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Research papers

Cumulative effects of cascade dams on river water cycle: Evidence from hydrogen and oxygen isotopes

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ABSTRACT

Cascade dams are known to influence the river water cycle, but their cumulative effects (CEs) are still not well understood. Water hydrogen (H) and oxygen (O) isotopes are hypothesized to be used to characterize the CEs. To test this hypothesis, we investigated water δD, $\delta^{18}O$, and related environmental factors in cascade reservoirs on the Wujiang River, Southwest China. The δD and $\delta^{18}O$ ranged from −64.2‰ to −45.4‰ and from −9.7‰ to −6.8‰, respectively, and showed obvious temporal and spatial variations. Water temperature is an important factor influencing these variations. After damming, an increase of water retention time caused the enrichment of heavy H-O isotopes in reservoir surface water, and thermal stratification induced a decrease of δD and $\delta^{18}O$ with depth. Due to bottom discharge, released water showed more negative δD and $\delta^{18}O$ than reservoir surface water, and these δD and $\delta^{18}O$ differences were controlled by water retention time and mean water depth of the reservoir. Overall, the CEs of cascade dams caused δD and $\delta^{18}O$ to display a jagged increase from upstream to downstream in the impounded Wujiang River. Therefore H-O isotopes can be used to estimate the CEs of cascade dams. As cascade dams can modify H-O isotope signatures, caution should be exercised when using H and O isotopes to trace the source of the impounded river water.

1. Introduction

Rivers provide the main channel for transporting water from land to the ocean, and play an important role in the global water cycle. Nowadays, approximately 70% of the world's rivers are intercepted by dams (Kummu and Varis, 2007). After damming, water retention time is prolonged, water area is enlarged, and downstream flow is changed (Vörösmarty and Sahagian, 2000; Lehner et al., 2011; Zhou et al., 2016). That in turn influences the nutrient biogeochemical cycles and ecosystems of the river and offshore environment (Humborg et al., 1997; Maavara et al., 2015; Han et al., 2018). Compared to a single dam, cascade dams can accumulate the effect on river water and nutrient cycles (e.g. Fan et al., 2015; Shi et al., 2017), and that is cumulative effects (CEs) of cascade dams. Quantitatively characterizing these CEs is a key to estimating the impact of cascade dam construction.

Hydrogen and oxygen (H-O) isotopes are useful geochemical tools to trace water migration and transformation, and help to reveal the water cycle between atmosphere, river, and groundwater (Craig, 1961; Gat, 1996; Li et al., 2015). Evaporation can result in fractionation of H-O isotopes; water vapor will be enriched in light isotopes; whereas precipitation will be enriched in heavy isotopes. Due to weaker evaporation, groundwater has lighter isotopes than surface water (Gat, 1996; Rozanski et al., 2001). Hence, different water sources have different H-O isotope signatures and the isotopes can therefore be used to discriminate water sources (Kendall and Coplen, 2001; Lachniet and Patterson, 2002; Meredith et al., 2009). As temperature and latitude also affect the H-O isotope signatures of precipitation (Dansgaard, 1964; Dutton et al., 2005), H-O isotopes are also used to study the response of lakes to climate factors such as temperature and seasonal precipitation; and the sensitivity of H-O isotopes to precipitation is usually higher in lakes with short retention time than in lakes with long retention time (Leng et al., 2006; Jonsson et al., 2009). Recently, H-O isotopes have been used to understand the effect of the dam on the river water cycle (Deng et al., 2016; Li et al., 2016).

In this study, we hypothesize that H-O isotopes can be used to characterize CEs of cascade dams. The impounded Wujiang River, Southwest China, is an ideal place to test this hypothesis, as there are many different aged reservoirs along this river and these reservoirs are usually under similar environmental conditions. Therefore, we have investigated water δD, $\delta^{18}O$, and related environmental factors in these reservoirs to understand their temporal and spatial variations and related control mechanism. Then, based on this understanding, CEs of

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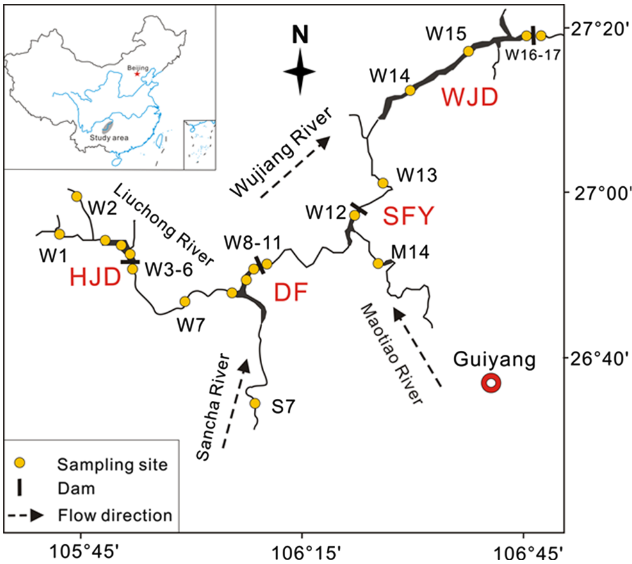

Fig. 1. Map showing sampling locations and numbers. HJD, Hongjiadu reservoir; DF, Dongfeng reservoir; SFY, Suofengying reservoir; WJD, Wujiangdu reservoir.

cascade dams were estimated. This study could be of great significance for expanding the application of H-O isotopes in river hydrological studies.

2. Material and methods

2.1. Study area

The Wujiang River is a tributary of the Changjiang (Yangtze) River, with a total length of 1037 km and a drainage area of 88 267 km^2 to the south of the Changjiang. The study area has a characteristic subtropical humid monsoon climate; the average annual temperature is 12.3 °C, with extreme temperatures of 35.4 °C in summer and −10.1 °C in winter. The annual precipitation ranges from 1100 to 1300 mm, and precipitation from May to October accounts for about 75% of the annual total. The Wujiang River has a fall of 2124 m and is one of the main rivers in a west-to-east power transmission project. Eleven reservoirs have been built on the main stream of the river, four of which were selected for the study (Fig. 1). They are Hongjiadu (HJD), Dongfeng (DF), Suofengying (SFY), and Wujiangdu (WJD) reservoirs, and the main features of these reservoirs are described in Table 1.

2.2. Sampling and analysis

The survey was conducted in October 2015 and January, April, and July 2016, which represent autumn, winter, spring, and summer, respectively. A total of 19 sites were selected, including the inflowing, reservoir, and released waters (Fig. 1). Water samples were taken down the depth profile at 0, 5, 15, 30, and 60 m at sites W5, W10, and W16, and from the surface, middle, and bottom layers at sites W3, W4, W8, W9, W14, and W15. The other sites were collected for surface water (upper 0.5 m). Water samples were obtained using Niskin bottle (General Oceanics, USA). Water temperature, pH, and dissolved oxygen were measured *in situ* with a calibrated automated multiparameter profiler (model: YSI 6600; YSI Inc., Yellow Springs, OH, USA). Water samples for δD and $\delta^{18}O$ measurements were filtered through 0.45 μm cellulose acetate membrane (Millipore Corporation) within 12 h at room temperature, and then put into 15 ml centrifuge tubes. The tubes were immediately closed without headspace with caps and sealed with film seal (Parafilm).

The δD and $\delta^{18}O$ of water were measured using a liquid water isotope analyzer (LGR, IWA-45EP, USA), with values reported using the standard δ notation relative to Vienna Standard Mean Ocean Water (V–SMOW). The analytical precision for δD and $\delta^{18}O$ were ± 0.3‰ and ± 0.1‰, respectively. Deuterium excess (*d*-excess or *d*) was calculated from the equation: $d = \delta D - 8\delta^{18}O$ (Dansgaard, 1964). Statistical analysis of the data was done using the SPSS package (version 22.0; IBM SPSS). Pearson's correlation coefficient analysis was conducted.

3. Results

3.1. Longitudinal variation along the Wujiang River

Surface water temperature (T) ranged from 10.98 °C to 28.23 °C with an average of 17.93 °C. Average T did not show significant difference between the reservoirs, but the reservoir surface water showed clearly higher T than river water (Fig. 2a). The T gradually increased from inflowing water to reservoir surface water, while that of released water was notably decreased. For example, in the HJD reservoir the average T of released water decreased up to 6.37 °C. Thus, the surface T of the main stream showed a jagged variation. As for the tributaries (sites W2, S7, and M14), their average T was lower than that of the main stream.

In surface water, the δD ranged from −63.8‰ to −45.4‰ with an average of −57.1‰, and the $\delta^{18}O$ ranged from −9.4‰ to −6.9‰ with an average of −8.4‰. The δD and $\delta^{18}O$ showed similar longitudinal variation, but notably different between the reservoirs (Fig. 2b and c). The δD and $\delta^{18}O$ were higher in reservoir surface water than corresponding inflowing and released waters, and generally, they showed a gradual increase from upstream to downstream of the river. Among the reservoirs, WJD had the highest average δD and $\delta^{18}O$ (−54.3‰ and −8.0‰, respectively), while DF showed the lowest ones (−58.4‰ and −8.5‰, respectively). And compared to their inflowing water, the δD and $\delta^{18}O$ in WJD reservoir increased by 7.3% and 11.0%, respectively, while those in DF reservoir only increased by 0.2% and 1.3%, respectively. The δD and $\delta^{18}O$ in released water were notably lower than those in reservoir surface water. For example, in WJD reservoir the average δD and $\delta^{18}O$ of released water decreased by 3.4% and 3.5%, respectively. The *d*-excess ranged from 2.7‰ to 14.0‰, with

Table1
The basic characteristics of the studied reservoirs.

Reservoir	Hongjiadu	Dongfeng	Suofengying	Wujiangdu
Catchment area (km^2)	9900	18,161	21,862	27,790
Average annual runoff ($\times 10^8 m^3$)	48.88	108.8	134.66	158.31
Average annual discharge (m^3/s)	155	345	427	502
Normal water level (m)	1140	970	835	760
Total reservoir capacity ($\times 10^8 m^3$)	49.25	8.63	1.57	21.4
Regulated storage capacity ($\times 10^8 m^3$)	33.61	4.9	0.85	13.5
Hydraulic retention time (yr)	1.01	0.08	0.01	0.14
Mean water depth (m)	61.18	43.81	27.54	45.05
Year of construction	2004	1994	2002	1979

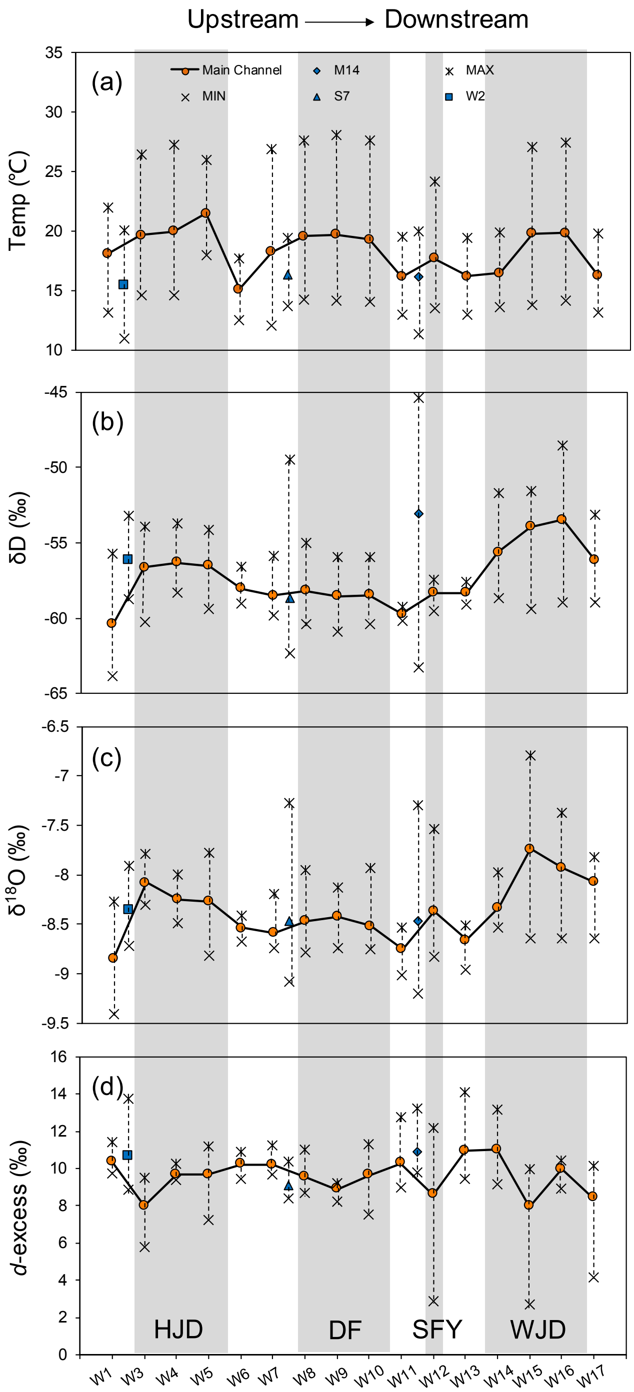

Fig. 2. Longitudinal variation of temperature (Temp), δD, $\delta^{18}O$, and *d*-excess in surface water of the Wujiang River. The sites W2, S7 and M14 were from the tributary of the Wujiang River. See Fig. 1 for site names and abbreviations of the reservoirs.

an average of 9.7‰. They did not show obvious longitudinal variation along the river. However, inflowing water usually showed higher *d*-excess than reservoir surface water (Fig. 2d).

3.2. Seasonal variation

In surface water, T, *d*-excess, δD, and $\delta^{18}O$ showed seasonal variations (Fig. 3). T exhibited more obvious variation than other parameters, with the highest average of 23.53 °C in July and the lowest of 13.64 °C in January. Comparatively, *d*-excess had the least seasonal

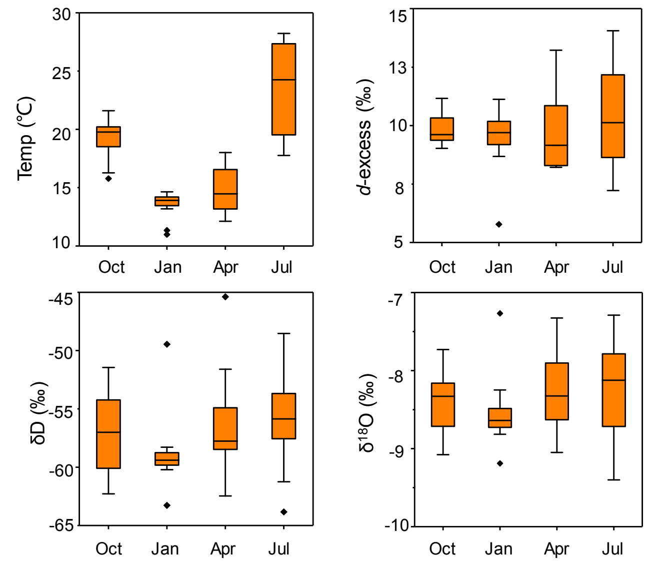

Fig. 3. Seasonal variation of temperature (Temp), δD, $\delta^{18}O$, and *d*-excess in surface water of the Wujiang River. Box boundaries indicate the 25th and 75th percentiles; whiskers extend to a maximum of 1.5 times the inter-quartile range; the inner horizontal line is the median; diamonds indicate outliers.

variation, but it still showed a high value and large amplitude in July. The δD and $\delta^{18}O$ showed moderate seasonal variations, with a large amplitude in July and a small amplitude in January.

3.3. Stratification

The HJD, DF, and WJD reservoirs showed obvious thermal stratification in summer, and the thermocline appeared at a layer of 5–20 m depths (Fig. 4). The δD and $\delta^{18}O$ of each reservoir were obviously stratified in summer and changed most dramatically in the thermocline; however, they showed weak stratification in other seasons. Water profile of the WJD reservoir exhibited the most obvious stratification, and the δD and $\delta^{18}O$ successively decreased from July to January. Generally, average T, δD, and $\delta^{18}O$ decreased with depth. However, the δD in DF reservoir was most negative in the thermocline and then weakly increased with water depth in the hypolimnion (Fig. 4).

3.4. The relationship between δD and $\delta^{18}O$

The δD and $\delta^{18}O$ of all dataset ranged from −64.2‰ to −45.4‰ and from −9.7‰ to −6.8‰, with an average of −57.6‰ and −8.5‰, respectively. There was a significant linear positive correlation between δD and $\delta^{18}O$, and slope and intercept of this linear regression line were lower than the global meteoric water line (GMWL) and local meteoric water line (LMWL) (Fig. 5). Most of the data were under the LMWL and the heavy isotopes were enriched, indicating that H-O isotope signatures were changed in the water cycle of these cascade reservoirs and thus deviated from that of local precipitation. The data from the WJD reservoir system were located in the upper right, HJD reservoir system in the lower left, and DF and SFY reservoir systems in the middle (Fig. 5), indicating that δD and $\delta^{18}O$ gradually increased from upstream to downstream.

4. Discussion

4.1. Environmental factors influencing H-O isotope signatures

In the global water cycle, land surface water is mainly supplied by precipitation, and rivers usually inherit the H-O isotope signatures of the precipitation (Kendall and Coplen, 2001). In general, H-O isotope

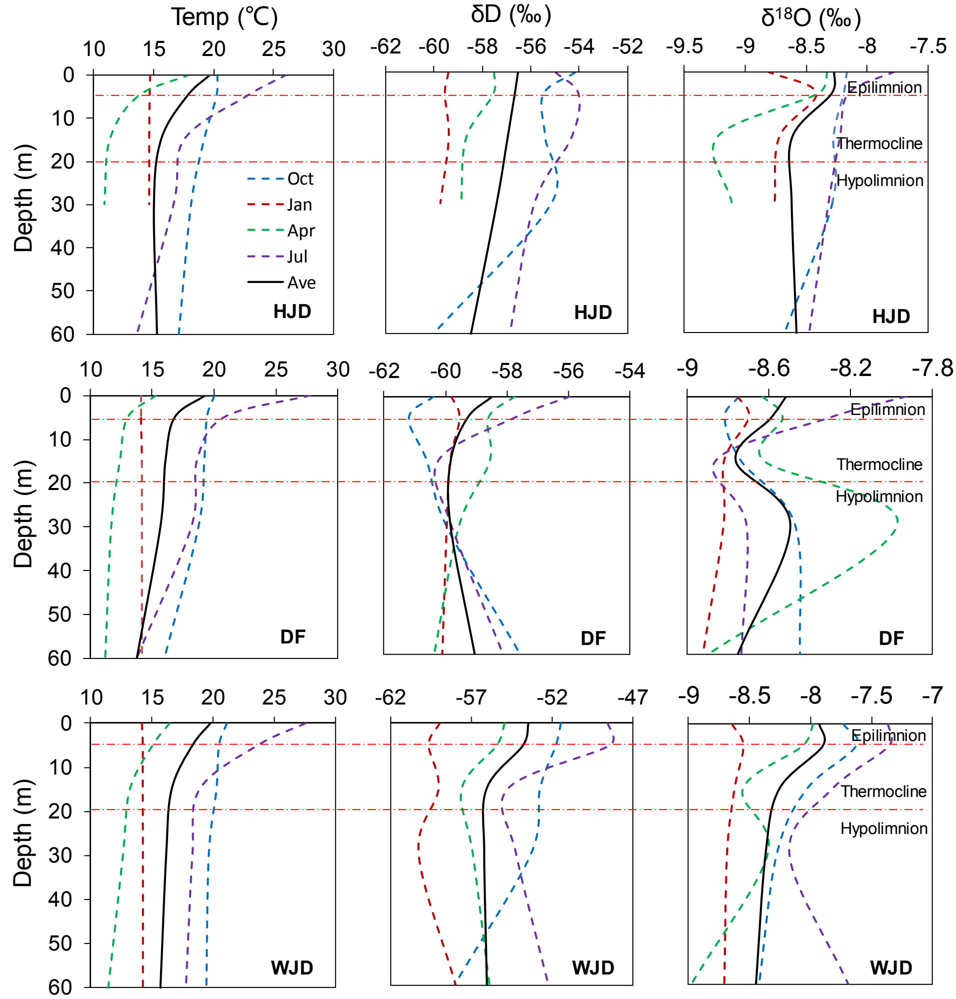

Fig. 4. Variation of temperature (Temp), δD, and $\delta^{18}O$ in water profiles of sites W5, W10, and W16. See Fig. 1 for site names and abbreviations of the reservoirs.

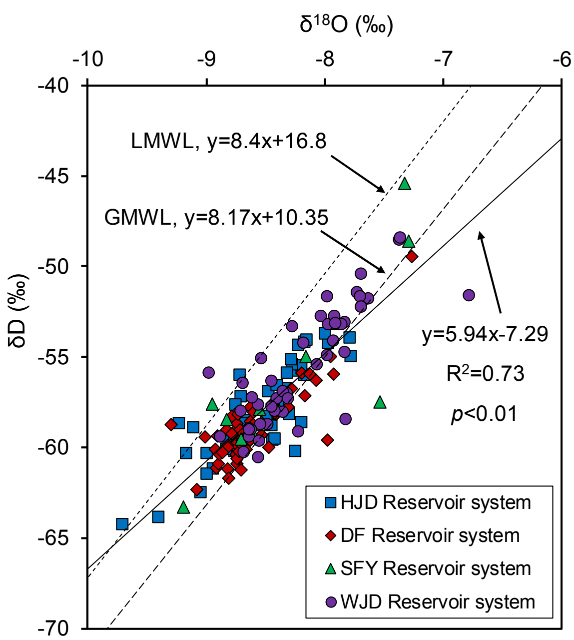

Fig. 5. Relationship between δD and $\delta^{18}O$ of all the dataset. Global meteoric water line (GMWL) is from Rozanski et al. (1993) and the local meteoric water line (LMWL) is based on the database from IAEA/WMO (2006). The reservoir system includes the inflowing, reservoir and released waters. The abbreviations of the reservoirs are referred to Fig. 1.

compositions of atmospheric precipitation are affected by factors including temperature, altitude, latitude, and the source and total amount of vapor (Dansgaard, 1964; Rozanski et al., 1993; Clark and Fritz, 1997). The *d*-excess derived from $\delta^{18}O$ and δD can reflect the difference in humidity between vapor source and evaporation (Rozanski et al., 1993). The *d* value in this study showed an average of 10.1‰, similar to that of precipitation in the temperate zone (ca. 10‰) (Dansgaard, 1964), and exhibited a comparatively small temporal and spatial variation, indicating that these reservoirs have similar humidity condition. Assuming that the effects of altitude and latitude can be neglected in the comparatively small study area, the H-O isotope signatures of precipitation will be mainly affected by temperature and vapor source. Water temperature showed significant correlations with δD ($R = 0.41$, $n = 170$, $p < 0.01$) and with $\delta^{18}O$ ($R = 0.39$, $n = 170$, $p < 0.01$), indicating that temperature is the main factor controlling the H-O isotope signatures in these cascade reservoirs, while δD and $\delta^{18}O$ did not show significant correlations with pH, dissolved oxygen, and chlorophyll (data are not shown here), suggesting that other chemical and biological factors seldom influence the H-O isotope signatures here.

Hydroelectric reservoirs are usually very deep and show seasonal thermal stratification (e.g. Elci, 2008; Han et al., 2018), which was also observed in the studied reservoirs. In summer, strong solar radiation leads to higher water T at the surface and lower water T at the bottom producing thermal stratification. By contrast, in winter, as surface water T decreased, the water profile mixed evenly and the stratification disappeared (Fig. 4). Thermal stratification caused corresponding variation of water density in the vertical profile, which finally led to the

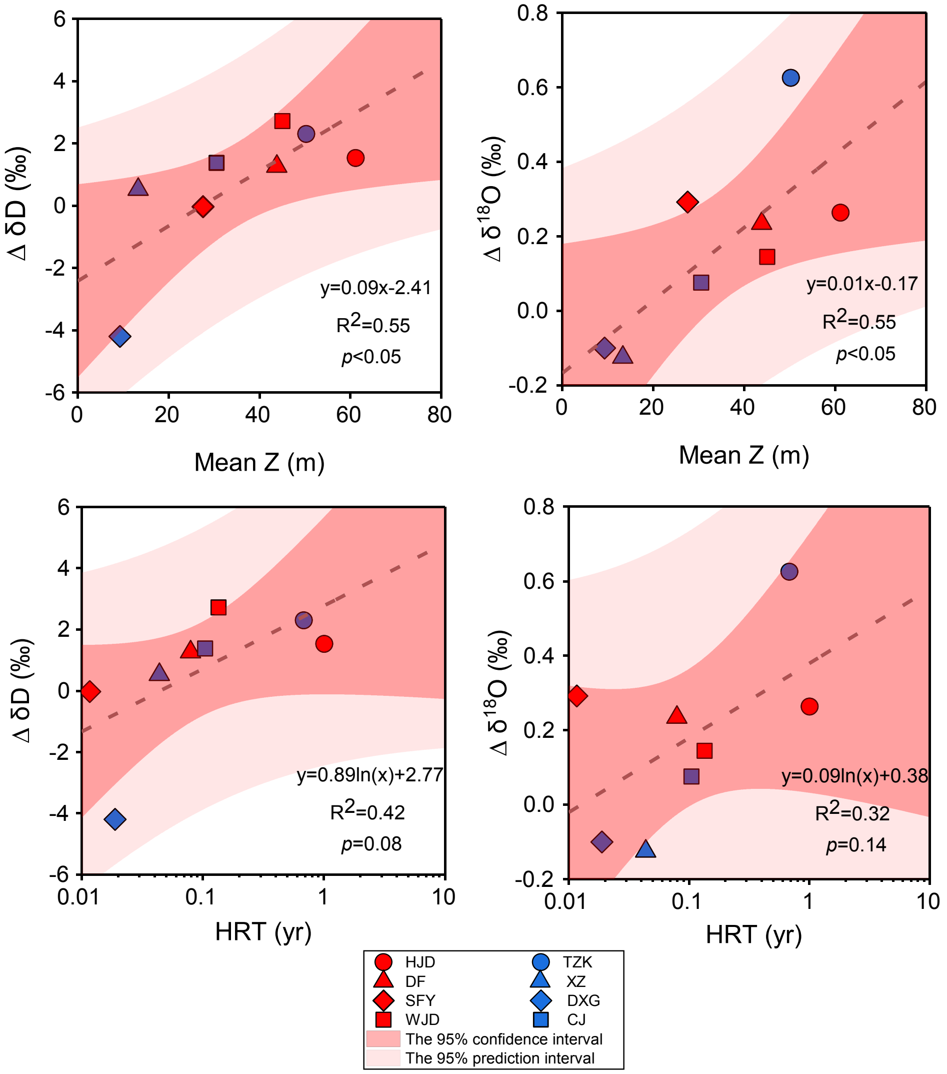

Fig. 6. Relationship between Δ δD (or Δ $\delta^{18}O$) and HRT (or Mean Z), respectively. Δ represents difference of δD (and $\delta^{18}O$) between reservoir surface water above dam and corresponding released water. HRT (hydraulic retention time) = V/Q, V is volume of reservoir, Q is discharge of reservoir, Mean Z is mean water depth of reservoir. The red symbols represent the reservoirs in this study, and their abbreviations are referred to Fig. 1. The blue symbols represent the cascade reservoirs of the Jialing River, which data were referred to Zhang et al. (2018). TZK, Tingzikou reservoir; XZ, Xinzheng reservoir; DXG, Dongxiguan reservoir; CJ, Caojie reservoir. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

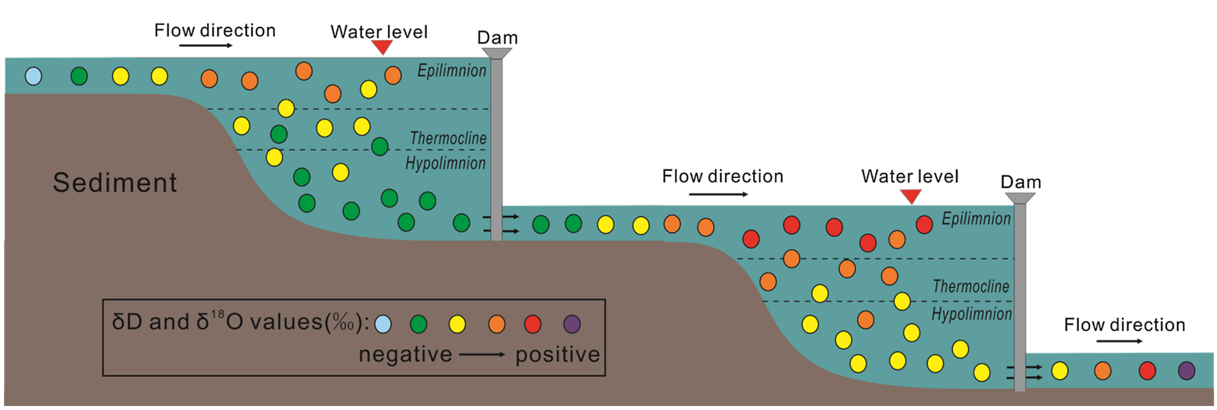

Fig. 7. Sketch map of cumulative effects of cascade dams on H-O isotope signatures.

presence of H-O isotope stratification. Evaporation caused the enrichment of heavy H-O isotopes in surface water, and so the H-O isotope compositions gradually become negative with depth (Fig. 4). Due to bottom discharge for power generation, the downstream water of dam exhibited relatively negative H-O isotope values. Considering that groundwater is enriched in light isotopes, an input of groundwater could also make the H-O isotopes of the bottom water more negative. However, this possibility can be ignored because the contribution of groundwater to the reservoirs was comparatively minor.

4.2. Cumulative effects of cascade dams

Water retention time usually increases after river damming (Vörösmarty and Sahagian, 2000), and H-O isotope differences induced

Table 2
$\delta^{18}O$, δD, and *d*-excess in the reported river-reservoir systems.

River	$\delta^{18}O$-H_2O (‰)		δD-H_2O (‰)		*d*-excess (‰)		Description	References
	Min	Max	Min	Max	Min	Max		
Orange River, South Africa	−8.0	2.0	—	—	—	—	Pre-dam (Jul 1970)	Talma et al. (2012)
	−4.0	1.0	—	—	—	—	Pos-dam (Aug 1970)	
Ebro River, Spain	−7.50 (−7.4)	−7.30	−51.4 (−50.5)	−49.6	8.80 (9.10)	9.40	Autumn (Sep-Nov), period of reservoir storage	Negrel et al. (2016)
	−8.40 (−8.25)	−8.10	−53.9 (−52.6)	−51.3	12.6 (13.05)	13.5	Spring (Mar-May), period of reservoir release	
Rio Grande River, USA	−14.0	—	−100.0	−68.0	—	—	Upstream (2001)	Vitvar et al. (2007); Hogan et al. (2012)
	—	—	-68.0	-63.0	—	—	Downstream after Dam (2001)	
	−13.0	−6.5	—	—	—	—	Upstream (2002)	
	−7.5	−6.3	—	—	—	—	Downstream after Dam (2002)	
	−14.0	−11.0	—	—	—	—	Upstream (2005)	
	−12.0	−8.0	—	—	—	—	Downstream after Dam (2005)	
Yangtze River, China	−15.4 (−9.3 ± 0.49)	−6.9	−112 (−64.4 ± 3.71)	−47	4.0 (9.95 ± 0.66)	16.8	Pre-TGD (dry season in 2006)	Wu et al. (2018)
	−14.4 (−10.7 ± 0.46)	−7.5	−110.8 (−80.5 ± 3.64)	−58.4	−0.4 (5.21 ± 0.64)	9.8	Pre-TGD (wet season in 2006)	
	−11.6 (−7.9 ± 0.58)	−6.1	−81.2 (−50.4 ± 4.81)	−37.8	10.9 (12.5 ± 0.24)	14.2	Pos-TGD (dry season in 2013)	
	−14.6 (−10.9 ± 0.39)	−6.9	−106.1 (−76.9 ± 2.95)	−47.7	5.9 (10.1 ± 0.30)	11.9	Pos-TGD (wet season in 2013)	
Euphrates River, Syria	−7.29	−7.21	−48.5	−47.9	9.4	9.8	upstream	Kattan (2012)
	−7.41	−7.34	−49.1	−48.5	9.7	10.4	Dam reservoir	
	−8.52	−8.39	−55.6	−55.1	12.5	13.0	downstream	

The numbers in parentheses is mean value or mean ± standard error for each indicated variable; — denotes no data for indicated variable in the database. TGD, Three Gorges Dam.

by evaporation will be larger with longer water retention time, leading to increased enrichment of heavy isotopes in the surface water. As a result, the surface δD and $\delta^{18}O$ of the reservoirs were higher than those of inflowing water, and the reservoirs with longer retention time (i.e. HJD and WJD reservoirs) had higher δD and $\delta^{18}O$ than those with shorter retention time (i.e. DF and SFY reservoirs) (Fig. 2). A similar effect of retention time on lake water δD and $\delta^{18}O$ has been reported (Leng et al., 2006; Jonsson et al., 2009). Strong evaporation can lead to a low *d*-excess (Peng et al., 2012). The *d*-excess of inflowing water was usually higher than that of reservoir water (Fig. 2), which also supported the presence of heavier H-O isotopes in the reservoir surface water.

There were notable differences in H-O isotope compositions between the surface water above the dam and the corresponding released water (i.e. ΔδD and $\Delta\delta^{18}O$; Fig. 2). These differences showed positive correlation with the water retention time and the mean water depth of the reservoir, respectively (Fig. 6), but did not exhibit significant correlation with reservoir age or total reservoir capacity. A shallow reservoir is readily homogenized due to the strong water exchange between the upper and lower layers, while a deep reservoir usually has thermal stratification which may result in the stratification of δD and $\delta^{18}O$ as discussed above. As a result, the ΔδD and $\Delta\delta^{18}O$ increased with the increase of mean water depth of the reservoir. When mean water depth and retention time were both small, δD and $\delta^{18}O$ stratification was insignificant but strong evaporation during bottom discharge could cause the δD and $\delta^{18}O$ of released water to be higher than those of surface water above the dam and ΔδD and $\Delta\delta^{18}O$ would be negative. This effect has been previously observed in the Xinzheng and Dongxiguan reservoirs on the Jialing River, China (Fig. 6) and also reported for reservoirs on the Euphrates River, Syria (Kattan, 2012).

In general, the H-O isotope signatures of released water are totally different from those of inflowing water after storage in the reservoir, and this effect can be accumulated by a cascade of dams. Consequently, δD and $\delta^{18}O$ increases gradually from upstream to downstream the dammed river, and abrupt drops of δD and $\delta^{18}O$ in released water are interspersed in this gradual trend (Fig. 7). A limited number of other reports have also supported the increase of δD and $\delta^{18}O$ after river damming (Table 2). Finally, the δD and $\delta^{18}O$ showed a jagged increase along the impounded Wujiang River.

5. Conclusions

There were notable spatial and temporal variations of δD and $\delta^{18}O$ in the impounded Wujiang River (δD from −64.2‰ to −45.4‰ and $\delta^{18}O$ from −9.7‰ to −6.8‰, respectively). After river damming, an increase of water retention time strengthened the evaporation of surface water and thus resulted in the enrichment of heavy H-O isotopes, and thermal stratification induced the decrease of δD and $\delta^{18}O$ with water depth. Therefore, water released from the reservoir showed more negative δD and $\delta^{18}O$ due to the bottom discharge for hydroelectricity. Water retention time and mean water depth of the reservoir were two important factors controlling H-O isotope differences between the reservoir surface water and the corresponding released water. Overall, CEs of cascade dams made δD and $\delta^{18}O$ a jagged increase from upstream to downstream of the impounded Wujiang River, and this finding demonstrates that H-O isotopes can be used to characterize the CEs of cascade dams. H-O isotopes are widely used to discern the contribution of different water source such as atmospheric precipitation and groundwater to a river (Jonsson et al., 2009; Meredith et al., 2009). As cascade dams can change river H-O isotope signatures, caution should be exercised in using these signatures to trace the water source of the impounded river.

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