61% of agricultural use in Texas (Katja et al., 2018; Wurbs and Ayala, 2014), 20% of the country Nile share in Egypt (El-Shirbeny and Abutaleb, 2018), and 40% of reservoir storage in Northwest Xinjiang in China (Shi et al., 2016) and Queensland in Australia (Craig et al., 2005). Evaporation losses will increase with the increasingly higher temperature (Maestre-Valero et al., 2013). By 2100, the evaporation losses are estimated to increase by 1.09 to 2.74 mm per year, thereby reducing the available surface water in the dry season by 5.5% to 10.4% (Althoff et al., 2020; Zhao and Gao, 2019). Such evaporation loss leads to loss of storage water without use for domestic, irrigation or agricultural purposes. Therefore, as the main water resources in arid and semi-arid regions, it is necessary to systematically assess the evaporation loss of river systems in the context of constant climate change.

As two of the constituent elements of river water and an excellent natural tracer, stable isotopes (^{18}O and ^{2}H) provide a simple and reliable tool for estimating of river water evaporation loss (Halder et al., 2015). Numerous studies have successfully estimated the evaporation loss of the large open waters using stable isotopes (Cui et

https://doi.org/10.5194/hess-2022-75
Preprint. Discussion started: 22 April 2022

al., 2017; Hernández-Pérez et al., 2020; Yapiyev et al., 2020), while few studies have focused on mobile water systems, such as natural rivers (Diamond and Jack, 2018) and artificial waterways (Chen and Tian, 2021). It may be that the flowing water system will bring some instability factors, such as the discharge from reservoirs or lakes (Luc and Bernhard, 2007; Aravena and Suzuki 1990), the inflow of important tributaries (Wu et al., 2018; Simpson and Herczeg, 1991), the exchange between groundwater and surface water (Winston and Criss, 2003), the return flow of irrigation water (Mohammed et al., 2016), the inconsistency between sampling schedule and flow velocity (Chen and Tian, 2021), the influence of rainfall during the sampling period (Skrzypek et al., 2015). Although there are some uncontrollable factors in the estimation of evaporation loss of the river system, it is necessary to carry out relevant research because surface river system is the main contributor to the surface evaporation (Chen and Tian, 2021).

As one of the most important inland rivers in Northwest China, the Shiyang River plays an important role in the production and life of local residents and social development. Previous studies on the Shiyang River Basin mainly focused on water vapor recycling (Li et al., 2016; Zhu et al., 2019), soil water evaporation (Yong et al., 2020), the interaction between groundwater and surface water (Ma et al., 2005), and plant water sources (Zhang et al., 2021). Although the study has paid attention to the evaporation of the Shiyang River Basin, it focused on the evaporation loss of stable isotopes while not the surface water (Sun et al., 2021). The objectives of this work are

https://doi.org/10.5194/hess-2022-75
Preprint. Discussion started: 22 April 2022

(a) to estimate the evaporation loss of surface water in the different river and lakes sections; (b) to analyze the factors that cause differences in evapotranspiration loss across the different river and lake sections; (c) to discuss uncertainties in estimating evaporative losses from rivers and lakes using isotopic data. This study provides a set of feasible observation and calculation schemes for the estimation of evaporation loss in the basin.

2. Study area

As one of the most important inland rivers in Northwest China, the Shiyang River (Fig. 1) has an indelible effect on the vigorous development of the Hexi Corridor, China. Originating in the Qilian Mountains in the south and disappearing in the Tengger Desert in the north, it covers a distance of 260 km (Shi et al., 2002). From south to north, the elevation of the Shiyang river gradually decreases. According to the altitude difference, Shiyang River Basin can be divided into two portions: the Qilian Mountains in the upper reaches with an elevation of 2,000 to 5,000 m and an alluvial plain in the middle and lower reaches with a peak of 1,300 to 2,000 m (Gao et al., 2016).

Due to the unique geographical location of the Shiyang River in the transitional zone between the eastern monsoon zone and the western arid zone in China, it is affected by the East Asian monsoon and Westerly Winds (Chen et al., 2008). Therefore, precipitation presents noticeable seasonal changes. Precipitation in the basin is high in the summer when the East Asian monsoon has a greater impact.

https://doi.org/10.5194/hess-2022-75
Preprint. Discussion started: 22 April 2022

Almost 70% of the annual rainfall is concentrated from June to September (Zhu et al., 2019). Besides, the seasonality of precipitation in this area has a high degree of spatial heterogeneity, generally decreasing along the Shiyang River pathway with the mean annual precipitation ranging from 200 to 700 mm in the southern mountainous region, from 150 to 300 mm in the middle oasis region, and less than 100 mm in the northern desert region (Sun et al., 2021). Potential evaporation generally exceeds precipitation in this area, and especially in the lower reaches of desert areas, which can reach 2,600 mm (Ma et al., 2012). The temperature gradually increases from mountain to desert, with an annual average temperature of 9.20℃ in the mountainous area, 10.35℃ in the oasis area, and 12.00 ℃ in the desert area. The relative humidity gradually decreases from mountainous to the desert, with an annual average relative humidity of 51.50% in the mountainous area, 49.37% in the oasis area, and 40.21% in the desert area, respectively. The temperature is higher in the summer and lowers in the winter. However, there is no obvious seasonal variation in relative humidity, but high relative humidity is highly correlated with the occurrence of precipitation. Agriculture and animal husbandry in the middle and lower reaches also consume a lot of water, making this area one of the regions in the world where water supply and demand are highly imbalanced.

https://doi.org/10.5194/hess-2022-75
Preprint. Discussion started: 22 April 2022

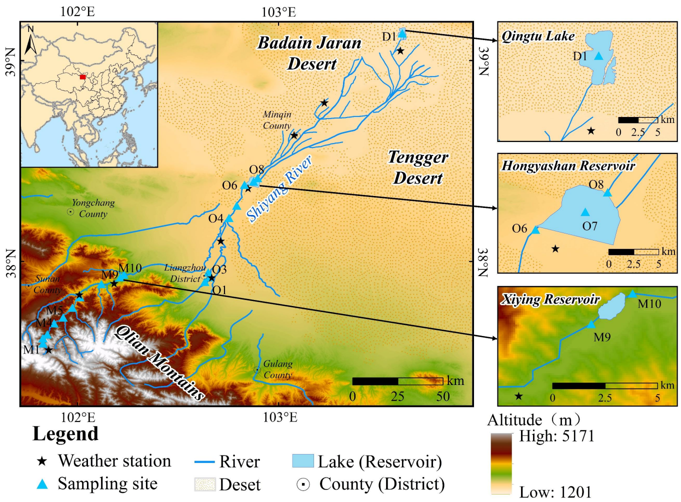


Fig. 1 Topographical overview of Shiyang River Basin and locations of the surface water sampling sites and automatic weather stations. The digital elevation data of this map is provided by Geospatial Data Cloud site, Computer Network Information Center, Chinese Academy of Sciences (http://www.gscloud.cn), and used under a Creative Commons license.

3. Materials and methods

3.1 Sampling design

This study investigates the stable isotopic composition of event-based precipitation and monthly surface water samples taken in the Shyiang River basin from April to October in the period from 2017 to 2019. The data has been examined previously by (Sun et al., 2021). Since the mountainous area in the upper reaches of the Shiyang River is the main source of runoff recharge, we set up 7 surface water observation stations in the mountainous area to more carefully detect the stable isotopic changes of surface water in the mountainous area. 5 surface water observation stations were also set up in natural rivers in the oasis area. In the desert

https://doi.org/10.5194/hess-2022-75
Preprint. Discussion started: 22 April 2022

area, 1 systematic observation station, including 10 sampling points, was set up in Qingtu Lake, the end of Shiyang River. In addition, we set up 2 reservoir observation stations, including Xiying Reservoir located in the river exit of Qilian Mountain and Hongyashan Reservoir located in the middle of the oasis area. The reservoir observation system includes inlet water, reservoir water and outlet water. From April to October during the period of 2017 to 2019, systematic sampling campaigns were conducted once a month from upstream to downstream along the Shiyang River.

From upstream to downstream, a total of 8 precipitation observation stations have been established, including 4 in the mountainous area, 3 in the oasis area, and 1 in the desert area. The collection of precipitation samples was based on the rainfall event. Once the rainfall stops, the water in the rain cylinder is immediately transferred to the standard sample bottle, labeled with time and place, and put in the refrigerator.

The meteorological data for this study were obtained from 8 automatic weather stations which were located in the same place as precipitation observation stations. These stations record meteorological data every 30 minutes, including temperature, relativity humidity, dew point temperature.

3.2 Stable isotope analysis

Stable isotopes of oxygen (^{18}O and ^{16}O) and hydrogen (^{2}H and ^{1}H) were analyzed in the Stable Isotope Lab of Northwest Normal University. Oxygen and hydrogen isotope ratios were measured using the Liquid Water Isotope Analyzer (DLT-100, Los Gatos Research, USA). Every water sample and isotope standard sample was

https://doi.org/10.5194/hess-2022-75
Preprint. Discussion started: 22 April 2022

continuously injected six times. To avoid the memory effect of isotope analysis, the first two injections were discarded and the average value of the last four injections was used in the examinations (Zhu et al., 2019). The isotopic composition of oxygen and hydrogen are reported in terms of delta (δ) notation in per-mil (‰, parts per thousand) and defined as follows:

$$\delta_{sample}(‰) = (\frac{R_{sample}}{R_{standard}} - 1) \times 1000 \quad (1)$$

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 Vienna Standard Mean Ocean Water (V-SMOW). Repeated analyses of internal standards provide an analytical precision of ±0.2‰ for oxygen and ±0.6‰ for hydrogen, respectively (Wang et al., 2016).

3.3 Craig-Gordon model

Craig and Gordon (1965) developed a conceptual model that describes the stable isotope evolution of open surface water during evaporation, which was used to solve the evolution of stable isotopic compositions of ocean surface water during the evaporation process. Based on the C-G model and previous researchers' verification of this model (Gibson et al., 2002; Gibson and Edwards, 2002; Horita and Wesolowski, 1994), Skrzypek et al. (2015) proposed the *Hydrocalculator* that allows the estimation of evaporation losses based on the stable isotopic composition of the input and output water of a pool and the local precipitation. It procedurals all calculation steps, and researchers only need to input relevant parameters to get the final calculation results, which makes the researcher's work more concise. Currently, this software is open to all researchers on http://hydrocalculator.gskrzypek.com.

Based on the distribution of reservoirs in the Shiyang River Basin and the sampling plan, we divide Shiyang River into seven sections (including 2 in the mountainous areas, 2 in the oasis areas, 1 in the desert areas and 2 reservoirs), and the evaporation loss of each section is calculated based on the *Hydrocalculator* software. Due to the constant inflow or outflow of river water in these sections, the steady-state model should be selected for the calculation of evaporation loss at each section. Therefore, we should select the value of columns *EI_H* and *EI_O* in the *output* file as the estimation results of the evaporation loss in these sections.

According to the runoff of each section, which is obtained in the Water Resources Utilization Center of Shiyang River Basin, Water Resources Department of Gansu Province (http://www.gs.xinhuanet.com/shiyanghe/index.htm), the evaporation loss of the entire Shiyang River Basin can be estimated.

$$f = \frac{\sum f_i \cdot V_i}{V} \quad (2)$$

where f is total evaporation loss, f_i is evaporation loss of each section, V_i is the runoff of each section (for a reservoir, it represents the storage capacity), and V is the total runoff.

4. Results

4.1 Temporal variation of stable isotopes in surface water of river-lake continuum

The stable isotopic composition of surface water in the Shiyang River shows

https://doi.org/10.5194/hess-2022-75
Preprint. Discussion started: 22 April 2022

Hydrology and Earth System Sciences
Discussions
Open Access

differences in different sections (Fig. 2, Table 1). From mountains to the oasis to the desert area, stable isotopic values show a trend of gradual enrichment. Especially in desert areas, due to the extremely arid environment and scarce vegetation cover, a large amount of surface water is susceptible to evaporation, and stable isotopic values are therefore quite enriched. From the perspective of time, there is a slight variation in stable isotopic values of surface water in mountainous and oasis areas during the sampling period. However, stable isotopic values of surface water in desert areas change a lot with time going by. It can be seen that stable isotopes were enriched in summer and depleted in spring and autumn of 2017, while stable isotopes do not show the same variation tendency despite the same great fluctuations of stable isotopic value in 2018. This is because the stable isotopic values of the lake water in Qingtu Lake are not only affected by evaporation, but also by human activities. When the water transfer period comes, the water discharged from Hongyashan Reservoir with lower stable isotopic value flows into Qingtu Lake, making the stable isotopic values of lake water lower. During the non-transportation period, the lake water evaporates continuously under hot and dry climate conditions, so the stable isotopes are gradually enriched.

https://doi.org/10.5194/hess-2022-75
Preprint. Discussion started: 22 April 2022

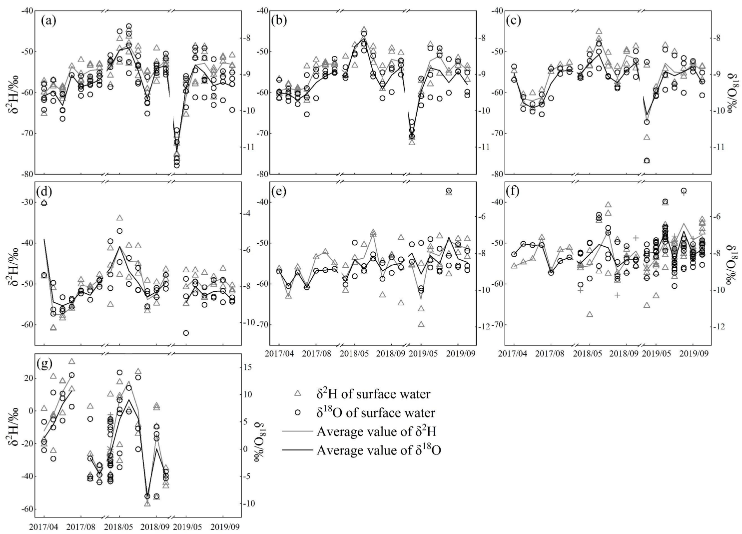


Fig. 2 Monthly variation of $\delta^{18}O$ and $\delta^{2}H$ in surface water of river-lake continuum during the sampling period. (a): Mountain 1; (b): Mountain 2; (c): Xiying Reservoir; (d): Oasis 1; (e): Oasis 2; (f): Hongyashan Reservoir; (g): Desert (Qingtu Lake).

Table 1 Characteristics of stable isotopic values of surface water at each sampling site during the sampling period.

Section	$\delta^{18}O$ (‰)			$\delta^{2}H$ (‰)		
	Max.	Min.	Mean	Max.	Min.	Mean
Mountain 1	-8.28	-11.12	-9.20	-48.36	-73.84	-55.59
Mountain 2	-8.01	-10.71	-9.16	-45.97	-71.58	-55.00
Xiying Reservoir	-8.45	-10.11	-9.15	-46.71	-67.06	-55.46
Oasis 1	-5.42	-9.08	-8.01	-57.54	-39.14	-49.54
Oasis 2	-7.13	-9.85	-8.72	-47.74	-63.75	-54.98
Hongyashan Reservoir	-6.79	-9.07	-7.98	-45.21	-57.50	-52.33
Desert (Qingtu Lake)	10.67	-8.64	1.93	21.65	-57.05	-11.85

4.2 Spatial variation of stable isotopes in surface water of river-lake continuum

Based on the dataset of stable isotopic composition analyzed from surface water, we obtain average values of stable isotopes at each sampling point during the

https://doi.org/10.5194/hess-2022-75
Preprint. Discussion started: 22 April 2022

Hydrology and Earth System Sciences Discussions
Open Access

sampling period. According to the distance between the sampling point and the river source, a variation trend of stable isotopic values of surface water along the Shiyang river is obtained, as seen in Fig. 3. Generally, with the flow of rivers, stable isotopes show a trend of gradual enrichment, which is mainly attributed to evaporation. The explanation may be rather the gradual increase of the degree of evaporation in the river water along the river pathway. The "inflow water" for each section, is the isotope composition of the preceding section, which becomes progressively enriched from upstream to downstream.

In mountainous areas, altitude ranges from 2,000 to 5,000 m. In addition, due to the climbing effect of air masses, there is more precipitation and higher vegetation coverage in mountainous areas. Alpine shrubs dominate the vegetation coverage in the upper reaches of the Shiyang River. Therefore, air humidity is higher due to the transpiration of high-density plants and large precipitation. Both lower temperature and higher humidity make the evaporation of surface water weaker in mountainous areas. Thus, the enrichment of isotopes is not apparent in the mountainous areas, as seen in Fig. 4. In oasis and desert areas, altitude ranges from 1,500 to 2,000m. The natural vegetation coverage is low, mainly distributed on both sides of river banks and roads. Especially at the end of the Shiyang River where the sandy soil has poor water holding capacity and the climate is dry, there is very little vegetation. Relatively higher temperatures and lower air humidity make evaporation severe (Sun et al., 2021). As shown in Fig. 3, the stable isotopes of surface water are the most enriched in the desert areas. However, there is a depletion between the sampling points O3 and O4, which may be caused by water transfer across river basins. (Beginning in 2001, Gansu Province implemented the Minqin Water Transfer Project to introduce 100 million m^3 Yellow River water into the Shiyang River every year, and the water outlet is located between the sampling points O3 and O4). The hydraulic connection between Hongyashan Reservoir and Qingtu Lake is maintained by the water conveyance channel, and this connection only exists during the water transfer period. Therefore, the stable isotopes of surface water are quite enriched in Qingtu Lake than Hongyashan Reservoir.

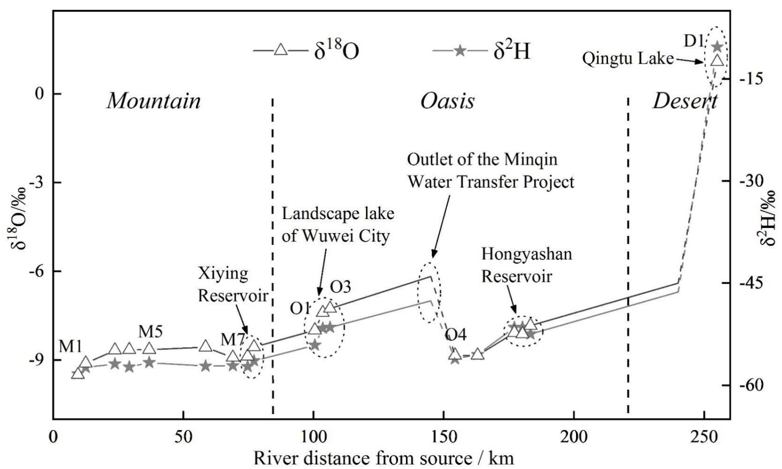


Fig. 3 Average values of stable isotopes in surface water collected at Shiyang river during the sampling period, plotted according to distance from the source.

4.3 Calculation of evaporation loss

Evaporation loss of each section ranges from 0.85% to 39.88%, estimated by $\delta^{18}O$, and from 1.61% to 42.86%, estimated by $\delta^{2}H$, respectively (Table 2). According

https://doi.org/10.5194/hess-2022-75
Preprint. Discussion started: 22 April 2022

to the estimated evaporation loss, it can be found that whether it is estimated by $\delta^{18}O$ or $\delta^{2}H$, it gradually increases with the flow of the Shiyang River. There is only an abnormal value in section oasis 2. Just as we found anomalies in isotope values between sampling O3 and O4, this is mainly caused by water transfer across river basins. Due to the impact of the Yellow River water transferred into the Shiyang River Basin, the estimation results of the evaporation loss of this section may be biased. The estimated evaporation loss of this section is lower than that of the adjacent upstream section oasis 1. In addition, the evaporation loss is significantly higher in large open water areas such as Xiying Reservoir and Hongyashan Reservoir. In the upper and middle reaches of the Shiyang River Basin, the impact of evaporation on water loss is limited. However, in the Qingtu Lake of desert area, the water lost by evaporation accounts for 41.37% of the water discharged from the Hongyashan Reservoir, and it accounts for most of the evaporation loss in the Shiyang River Basin. Due to the hot weather and extremely arid environment, the high evaporation loss is considered reasonable in Qingtu Lake.

The annual average runoff of each section of Shiyang River is 337 million m^3 in Mountain 1, 384 million m^3 in Mountain 2, 406 million m^3 in Xiying Reservoir, 130 million m^3 in Oasis 1, 299 million m^3 in Oasis 2, 393 million m^3 in Hongyashan Reservoir, and 350 million m^3 in Desert (Qingtu Lake), respectively. Based on Eq. 2, the evaporation loss of mountainous river (including the sections of Mountain 1 and Mountain 2) is estimated to 1.30%, the evaporation loss of oasis river (including the

https://doi.org/10.5194/hess-2022-75
Preprint. Discussion started: 22 April 2022

sections of Oasis 1 and Oasis 2) is estimated to be 2.87%, and the total evaporation loss of river-lake continuum in Shiyang River Basin is estimated to 14.66%, which is a major loss for the Shiyang River Basin where water resources are already scarce.

Table 2 Comparison of evaporation loss calculated from changes in stable isotopes flowing into and out of each section in Shiyang River.

	$\delta^{18}O$-based (%)	$\delta^{2}H$-based (%)	Mean (%)
Mountain 1	0.85	1.63	1.24
Mountain 2	1.11	1.61	1.36
Xiying Reservoir	2.01	2.55	2.28
Oasis 1	2.27	3.86	3.06
Oasis 2	2.02	3.54	2.78
Hongyashan Reservoir	7.02	8.93	7.97
Desert (Qingtu Lake)	39.88	42.86	41.37
Shiyang River Basin	13.55	15.75	14.66

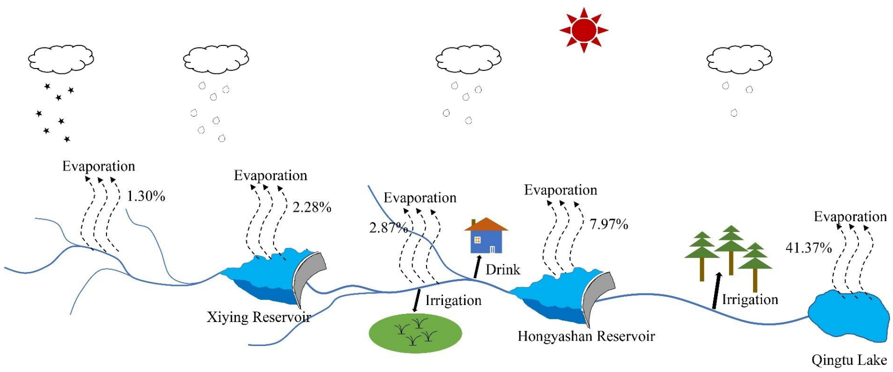


Fig. 4 A schematic of the Shiyang River, showing the source and consumption of river water and the strength of evaporation on different sections.

5. Discussions

5.1 Difference in evaporation loss estimation based on $\delta^{18}O$ and $\delta^{2}H$

Compared with the GMWL, the Local Meteoric Water Line (LMWL) is constructed from the stable isotopes of hydrogen and oxygen in local precipitation,

https://doi.org/10.5194/hess-2022-75
Preprint. Discussion started: 22 April 2022

which would better describe local meteorological conditions. Similarly, SWL is fitted by $\delta^{18}O$ and δ^2H of surface water in Shiyang River (Fig.5). It plays an important role in revealing the isotopic composition of local surface water and the strength of its evaporation. Except for section mountain 1, the slopes of SWL in other sections are all lower than that of GMWL and LMWL. Theoretically, the slope is lower than 8 because evaporation is driven by equilibrium and kinetic isotope effects (Craig, 1961; Kattan, 2008). The lower the slope, the lower relative humidity, the higher the evaporation rate. Whether surface water is transformed from groundwater or directly recharged by precipitation, it will be affected by evaporation during the replenishment process and the flow process (Cui et al., 2017). Therefore, the stable isotopes of the river water have changed, and the heavy stable isotopes are gradually enriched in the residual water with the increase of the downstream distance. As shown in Fig. 5, the slope of the SWL of each section shows a gradually decreasing trend with the flow of the Shiyang River. (Sun et al., 2021) have also found the rule of the increasingly lower slope of SWL with the decrease of elevation under the control of temperature and relatively humidity.

According to the estimation results in Table 2, it can be seen that the evaporation loss estimated based on δ^2H is inconsistent with the evaporation loss estimated based on $\delta^{18}O$, and the results based on δ^2H are significantly larger than that based on $\delta^{18}O$. Most previous studies focus on evaporation loss of sizeable open water in a relatively stable state, while this work presented here focuses on evaporation loss of rivers in a

https://doi.org/10.5194/hess-2022-75
Preprint. Discussion started: 22 April 2022

flowing state, which may lead to a difference in evaporation loss estimated based on δ^2H and $\delta^{18}O$. In addition, this difference may also be caused by the inconsistency between the sampling schedule and the flow velocity of river water (Chen and Tian, 2021), resulting in the evaporation loss estimation affected by the possible temporal change in source water isotopes. (Wu et al., 2017) point out that precipitation could also cause this difference. If rainfall occurs during the sampling period, the rainwater mixes into the river water, causing inconsistency in the samples collected upstream and downstream. Therefore, sampling should be carried out during the raining-free period to eliminate the impact of precipitation on the river water. This difference may also be caused by ambient vapor isotopes (Mayr et al., 2007). In this work, ambient vapor isotopes are derived from precipitation isotopes, which may differ from the isotopes in the actual ambient vapor, reducing the representative of the ambient vapor isotopes above the river. The reason for this difference may also come from the influence of the averaging of meteorological parameters used in the *Hydrocalculator*. Moreover, this difference seems to be common in evaporation loss estimation based on $\delta^{18}O$ and δ^2H (Gibson et al., 1993; Haig et al., 2020).

https://doi.org/10.5194/hess-2022-75
Preprint. Discussion started: 22 April 2022

Hydrology and Earth System Sciences
Discussions

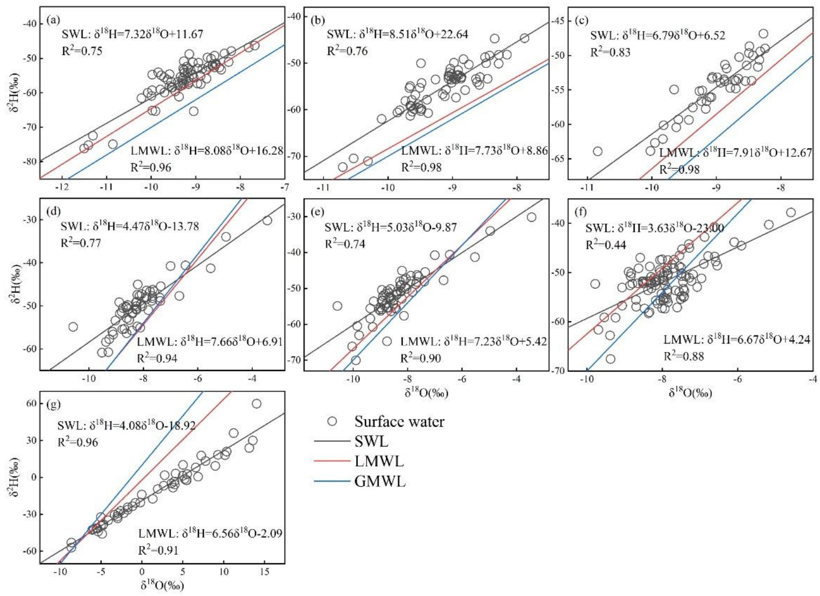


Fig. 5 $\delta^{18}O$ and $\delta^{2}H$ relationship for the surface water samples collected in the 7 sections and their corresponding LMWL and SWL. (a): Mountain 1; (b): Mountain 2; (c): Xiying Reservoir; (d): Oasis 1; (e): Oasis 2; (f): Hongyashan Reservoir; (g): Desert (Qingtu Lake).

5.2 Uncertainties

There may be several possible issues with the evaporation estimation in this work. These issues mainly include sampling design, conceptual model for the flow of water in the Shiyang River system, and calculation of related input parameters.

5.2.1 Water conservancy projects

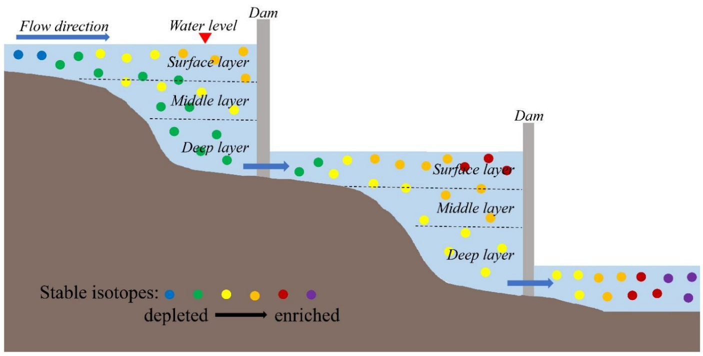
Research has proved that water conservancy projects such as reservoirs play an important role in shaping river water parameters (Grabowska, 2012). The construction of various water conservancy projects on the Shiyang River and agricultural irrigation will affect our estimation of the evaporation results. In the Shiyang River Basin, a series of hydropower stations and reservoirs have been built for flood control and

https://doi.org/10.5194/hess-2022-75
Preprint. Discussion started: 22 April 2022

irrigation, and Xiying Reservoir and Hongyashan Reservoir are the typical ones (Fig. 1). When the runoff is adjusted by water conservancy engineering facilities, it will inevitably cause the flow velocity to be different from the natural state under the conditions of manual intervention. For example, before the dry season, the discharge of water will be reduced in response to a possible later drought, and the downstream flow velocity will slow down due to the reduction of the discharge of water, and the same is true before the rainy season. If our sampling schedule coincides with the runoff adjustment of the water conservancy project, this will definitely affect the evaporation estimation. Therefore, we will avoid the reservoir storage adjustment period before making a sampling schedule.

Although there is manual intervention in the runoff, the input and output of water are kept in a relatively stable state for a water conservancy project. However, water conservancy projects would also cause water retention (Wang et al., 2019). After flowing through the water conservancy projects, the outflowing water comes from the deep layer of reservoirs, and the stable isotopes of the deep layer are more enriched than those of the surface layer, which may affect the evaporation estimation to a certain extent (Fig. 6). Therefore, to reduce the impact of water retention caused by water conservancy projects on the evaporation estimation, they are considered a separate section when estimating river evaporation. For example, we estimate the evaporation loss of Xiying Reservoir and Hongyashan Reservoir in this work, respectively.

https://doi.org/10.5194/hess-2022-75
Preprint. Discussion started: 22 April 2022

384 

385 Fig. 6 A schematic describing the effect of dams on the distribution of stable isotopes in surface

386 water of river-lake continuum.

387 **5.2.2 Non-in-stream-evaporative causes of isotope changes**

388 *Hydrocalculator* is proposed based on the C-G model. An important premise of

389 the C-G model is that there is no input from other water bodies in the study area (i.e.,

390 no additional surface water, groundwater, or rainfall inflow during the study period)

391 (Skrzypek et al., 2015). However, this is an ideal state. In fact, groundwater and

392 surface water constantly recharge each other in the process of river flows, and this

393 process is difficult to quantify with current technology. The continuous mutual

394 transformation between groundwater and surface water causes constant changes in the

395 stable isotopic values of surface water. Ultimately, the water we collect downstream is

396 not only enriched by evaporation, but also enriched or depleted by the inflow of

397 groundwater. However, there are large uncertainties in quantifying the conversion

398 volume of surface water to groundwater, so it is difficult to calculate the extent of its

399 influence on the evaporation estimation of the Shiyang River.

400 Equally challenging to quantify are the irrigation return flows from the vigorous

https://doi.org/10.5194/hess-2022-75
Preprint. Discussion started: 22 April 2022

agricultural activity in the middle and lower reaches of the Shiyang River. The Wuwei and Minqin Oasis, located in the middle and lower reaches of the Shiyang River Basin, are one of the most important grain bases in the Hexi Corridor. Agricultural activities are vigorous in this area. However, the booming agrarian production inevitably requires many water resources (Jia et al., 2020). Flood irrigation is the main irrigation method in this area. This method not only causes the loss of a large number of water resources due to evaporation, but also increases the return of irrigation water. This infiltration may have a significant cumulative effect on river flow and stable isotopic composition (Yoshida et al., 2016).

5.2.3 Model sensitivity analysis

The estimated evaporation loss exhibits an increasing trend with the increase of temperature (T), relative humidity (h) and isotopic values of outflow water (δ_Q), while shows a decreasing trend with the increase of isotopic values of precipitation (δ_R) (Fig. 8). In addition, the response of evaporation loss to different variables differed substantially. Among those variables, relative humidity is the factor that has the greatest impact on evaporation loss estimation, followed by stable isotopes of precipitation and temperature (Fig. 7). The evaporation loss increased most steeply with high relative humidity conditions (Fig. 7cd). The relative humidity significantly influences evaporation flux over the surface water and determines the isotope kinetic fractionation. As shown in Fig. 7cd, the estimated evaporation loss increases sharply at a given isotopic value when the relative humidity changed by 10%, but increases

https://doi.org/10.5194/hess-2022-75
Preprint. Discussion started: 22 April 2022

rapidly under conditions of high humidity (h = 70%). Isotopic composition of atmospheric water vapor (δ_A) is the direct controlling factor of evaporation loss, but in this work, δ_A is calculated from isotopic composition of precipitation (δ_R) because it is difficult to measure it directly in remote regions (Gibson, 2002; Li et al., 2021; Wu et al., 2017). The high variability in δ_R possibly increases the uncertainty of the calculated evaporation loss values. As observed in Fig. 8ef, an increase in $\delta^{18}O_R$ by 3‰ or δ^2H_R by 10‰ will lead to a decrease in evaporation loss at any given δ_Q. evaporation loss increased more sharply with an increase in δ_Q under low δ_R values. In addition, although evaporation loss ratios change slightly with the variation of temperature (Fig. 7ab), the temperature is also an important factor influencing the evaporation flux over surface water (Kumar and Nachiappan, 1999). It determines the isotopic fractionation at the interface between the surface water and vapor (Horita et al., 2008), and affects the estimation of evaporation loss. This analysis indicates that the main sources of uncertainties of evaporation loss are mainly derived from the h, followed by δ_R and T.

https://doi.org/10.5194/hess-2022-75
Preprint. Discussion started: 22 April 2022

Hydrology and Earth System Sciences
Discussions

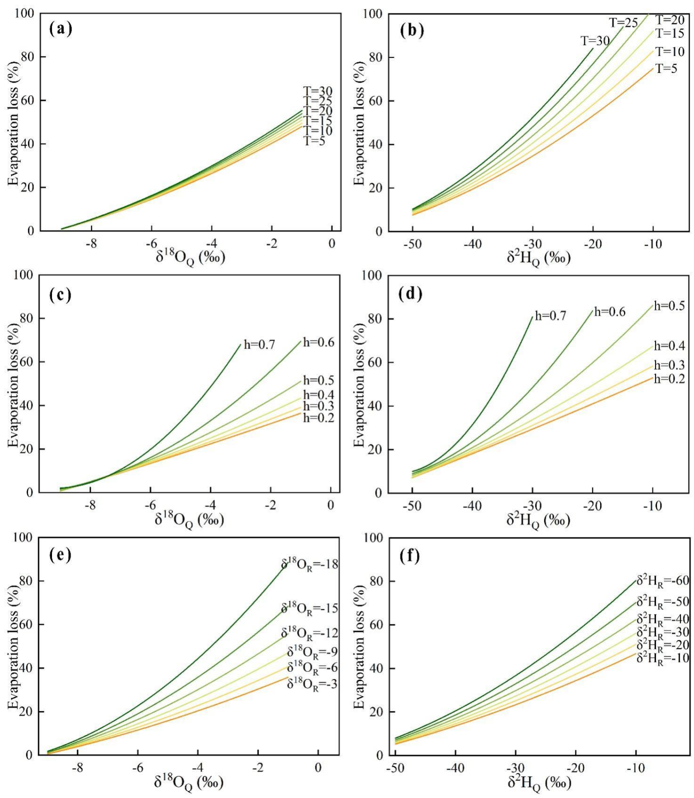


Fig. 7 The uncertainty assessment of E/I as the variations of input variables ($\delta^{18}O_Q$, δ^2H_Q, $\delta^{18}O_R$, δ^2H_R, h, T).

5.3 Implications

The quantification of the water balance in the Shiyang River Basin provides important insights into the hydrological processes in arid and semi-arid regions. Although the annual precipitation is in short supply, agriculture is highly developed in Shiyang River Basin, and agricultural water mainly comes from the extraction of groundwater and the interception of river water. In order to intercept the incoming water, a series of small and medium-sized reservoirs were built. There is no doubt that the construction of the reservoirs has increased the water area and increased the water

https://doi.org/10.5194/hess-2022-75
Preprint. Discussion started: 22 April 2022

loss due to evaporation in lower reaches where evaporation is initially strong, which is consistent with our evaporation loss estimation. The evaporation loss of Xiying Reservoir and Hongyashan Reservoir is relatively large, which are 2.28% and 7.97%, respectively. For arid and semi-arid regions, how to reduce unnecessary waste of water is an important part of the sustainable development of water resources. This work could provide a management basis for water resources management departments. In the next step, relevant research can be carried out to discuss how to reduce the large amount of water evaporation caused by the construction of the reservoirs. For example, transfer surface reservoirs to the ground (Ouerdachi et al., 2012), or cover floating balls on the surface reservoirs (Rezazadeh et al., 2020).

Previous research on evaporation loss mainly focused on large open water bodies such as lakes and reservoirs, while paying less attention to natural rivers. The proposal of this work has potential application for the study of regional hydrological cycles in other regions of the world. However, each river system has its own unique features. The sampling design should conform to its characteristics and consider all possible influence factors. For example, the impact of precipitation on river water is greater in humid regions than that in arid regions. When estimating evaporation loss, the impact of precipitation in the moist areas should be fully considered. In addition, the sampling schedule should be as consistent as possible with the flow velocity. For rivers with long distances, appropriate encryption sampling is required. If an important tributary flows in, samples of the tributary should also be collected.

Moreover, long-term observations will make the results more reliable and convincing.

6. Conclusions

Research on the evaporation loss of the river-lake continuum in the Shiyang River shows that stable isotopic technology can be used as a quantitative analysis tool to reveal the water balance of a basin. We have conducted systematic observations of stable isotopes of the river-lake continuum from the source to the end of the Shiyang River for three years. The results show that stable isotopes in the river-lake continuum gradually enriched from the source to the end of the Shiyang River. Besides, the stable isotopes of river water show obvious seasonal variations, enriched in summer and depleted in spring and autumn. Based on the *Hydrocalculator*, we estimate the evaporation loss of each section of the Shiyang River. The evaporation loss of Shiyang River is estimated to be 1.30% in the mountainous rivers, 2.28% in the mountainous reservoir (Xiying Reservoir), 2.87% in the oasis rivers, 7.97% in oasis reservoir (Hongyashan Reservoir), and 41.37% in the terminal lake (Qingtu Lake). The estimation loss shows a trend of gradual increase from upstream to downstream. No matter in mountain or oasis, the evaporation loss of reservoir is much higher than that of the river. The largest evaporation loss appears in the section of Qingtu Lake at the end of Shiyang River, with a value of 41.37%, which also explains the disappearance of Shiyang River here. According to the water volume and evaporation loss of each section, the evaporation loss of the entire river basin is calculated to be about 14.66%.

https://doi.org/10.5194/hess-2022-75
Preprint. Discussion started: 22 April 2022

Furthermore, we also observed the inconsistency of evaporation loss estimation based on $\delta^{18}O$ and $\delta^{2}H$, which may be associated with the factors including inconsistency of sampling schedule and flow velocity, rainfall during the sampling period, representativeness of ambient vapor stable isotopes, and meteorological parameters used in the model. Although there are some uncontrollable factors in estimating natural river evaporation loss, this work provides a stable isotopic method for assessing water volume variations in natural river basins.

Acknowledgments:

This work was supported by the National Natural Science Foundation of China [grant number: 41867030, 41971036]. The authors are very grateful to their colleagues in the Northwest Normal University for their help in fieldwork, laboratory analysis, data processing.

References:

Althoff, D., Rodrigues, L.N. and Da Silva, D. D.: Impacts of climate change on the evaporation and availability of water in small reservoirs in the Brazilian savannah. Climatic Change, 159(2), 215-232, 2020.

Aravena, R. and Suzuki, O.: Isotopic Evolution of River Water in the Northern Chile Region. John Wiley & Sons, Ltd, 26(12), 1990.

Brutsaert, W.: Catchment-scale evaporation and the atmospheric boundary layer. Water Resources Research, 22(9S), 39S-45S, 1986.

Chen, F. H., Yu, Z. C., Yang, M. L., Ito, E., Wang, S. M., Madsen, D. B., Huang, X. Z., Zhao, Y., Sato, T., Birks, H. J. B., Boomer, I., Chen, J. H., An, C. C., Wünnemann, B.: Holocene moisture evolution in arid central Asia and its out-of-phase relationship with Asian monsoon history. Quaternary Science Reviews, 27(3), 351-364, 2008.

Chen, Y. L. and Tian, L. D.: Canal surface evaporation along the China's South-to-North Water

https://doi.org/10.5194/hess-2022-75
Preprint. Discussion started: 22 April 2022

Diversion quantified by water isotopes. Science of The Total Environment, 779, 146388, 2021.

Christophe, R., Bertrand, M., Jean-Pierre, G., Marc, L. and Chantal, P.: Stable isotope study of rainfall, river drainage and hot springs of the kerguelen archipelago, SW Indian Ocean. Geothermics, 83, 101726, 2020.

Craig, H.: Isotopic Variations in Meteoric Waters. Science, 133(3465), 1702-3, 1961.

Cui, J., Tian, L., Biggs, T.W. and Wen, R.: Deuterium-excess determination of evaporation to inflow ratios of an alpine lake: Implications for water balance and modeling. Hydrological Processes, 31(5), 1034-1046, 2017.

Diamond, R.E. and Jack, S.: Evaporation and abstraction determined from stable isotopes during normal flow on the Gariep River, South Africa. Journal of Hydrology, 559, 569-584, 2018.

Dogramaci, S., Skrzypek, G., Dodson, W. and Grierson, P.F.: Stable isotope and hydrochemical evolution of groundwater in the semi-arid Hamersley Basin of subtropical northwest Australia. Journal of Hydrology, 475, 281-293, 2012.

El-Shirbeny, M.A. and Abutaleb, K.A.: Monitoring of Water-Level Fluctuation of Lake Nasser Using Altimetry Satellite Data. Earth Systems and Environment, 2(2), 367-375, 2018.

Gao, H., Li, Z., Pan, B., Liu, F. and Liu, X.: Fluvial responses to late Quaternary climate change in the Shiyang River drainage system, western China. Geomorphology, 258, 82-94, 2016.

Gibson, J. J., Edwards, T. W. D., Bursey, G. G. and Prowse, T. D.: Estimating Evaporation Using Stable Isotopes: Quantitative Results and Sensitivity Analysis for Two Catchments in Northern CanadaPaper presented at the 9th Northern Res. Basin Symposium/Workshop (Whitehorse/Dawson/Inuvik, Canada - August 1992). Hydrology Research, 24(2-3), 79-94, 1993.

Gibson, J. J., Prepas, E. E. and McEachern, P.: Quantitative comparison of lake throughflow, residency, and catchment runoff using stable isotopes: modelling and results from a regional survey of Boreal lakes. Journal of Hydrology, 262(1), 128-144, https://doi.org/10.1016/S0022-1694(02)00022-7, 2002.

Gibson, J.J. and Edwards, T.W.D.: Regional water balance trends and evaporation-transpiration partitioning from a stable isotope survey of lakes in northern Canada. Global Biogeochemical Cycles, 16(2), 10-1-10-14, 2002.

Grabowska, M.: The role of a eutrophic lowland reservoir in shaping the composition of river phytoplankton. Ecohydrology & Hydrobiology, 12(3), 231-242, 2012.

Haig, H.A. Hayes, N. M., Simpson, G. L., Yi, Y., Wissel, B., Hodder, K. R. and Leavitt, P. R.: Comparison of isotopic mass balance and instrumental techniques as estimates of basin hydrology in seven connected lakes over 12 years. Journal of Hydrology X, 6, 100046, 2020.

Halder, J., Terzer, S., Wassenaar, L. I., Araguás-Araguás, L. J. and Aggarwal,P. K.: The Global Network of Isotopes in Rivers (GNIR): integration of water isotopes in watershed observation and riverine research. Hydrology and Earth System Sciences, 19(8), 3419-3431, https://doi.org/10.5194/hess-19-3419-2015, 2015.

Hernández-Pérez, E., Levresse, G., Carrera-Hernández, J. and García-Martínez, R.: Short term evaporation estimation in a natural semiarid environment: New perspective of the Craig-Gordon isotopic model. Journal of Hydrology, 587, 124926, 2020.

Horita, J. and Wesolowski, D.J.: Liquid-vapor fractionation of oxygen and hydrogen isotopes of water from the freezing to the critical temperature. Geochimica et Cosmochimica Acta, 58(16), 3425-3437, 1994.

Jasechko, S., Sharp, Z. D., Gibson, J. J., Birks, S. J., Yi, Y. and Fawcett, P. J.: Terrestrial water fluxes dominated by transpiration. Nature, 496(7445), 347-50, 2013.

Jia, H., Qian, H., Zheng, L., Feng, W. W., Wang, H. K. and Gao, Y. Y.: Alterations to groundwater chemistry due to modern water transfer for irrigation over decades. Science of The Total Environment, 717(15), 137170, https://doi.org/10.1016/j.scitotenv.2020.137170, 2020.

Katja, F. et al.: Reservoir Evaporation in the Western United States: Current Science, Challenges, and Future Needs. Bulletin of the American Meteorological Society, 99(1), 2018.

Kattan, Z.: Estimation of evaporation and irrigation return flow in arid zones using stable isotope ratios and chloride mass-balance analysis: Case of the Euphrates River, Syria. Journal of Arid Environments, 72(5), 730-747, 2018.

https://doi.org/10.5194/hess-2022-75
Preprint. Discussion started: 22 April 2022

Li, X. X., Feng, Q., Wang, Q. J., Kong, Y. L., Cheng, A. F., Yong, S., Li, Y. G., Li, J. G. and Guo, X. Y.: Contributions of local terrestrial evaporation and transpiration to precipitation using δ 18 O and D-excess as a proxy in Shiyang inland river basin in China. Global and Planetary Change, 146: 140-151, https://doi.org/10.1016/j.gloplacha.2016.10.003, 2016.

Luc, R. and Bernhard, M.: Isotope hydrology of the Oldman River basin, southern Alberta, Canada. Hydrological Processes, 21(24), 2007.

Ma, J. Z., Wang, X. S. and Edmunds, W. M.: The characteristics of ground-water resources and their changes under the impacts of human activity in the arid Northwest China—a case study of the Shiyang River Basin. Journal of Arid Environments, 61(2), 277-295, 2015.

Ma, J. Z., Zhang, P., Zhu, G. F., Wang, Y. Q., Edmunds, W. M., Ding, Z. Y. and He, J. H.: The composition and distribution of chemicals and isotopes in precipitation in the Shiyang River system, northwestern China. Journal of Hydrology, 436-437, 92-101, https://doi.org/10.1016/j.jhydrol.2012.02.046, 2012.

Maestre-Valero, J. F., Martínez-Granados, D., Martínez-Alvarez, V. and Calatrava, J.: Socio-Economic Impact of Evaporation Losses from Reservoirs Under Past, Current and Future Water Availability Scenarios in the Semi-Arid Segura Basin. Water Resources Management, 27(5), 1411-1426, 2013.

Majidi, M., Alizadeh, A., Farid, A. and Vazifedoust, M.: Estimating Evaporation from Lakes and Reservoirs under Limited Data Condition in a Semi-Arid Region. Water Resources Management, 29(10), 3711-3733, 2015.

Mayr, C., Lücke, A., Stichler, M., Trimborn, P., Ercolano, B., Oliva, G., Ohlendorf, C., Soto, J., Fey, M., Haberzettl, Y., Janssen, S., Schäbitz, F., Schleser, G. H., Wille, M. and Zolitschka, b.: Precipitation origin and evaporation of lakes in semi-arid Patagonia (Argentina) inferred from stable isotopes (δ18O, δ2H). Journal of Hydrology, 334(1-2), 53-63, https://doi.org/10.1016/j.jhydrol.2006.09.025, 2007.

Mohammed, A.M., Krishnamurthy, R.V., Kehew, A.E., Crossey, L.J. and Karlstrom, K.K.: Factors affecting the stable isotopes ratios in groundwater impacted by intense agricultural practices: A case study from the Nile Valley of Egypt. Science of The Total Environment,

https://doi.org/10.5194/hess-2022-75
Preprint. Discussion started: 22 April 2022

573, 707-715, 2016.

Ouerdachi, L., Boutaghane, H., Hafsi, R., Tayeb, T.B. and Bouzahar, F.: Modeling of Underground Dams Application to Planning in the Semi Arid Areas (Biskra, Algeria). Energy Procedia, 18, 426-437, 2012.

Rezazadeh, A., Akbarzadeh, P. and Aminzadeh, M.: The effect of floating balls density on evaporation suppression of water reservoirs in the presence of surface flows. Journal of Hydrology, 591, 125323, 2020.

Shi, Q., Chen, F., Zhu, Y. and Madsen, D.: Lake evolution of the terminal area of Shiyang River drainage in arid China since the last glaciation. Quaternary International, 93-94, 31-43, 2002.

Simpson, H.J. and Herczeg, A.L.: Stable Isotopes as an Indicator of Evaporation in the River Murray, Australia. Water resources research, 27(8), 1925-1935, 1991.

Skrzypek, G., Mydłowski, A., Dogramaci, S., Hedley, P., Gibson, J. J. and Grierson, P. F.: Estimation of evaporative loss based on the stable isotope composition of water using Hydrocalculator. Journal of Hydrology, 523, 781-789, 2015.

Sun, Z. G., Zhu, G. F., Zhang, Z. X., Xu, Y. X., Yong, L. L., Wan, Q. Z., Ma, H. Y., Sang, L. Y. and Liu, Y. W.: Identifying surface water evaporation loss of inland river basin based on evaporation enrichment model. Hydrological Processes, 35(3), e14093, https://doi.org/10.1002/hyp.14093, 2021.

Wang, B., Zhang, H., Liang, X., Li, X. and Wang, F.: Cumulative effects of cascade dams on river water cycle: Evidence from hydrogen and oxygen isotopes. Journal of Hydrology, 568: 604-610, 2019.

Wang, S., Zhang, M., Che, Y., Chen, F. and Qiang, F.: Contribution of recycled moisture to precipitation in oases of arid central Asia: A stable isotope approach. Water Resources Research, 52(4): 3246-3257, 2016.

Winston, W. and Criss, R.: Oxygen isotope and geochemical variations in the Missouri River. Environmental Geology, 43(5), 546-556, 2003.

Wu, H. W., Li, J., Song, F., Zhang, Y. A., Zhang, H. X., Zhang, C. C. and He, B.: Spatial and temporal patterns of stable water isotopes along the Yangtze River during two drought years.

https://doi.org/10.5194/hess-2022-75
Preprint. Discussion started: 22 April 2022

Hydrological Processes, 32(1), 2018.

Wu, H. W., Li, X. Y., He, B., Li, J., Xiao, X., Liu, L. and Liu, J. Z.: Characterizing the Qinghai Lake watershed using oxygen-18 and deuterium stable isotopes. Journal of Great Lakes Research, 43(3), 33-42, https://doi.org/10.1016/j.jglr.2017.03.010, 2017.

Wurbs, R.A. and Ayala, R.A.: Reservoir evaporation in Texas, USA. Journal of Hydrology, 510, 1-9, 2014.

Yapiyev, V., Skrzypek, G., Verhoef, A., Macdonald, D. and Sagintayev, Z.: Between boreal Siberia and arid Central Asia – Stable isotope hydrology and water budget of Burabay National Nature Park ecotone (Northern Kazakhstan). Journal of Hydrology: Regional Studies, 27, 100644, 2020.

Yong, L, L., Zhu, G. F. and Wan, Q. Z.: The Soil Water Evaporation Process from Mountains Based on the Stable Isotope Composition in a Headwater Basin and Northwest China. Water, 12(10), 2711, 2020.

Yoshida, Y., Masumoto, T., Horikawa, H., Kudo, R., Minakawa, H. and Nawa, N.: River Basin Scale Analysis on the Return Ratio of Diverted Water from Irrigated Paddy Areas. Irrigation and Drainage, 65(S1), 31-39, 2016.

Zhang, W. L., Zhao, P., Zhu, S. J., Chai, C. W., Jiang, S. X., Geng, D. M. and Zhang, F.: Research on seasonal water use strategy of artificial Haloxylon ammodendron in the lower reaches of the Shiyang River. Pratacultural Science, 38(5), 880-889, 2021.(in Chinese)

Zhao, G. and Gao, H.: Estimating reservoir evaporation losses for the United States: Fusing remote sensing and modeling approaches. Remote Sensing of Environment, 226, 109-124, 2019.

Zhu, G. F., Guo, H. W., Qin, D. H., Pan, H. X., Zhang, Y., Jia, W. X. and Ma, X. G.: Contribution of recycled moisture to precipitation in the monsoon marginal zone: Estimate based on stable isotope data. Journal of Hydrology, 569, 423-435, https://doi.org/10.1016/j.jhydrol.2018.12.014, 2019.