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River damming and drought affect water cycle dynamics in an ephemeral river based on stable isotopes: The Dagu River of North China

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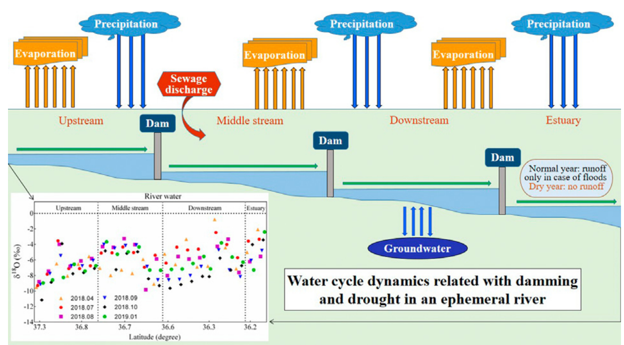
HIGHLIGHTS

- Explore water cycle dynamics of an ephemeral river using the D and ^{18}O isotopes
- The accumulative impacts of cascade dams enrich river water isotopes downstream.
- The drought in 2019 highlights the inter-annual variations of river water isotopes.
- Damming and drought change water cycle dynamics and exacerbate water shortage.

GRAPHICAL ABSTRACT



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ABSTRACT

The flow regime and biogeochemical cycles are greatly affected by river damming and drought, especially in ephemeral rivers. However, the combined effects have been rarely considered. This study, taking the Dagu River in Jiaodong Peninsula of North China as an example, investigated the dynamic changes in water cycle related to river damming and drought using stable water isotopes for the period 2018–2019. The results indicated that river water isotopes significantly varied temporally and spatially. The temporal variations in river water isotopes appeared to be linked with those in precipitation, but the relationship between river water and precipitation isotopes was greatly affected by river damming, river water-groundwater exchange and potential water pollution. Spatially, a single dam exhibited no significant effect on river water isotopes, but the accumulative impacts of cascade dams resulted in the enrichment of heavy isotopes in river water towards the downstream through increasing hydraulic residence time and water evaporation largely. The inter-annual variations in river water isotopes with increased evaporative fractionation were highlighted by their strong response to the drought in 2019. The combined effects of cascade dams and drought greatly changed water cycle dynamics and further exacerbated water shortage, which should thus be fully considered for water resource management, especially for regions with water-limited but heavily-regulated rivers.

1. Introduction

In the past century, dam and reservoirs have been constructed to provide water supply for drinking water and agriculture irrigation, for reducing floods and droughts and for generating electricity, which have produced great economic benefits (Zhan et al., 2015; Lu et al.,

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2018; Munoz et al., 2018; Peñas and Barquínc, 2019; Wang et al., 2020b; Maavara et al., 2020). However, river damming has been threatening river ecosystems (Ru et al., 2020). Presently, there have been about two-thirds of global rivers retained by reservoirs and dams (Kummu and Varis, 2007; Maavara et al., 2020). The 2016 Paris Agreement and the greater need for renewable energy will motivate the surge in dam construction in the future (Grill et al., 2015; Maavara et al., 2020). The increasing dams can lead to the river discontinuity and fragmentation, change the flow regime in terms of magnitude, frequency, duration and timing, and subsequently influence sediments, chemicals, nutrients, energy and biota (Zhan et al., 2015; Négrel et al., 2016; Murgulet et al., 2016; Lu et al., 2018; Wang et al., 2019; Peñas and Barquínc, 2019; Mellado-Díaz et al., 2019; Grill et al., 2019; Kumar and Jayakumar, 2020; Maavara et al., 2020). Especially in densely-populated but water-limited coastal areas, rivers are heavily regulated, resulting in major hydrological and ecological alterations, such as no (freeing) river flow, decline of freshwater flux into the sea, coastal wetland shrinkage, seawater intrusion, and decrease or loss of land–sea ecological connectivity (Hillel et al., 2015; Murgulet et al., 2016; Jiang and Wang, 2019; Grill et al., 2019).

These problems can be further aggravated by drought, which has been recognized as an extremely widespread and most expensive natural disaster. Drought can have adverse impacts on water cycle dynamics and water resources as well as on the society, the economy, and the environment (Mishra and Singh, 2010; Sheffield et al., 2012; Yang et al., 2019; Saranya et al., 2020). With global climate change and increased anthropogenic activities, drought disasters are expected to frequently occur mainly because of regional precipitation decreases and evaporation increases driven by global warming (Sheffield et al., 2012; Wang et al., 2020a). In regions with water-limited but heavily-regulated rivers, droughts can have devastating effect on water supply, agriculture and river ecosystem, and thus can cause serious economic and social losses.

The combined effects of river damming and drought on river water cycles have been seldom considered, but are essential for water resource management and river health protection. Stable isotopes of hydrogen and oxygen (H—O) can facilitate not only to characterize water cycles among precipitation, surface water and groundwater (Deng et al., 2016; Zhao and Li, 2017; Hao et al., 2019; Li et al., 2019a; Li et al., 2019b; Saranya et al., 2020), but also to explain flow alterations subjected to the water regulation effect of dams (Hillel et al., 2015; Soulsby et al., 2015; Deng et al., 2016; Vanplantinga et al., 2017; Wang et al., 2019) or under extreme conditions such as drought (Vanplantinga et al., 2017; Wu et al., 2018; Chiogna et al., 2018; Saranya et al., 2020) and flood (Adame et al., 2016). Studies on evaluating the damming and drought effects on water cycle dynamics using the H—O isotopes have been conducted but focused mostly on large river systems (e.g. Négrel et al., 2016; Deng et al., 2016; Vanplantinga et al., 2017; Wang et al., 2019). For example, Deng et al. (2016) and Wu et al. (2018) found that Three Gorges Dams (TGD) largely buffered the variations in river water isotopes and caused the one-month slowdown of Changjiang river water cycle to precipitation, while drought led to greater isotopic enrichment in the Changjiang River. Wang et al. (2019) concluded that the cumulative effects of cascade dams resulted in a jagged increase of the H—O isotopes along the impounded Wujiang River. However, few has been reported for small and medium rivers and more rarely for ephemeral rivers.

The Dagu River is a heavily-regulated coastal river in Jiaodong Peninsula of North China (Fig. 1). There are 14 large and medium-sized reservoirs as well as 20 major dams constructed on this river for meeting the demand of human water consumption. Commonly, these dams are opened only in case of floods but closed at most of other times. As a consequence, the Dagu River has been changed into an ephemeral river, particularly since 1980s. No flow and river drying-up in some reaches have frequently occurred during the non-flood season (Jiang and Wang, 2019). In case of dry years such as the 2019 year, the Dagu River has been cut off throughout the entire year. Accordingly, water cycle dynamics have been greatly altered and some water-related problems have been exacerbated, which further have influenced the ecosystem of river estuary and Jiaozhou Bay.

This study would employ the stable H—O isotopes to trace water cycle dynamics of the Dagu River related with river damming and drought. The specific objectives were to (a) explore the spatial-temporal variations of river water isotopes, (b) investigate how a single dam or cascade dams affected river water isotopes and water cycle dynamics, and (c) examine the drought effect on river water isotopes and water cycle dynamics.

2. Materials and methods

2.1. Study area

The Dagu River is the largest river of Jiaodong peninsula with the total length of 179 km and the drainage area of 6131.3 km^2, which discharges into the Jiaozhou Bay (Fig. 1). Its main tributaries include Zhu River, Xiaogu River, Wugu River, Luoyao River, Liuhao River, Nanjiaolai River, Taoyuan River and Yunxi River (Fig. 1). This river is also the largest water resource of Qingdao City and thus, it is recognized as the "Mother River" of Qingdao City (Li et al., 2008).

The Dagu watershed is characterized by the temperate monsoon continental climate. Its annual precipitation is 688.2 mm with an obvious seasonal and interannual variability. Appropriately 80% of the total precipitation falls during the monsoon season (June–September). The annual mean temperature is 12.3 °C, the annual mean evaporation is 983.9 mm and the annual average runoff is 6.3×10^8 m^3. The Dagu watershed is a typical agricultural watershed in North China. Farmland is the predominant land use type, occupying appropriately 71% of the whole watershed (2010). The rural residential area and urban construction land account for about 12%. The proportion of other land use types including grassland, forest and water body is only 17%.

2.2. Sampling and data analysis

In the study area, water resources mainly rely on atmospheric precipitation. Thus, dams and reservoirs play an important role in water storage, flood regulation and water supply. Due to limited water resources, dams are commonly closed during most of the year. In 2019, a severe drought caused by the El Nino event happened, which resulted in river drying up at most reaches and serious water scarcity. Therefore, the surveys were conducted for collecting samples of river water, groundwater and rainwater to reveal the influences of damming and drought on river water cycles. Taking account for the effects of damming and tributary inflow, surface water (upper 0.5 m) were sampled from 22 sites (S1–S21) (Fig. 1) along the Dagu River in April, July, August, September and October 2018 as well as January and August 2019. Samples from April 2018 to January 2019 were used to explore the spatial-temporal variations of river water isotopes during one year and the damming effects on water cycle dynamics. Samples in August 2019 were applied to verify the effect of the drought event on isotopes in river water, precipitation and groundwater and river water cycles by the comparison with those in August 2018. In addition, samples at sites S20 and S21 (Fig. 1) were used only to depict river water isotopes at the estuary, which were omitted when analyzing the linear relationship between river water δD and $\delta^{18}O$ for the whole river to avoid the influence of seawater.

To reflect the impact of a single dam, 8 samples of river surface water around the Yifeng dam and Nancun dam (Fig. 1) respectively were taken in October 2018 (the normal season) and January 2019 (the dry season) (not sampled in the wet season). The sampling distances before and after each dam were appropriately 100 m, 300 m, 500 m, and 1 km. Water temperature (T) and electrical conductivity (EC) at each sampling

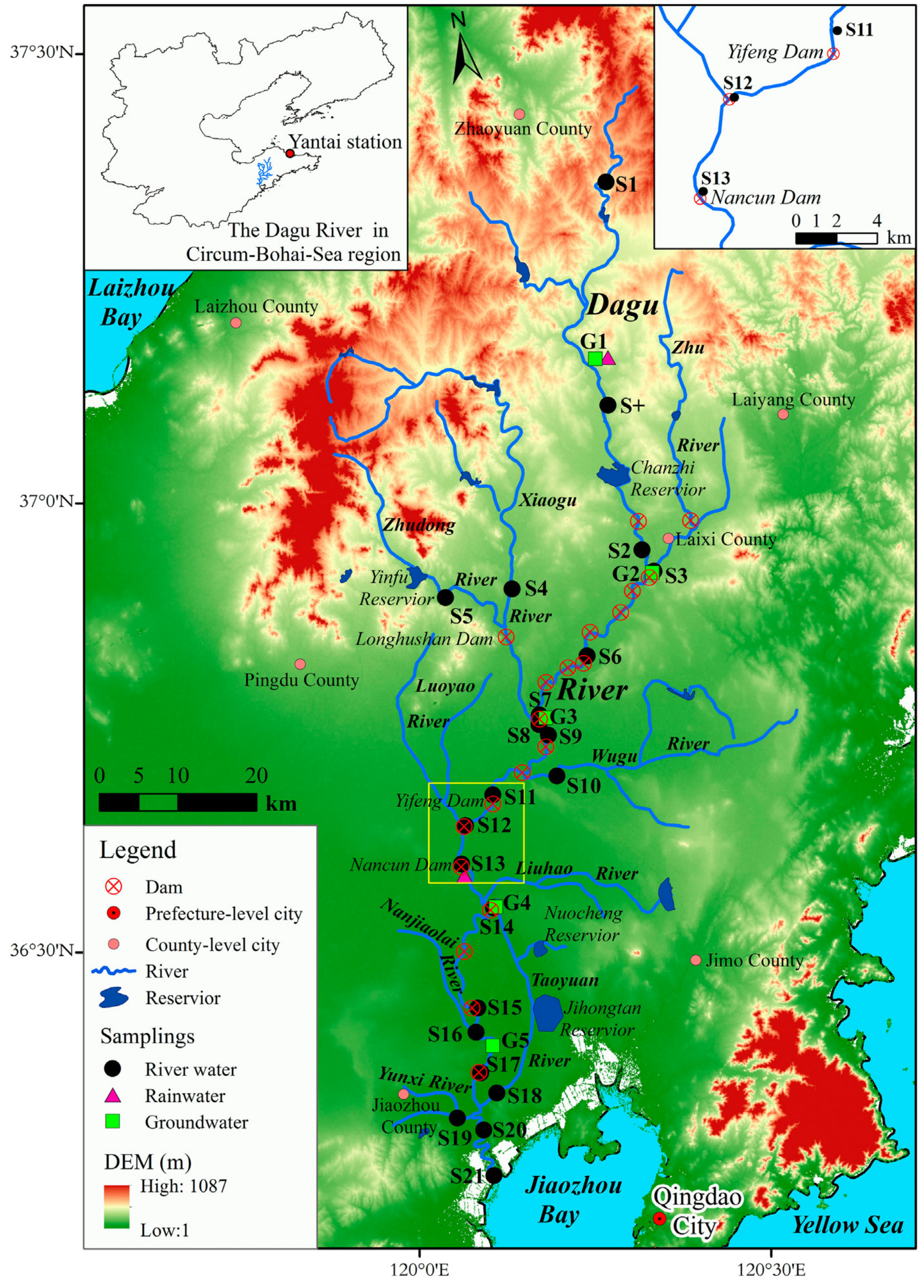

Fig. 1. Location map of the study area and samplings.

site were measured in situ with a multi-parameter water quality meter (YSI6600V2, USA).

Shallow groundwater from 5 drinking-water wells with depths of 7–8 m (G1–G5) (Fig. 1) was sampled simultaneously with river water samplings. Despite of few groundwater samples, it can be helpful for understanding the potential connectivity between river water and groundwater. The 88 rain samples were collected at 2 sites (Fig. 1) from June 2018 to August 2019, when was corresponded to river water samplings except for April 2018, to verify the impact of precipitation on river water cycles. All rain samples were collected as individual events using rain gauges.

All water samples were filtered through 0.45 μm cellulose acetate membrane at room temperature, and then put into chromatographic (isotope measurements) or polyethylene bottles (concentration measurements) for further analysis. The Cl^- concentration of river water was determined in the laboratory using ion chromatography (Dionex ICS3000, USA). The H—O isotopic compositions were measured using an automatic in-line elemental analyzer (FlashEA HT) connected to the MAT253 stable isotope mass spectrometer (Thermo Fisher, USA) at the Analysis and Measurement Center of Yantai Institute of Coastal Zone Research, Chinese of Academy Sciences. The technique involves the sample water reacted with carbon in the helium carrier gas at 1450 °C. The produced gases of H_2 and CO are separated by the gas chromatograph and are analyzed in the stable isotope mass spectrometer. The measured results of isotope signatures were expressed as parts per mil (‰) relative to the Vienna Standard Mean Ocean Water (VSMOW) using δ notation. The measurement accuracies were ± 1‰ for δD and ± 0.1‰ for $\delta^{18}O$.

In addition, precipitation isotope data as well as air temperature and rainfall amount data at Yantai station (Fig. 1) for the period 1986.03–1991.04 were obtained from the IAEA Global Network of Isotopes in Precipitation (GNIP) Database. The local meteoric water line (LMWL) was determined for the Dagu River using all of precipitation isotope data.

Deuterium excess (d-excess) can provide information about water processes (Wang et al., 2018), which is defined as d-excess = $\delta D - 8 \times \delta^{18}O$ (Dansgaard, 1964). This indicator is not impacted by the latitude effect, precipitation amount effect and distance-from-coast effect (Deng et al., 2016). Thus, the d-excess can better trace different water masses and river water cycles, in contrast to the H—O isotope signatures (Deng et al., 2016).

The difference of $\delta^{18}O$ between river water and precipitation ($\Delta^{18}O_{RIV\text{-}PPT}$), considering the residence time of one month from precipitation to river water, was determined to assess the degree of surface water evaporation (Dutton et al., 2005; Vanplantinga et al., 2017). If it is positive, the river water experiences evaporation compared to precipitation. In contrary, the river water is possibly resulted from other water sources such as snowmelt or groundwater. Likewise, the difference of $\delta^{18}O$ between groundwater and precipitation ($\Delta^{18}O_{GW\text{-}PPT}$) with the residence time of one month from precipitation to groundwater (Liu, 2012; Hu, 2019; Zhang et al., 2019) was also calculated to examine whether the drought had impact on groundwater.

For this study, the Pearson's correlation coefficients were analyzed using the Statistical Package for Social Sciences (SPSS 19.0) software.

3. Results

3.1. Temporal variations in water isotopes

The statistical parameters of isotopes in river water, precipitation and groundwater for the period 2018.04–2019.01 were shown in Table 1. The δD and $\delta^{18}O$ were − 51.9 ± 10.0‰ and − 6.4 ± 1.8‰ for river water, −54.1 ± 16.4‰ and − 8.5 ± 2.5‰ for precipitation, −68.2 ± 5.5‰ and − 9.1 ± 0.7‰ for groundwater, respectively. The δD and $\delta^{18}O$ were the largest for river water while the lowest for groundwater. There also exhibited temporal and spatial variations in these values.

Temporally, the precipitation isotopes, when also taking account for the IAEA data, varied with wet events and months (Fig. 2a). They were negatively correlated with precipitation amount and positively correlated with temperature, but these relationships were not significant (Fig. 2b and c), implying that precipitation isotopes had no obvious precipitation amount and temperature effects. However, significant positive and negative correlations between precipitation $\delta^{18}O$ and temperature were found in Fig. 2d respectively upon the conditions of strong wind and lower humidity ($T < 10$ °C from January to March and November to December) as well as the conditions of higher temperature and humidity ($T > 18$ °C for May and the monsoon season). The correlation between precipitation $\delta^{18}O$ and precipitation amount was very weak for any precipitation type. These results were possibly caused by the influence of moisture source. For the study area, summer rainfall is mainly affected by the East Asian monsoon, and in early summer, the stalemating between northern cold air and Pacific warm moisture often produces intense and long rainfall events, thereby resulting in the reverse relationship between precipitation isotopes and temperature.

For river water, the temporal variations in $\delta^{18}O$ isotopes seemed to be more distinct towards the lower reaches (Fig. 3a). In specific, the variation coefficients of river water isotopes were 22.6%, 30.4%, and 30.5% respectively for the upper, middle and lower reaches. Further, the patterns in temporal variations varied with reaches; for example, the river water $\delta^{18}O$ isotopes in April 2018 were the most depleted for the middle reaches, but they were the most enriched in the lower reaches. As such, it suggested that the river water isotopes was influenced by other factors except for atmospheric precipitation, which will be detailed later. For groundwater, there were more depleted heavy isotopes in the monsoon season than those in the non-monsoon season, but the temporal variation was relatively small and not significant (Table 1, Fig. 3b).

3.2. Spatial variations in water isotopes

For river water, the $\delta^{18}O$ isotopes were getting more enriched downwards in the upper and lower reaches, while they were getting more depleted in the middle reaches (Fig. 3a). In general, without new inputs of isotopic-depleted water, river water should be experiencing stronger evaporation towards the lower reaches. The abrupt change pattern in the middle reaches was mainly attributed to the tributary inflow since water samples were more depleted in heavy isotopes in the tributaries than those in the mainstream (Table 1). For groundwater, heavy isotopes were overall getting more enriched downwards, similar to river

Table 1
Statistics of isotopic compositions of river water, precipitation and groundwater in the Dagu Watershed for the period 2018.04–2019.01.

Parameter	River/Estuary	Season	δD (‰)				$\delta^{18}O$ (‰)				d-excess (‰)				Significance of differences (only the significance level at p < 0.05 was listed)
			Mean	Max	Min	SD	Mean	Max	Min	SD	Mean	Max	Min	SD	
River water	River (except for estuary)	On the whole	−51.9	−17.0	−71.1	10.0	−6.4	−0.8	−11.2	1.8	−0.7	+18.1	−13.9	6.9	Seasonal difference: $\delta^{18}O$**, d-excess**
		Monsoon season	−50.6	−29.3	−71.0	10.0	−6.0	−2.5	−9.8	1.8	−2.5	+10.0	−13.9	5.9	River water VS Precipitation: $\delta^{18}O$**, d-excess**
		Non-monsoon season	−53.2	−17.0	−71.0	9.9	−6.8	−0.8	−11.2	1.8	+1.1	+18.1	−13.4	7.3	River water VS Groundwater: δD**, $\delta^{18}O$**, d-excess**
	Mainstream	–	−52.1	−17.0	−71.1	11.5	−6.4	−0.8	−11.2	2.1	−1.1	+18.1	−13.9	7.2	
	Tributary	–	−52.0	−35.9	−71.0	7.2	−6.6	−3.2	−9.8	1.4	+0.4	+13.5	−13.7	6.2	
	Upstream	–	−55.4	−31.5	−71.1	9.2	−7.2	−3.5	−11.2	1.6	+2.0	+18.1	−7.7	5.7	Upstream VS Middle stream:
	Middle stream	–	−50.6	−38.5	−71.0	9.2	−5.9	−3.2	−9.8	1.8	−3.2	+12.4	−13.9	7.1	δD**, $\delta^{18}O$**, d-excess**
	Downstream	–	−50.3	−17.0	−68.7	10.7	−6.2	−0.8	−9.6	1.9	−0.7	+13.9	−13.4	6.8	Upstream VS Downstream:
	Estuary	–	−32.6	−10.8	−49.9	10.1	−4.5	−2.1	−7.3	1.6	+3.2	+19.8	−14.0	8.0	δD**, $\delta^{18}O$** River VS Estuary: δD**, $\delta^{18}O$**
Precipitation	–	On the whole	−54.1	−29.3	−89.1	16.4	−8.5	−4.1	−14.4	2.5	+13.6	+47.4	−5.3	12.7	Seasonal difference: $\delta^{18}O$**, d-excess**
	–	Monsoon season	−54.5	−29.3	−89.1	17.2	−7.9	−4.1	−12.4	2.2	+8.9	+33.6	−5.3	8.6	Precipitation VS River water: $\delta^{18}O$**, d-excess**
	–	Non-monsoon season	−52.9	−36.1	−76.5	13.5	−10.4	−4.4	−7.1	2.3	+30.5	+47.4	+13.6	10.2	Precipitation VS Groundwater: δD**, d-excess**
Groundwater	–	On the whole	−68.2	−58.0	−77.2	5.5	−9.1	−7.8	−10.1	0.7	+4.7	+12.1	−0.3	4.0	Seasonal difference: d-excess**
	–	Monsoon season	−67.2	−58.0	−75.5	5.9	−9.2	−7.8	−10.1	0.7	+6.6	+12.1	−0.3	4.4	Groundwater VS Precipitation: δD**, d-excess**
	–	Non-monsoon season	−69.3	−58.9	−77.2	5.2	−9.0	−8.2	−9.9	0.6	+2.8	+7.7	+0.7	2.3	Groundwater VS River water: δD**, $\delta^{18}O$**, d-excess**

Max, maximum value; Min, minimum value; SD, standard deviation.
** Presented the significant level at $p < 0.05$; VS, versus.

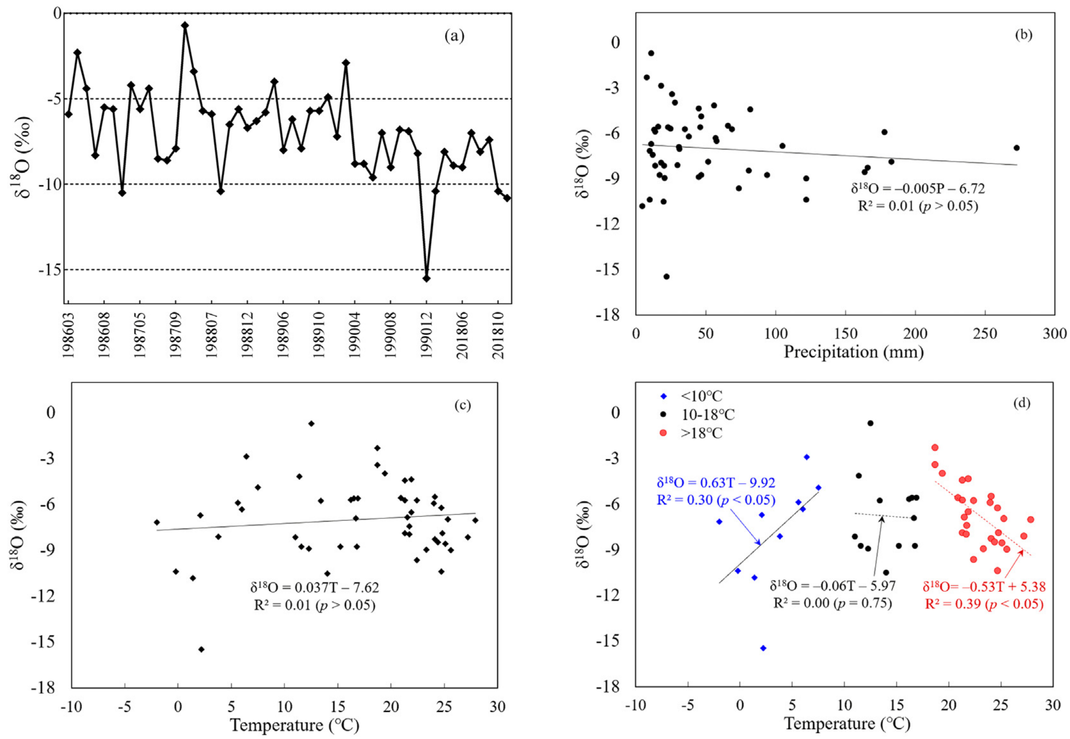

Fig. 2. δ^{18}O isotopic compositions of local precipitation for the period 1986.03–1991.04 and 2018.06–2018.12. a) temporal variation of δ^{18}O, b) the relationship between δ^{18}O and precipitation amount, c) the relationship between δ^{18}O and temperature, and d) the relationship between δ^{18}O and temperature in different temperature gradients.

water (Fig. 3b), implying the potential connectivity between river water and groundwater.

3.3. Dual isotope comparison

Dual isotope comparison can be applied to give insights into water sources and the relationship between different water components (Zhan et al., 2015; Liu et al., 2015; Li et al., 2017; Zhao et al., 2018). The slope of river water isotopes regression line (RWL) was 4.97 ($R^2 = 0.84$, $n = 116$) and was close to that of the LMWL $\delta D = 6.02\delta^{18}O - 4.96$ ($R^2 = 0.79$, $n = 50$) (Fig. 4a). Further, the volume-weighted mean isotopic compositions of precipitation anchored most data points of river water isotopes, but most river samples fell below the LMWL (Fig. 4a). It reflected that river water was mainly sourced from precipitation (Xiong et al., 2020) but has experienced strong water evaporation (Li et al., 2017; Hao et al., 2019; Saranya et al., 2020). River samples partly anchored by groundwater data points and river water were overall more enriched in heavy isotopes than groundwater (Fig. 4a), suggesting that river water also received groundwater recharge. For groundwater, the isotopes suggested that groundwater may come from multiple sources such as atmospheric precipitation and river water (Fig. 4a), which will be detailed later.

3.4. The drought condition in 2019

For the study area, the annual precipitation in 2018 (664.2 mm) was similar as the long-term mean annual precipitation (688.2 mm); however, the annual precipitation in 2019 (482.4 mm) was 30% lower than the mean annual precipitation and the reduction occurred mainly in May, June and September (Fig. S1). This presented the drought condition of 2019 in the Dagu River, which can be further confirmed by our field survey. For example, the river around the Yifeng Dam was almost dry in August 2019, but it had broad water surface in August 2018

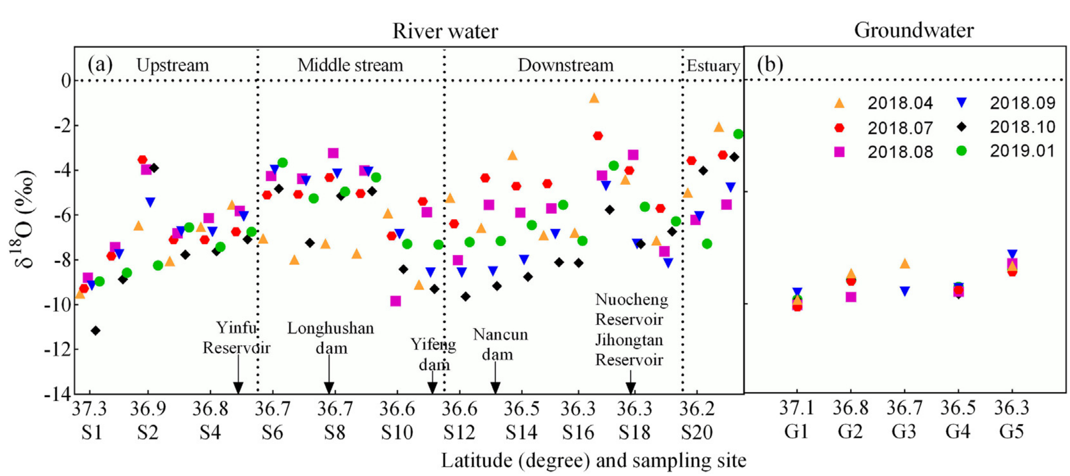

Fig. 3. Spatial-temporal variations in δ^{18}O of river water (a) and groundwater (b).

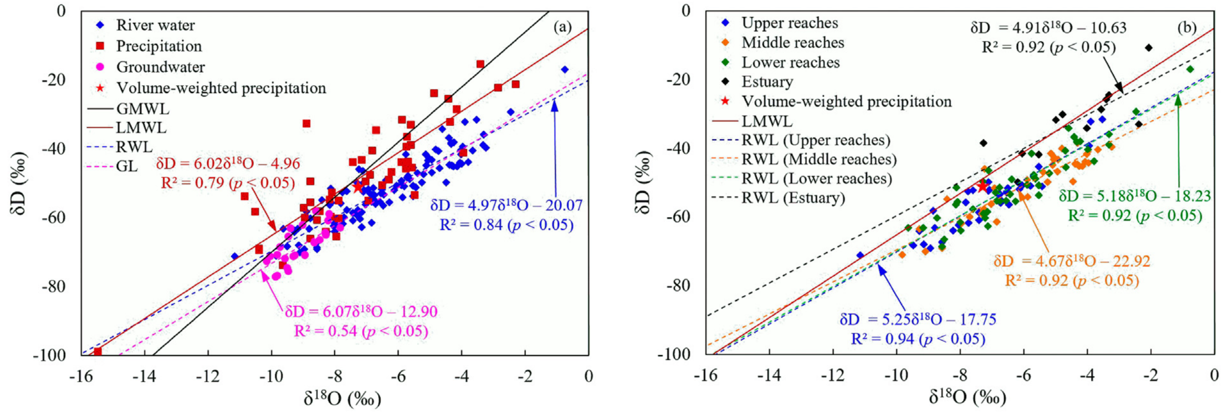

Fig. 4. Isotopic compositions of river water, precipitation and groundwater in the Dagu Watershed. a) all samples including river water (except for the estuary), precipitation (1986.03–1991.04 and 2018.06–2018.12) and groundwater, b) river water samples from the upper, middle, lower reaches, and the estuary. (GMWL: global meteoric water line; LMWL: local meteoric water line; RWL: river water line; GL: groundwater line).

(Fig. S2). Therefore, the drought had a great effect on water cycle dynamics and river ecosystems, which will be discussed later.

4. Discussion

4.1. How do river water cycles vary temporally as evidenced from water isotopes?

The $\delta^{18}O$ of river water had significant seasonal variations (Table 1, $p < 0.05$), and they changed with those of precipitation significantly (Fig. S3, $p < 0.05$). It may reveal the dominant role of precipitation in recharging river, which was similar as earlier studies (e.g., Kendall and Coplen, 2001; Dutton et al., 2005; Zhan et al., 2015; Reckerth et al., 2017; Ogrinc et al., 2018). As the recharge source for the Dagu River, the characteristics and variability of precipitation have a direct impact on water cycle dynamics. The LMWL (Fig. 4a) exhibited a flatter slope and a smaller intercept compared to the GMWL (global meteoric water line) (Craig, 1961), suggesting that precipitation was affected by the sub-cloud secondary evaporation. During the monsoon season, water vapor primarily comes from the ocean and experiences isotopic kinetic fractionation stimulated by the high temperature. In consequence, it led to the $\delta^{18}O$ enrichment in falling raindrops and in turn in river water (Table 1, Fig. S3). From the evidence of water isotopes, the seasonal variation in river water cycles should be primarily controlled by precipitation. Unfortunately, the long-term isotopic observations especially for river water in the study area are very scarce, which greatly limit the application of isotopic tracers in river water cycle studies at different temporal scales (Li et al., 2016).

The more obvious seasonal variations of river water isotopes towards the downstream were closely linked to the tributary inflow and the flood release. For example, a heavy rainfall happened on August 30 of 2018, which resulted in the flood release from dams. As a consequence, river water isotopes after August 2018 dramatically reduced and their seasonal differences expanded, especially for the lower reaches (Fig. 3a). This implied that except for atmospheric precipitation, river damming also influenced the seasonal variations of river water cycles.

The more depleted $\delta^{18}O$ isotopes for the middle reaches in April 2018 was connected to the groundwater irrigation and water release from upstream reservoirs. There are large-area vegetable lands distributed in the middle reaches. Scarce precipitation and the almost drying river in spring (March to May) cannot meet the water demand for vegetable planting and irrigation. Therefore, a good amount of groundwater wells have been excavated for irrigation. Irrigation return flow into the river could result in the abnormal river water isotopes in April 2018. In addition, the upstream reservoirs also release water for irrigation, which in turn affect river water isotopes. Overall, the isotopic records suggested that anthropogenic water regulation of dams and reservoirs as well as groundwater abstraction for flood prevention or agricultural irrigation can affect the seasonal variations in river water cycles.

4.2. How do dams influence the spatial variations in river water cycles based on water isotopes?

First, we examined whether a single dam had a remarkable effect on the spatial variations in river water isotopes and water cycle dynamics. Two dams were selected for this purpose. One dam is the Yifeng dam, which is the largest arc mirror sluice in Asia and is the boundary between the middle and lower reaches (Fig. 1). The other dam is the Nancun rubber dam, where is one site set for collecting precipitation samples in the lower reaches (Fig. 1). The isotopes of river water samples around each dam had no significant difference in both seasons (Fig. 5), implying that a single dam did not exhibit a distinct effect on river water isotopes. Our finding was different from some other rivers. For instance, Wang et al. (2019) reported a significant variation between reservoir surface water and released water in Wujiang River. This difference from Wang et al. (2019) was because cascade damming have divided the Dagu River into some similar long narrow lakes due to limited water resources. The hydraulic connectivity between the upstream and downstream is blocked or even cut off by each dam and no flow is discharged through the dam except for the monsoon season or the irrigation period. In this case, river water cycles were dominated by precipitation, evaporation, river water-groundwater exchange, and sometimes sewage input. Thus, river water isotopes appeared to be similar before and after a single dam.

River water were overall enriched in the $\delta^{18}O$ isotopes from upstream to downstream (Fig. 3a), suggesting the accumulative impacts of cascade dams on river water cycles. Spatially, river water were more depleted in heavy isotopes in the upper reaches than those in the middle and lower reaches (Fig. 4b), further indicating that the evaporative fractionation was becoming greater towards the downstream. For the middle reaches, although river water were more depleted in heavy isotopes downwards, the slope of the RWL was overall lower than that of the upper and lower reaches (Fig. 4b), which was mainly owning to more dense dams in the middle reaches (Fig. 1). For tributaries, we also observed the $\delta^{18}O$ enrichment at sites S8 and S18, which were primarily related to the combined influence of upstream dam and large reservoir (Fig. 1, Fig. 3a). At the river estuary, the heavy isotopes were more enriched compared to the river (Table 1, Fig. 3a). Moreover, they were close tightly to the LMWL and were much more positive than the volume-weighted mean isotopic compositions of precipitation (Fig. 4b), showing that atmospheric precipitation rather than

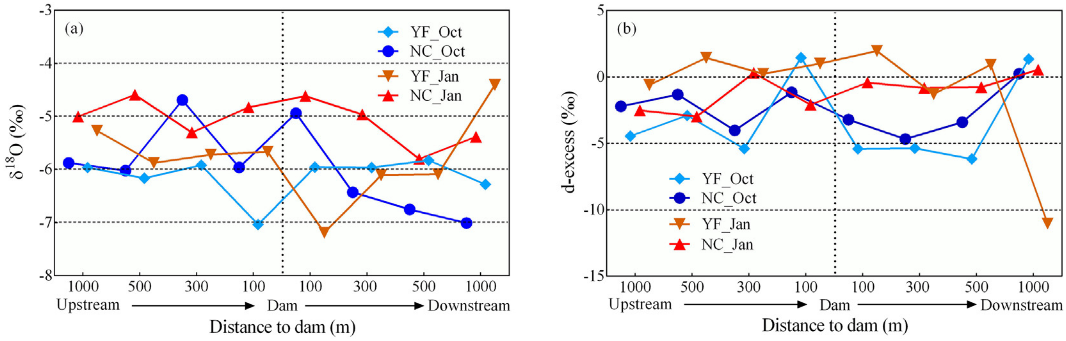

Fig. 5. The distribution of δ^{18}O (a) and d-excess (b) of river water around the Yifeng (YF) dam and the Nancun (NC) dam.

river water was the primary source of estuarine water. This phenomenon further revealed the effect of cascade dams, which impeded freshwater flowing into the ocean. Concurrently, the cutoff wall of groundwater reservoir, which has been built for preventing seawater intrusion (Xiong et al., 2020), also hindered submarine groundwater discharge (SGD) into the ocean. Earlier studies highlighted that the SGD into the Jiaozhou Bay should not be underestimated, which were equivalent to or even more than the discharge fluxes of the Dagu River (Qu et al., 2017; Zhang et al., 2017). Therefore, river damming combined with the underground cutoff wall greatly altered the longitudinal hydrological connectivity and water cycle dynamics.

In fact, cascade damming retained limited water resources in different reaches of the Dagu River during most of the year, largely increasing the hydraulic residence time and water evaporation while reducing the river runoff. In turn, hydrodynamic conditions and ecosystems in the river estuary and offshore areas were greatly changed. Therefore, river damming on coastal rivers caused negative ecological effects for the "river-estuary-offshore" system, although it produced considerable economic benefits, which stimulated the debate about the benefits and influences of dams (Zhan et al., 2015). The balance between them is vital to water resource management and ecological protection in coastal zones where water resources are scarce. In addition, it should be noted that the increasing hydraulic residence time could enhance the exchange between river water and groundwater and highlight the possible impact of sewage discharge on river water cycles. As a result, the temporal, longitudinal, vertical and lateral connectivity were all changed by cascade dams (Grill et al., 2019).

The calculated $\Delta^{18}O_{RIV\text{-}PPT}$ was a positive value with +2.1‰ for the Dagu River, which exceeded that of the Brazos River in Texas (+1.7‰) where have been jointly impacted by dams and drought (Vanplantinga et al., 2017). Moreover, the d-excess was relatively low (-0.7 ± 6.9‰), which average was lower than that of both local and global precipitation as well as most global rivers, and even lower than some rivers with little annual rainfall (e.g., the Heihe River, Shulehe River and Shiyanghe River, the Liao River) and some regulated rivers during drought conditions (e.g., the Yangtze River) (Table S1). These findings further demonstrated that the Dagu River experienced pronounced evaporation because of the accumulative effects of cascade dams, which partly contributed to the waste of limited water resources. This implied that cascade dams constructed in ephemeral rivers are unfavorable for sustainable water resource management and river health protection. Hence, it is strongly recommended to store more precipitation resources in the underground (such as underground reservoirs), which can increase groundwater recharge and reduce harms caused by groundwater over-exploitation (e.g., groundwater level drop, groundwater funnel formation, land subsidence, seawater intrusion).

In the study area, groundwater mainly comes from precipitation, evidenced from the dual isotope comparison that groundwater isotope data points fell below LMWL and anchored by precipitation isotope data points (Fig. 4a). This was consistent with earlier results of the model estimation (FEFLOW, MODFLOW) or water isotopic tracers (Yang, 2012; Yin, 2019; Xiong et al., 2020; Zhang et al., 2020). River water also contributes to groundwater recharge based on the dual isotope comparison that the groundwater data points distributed between precipitation and river water (Fig. 4a). This was also similar to previous reports (Yang, 2012; Liu et al., 2016; Xiong et al., 2020; Zhang et al., 2020). However, the potential connectivity between river water and groundwater depends on the river water level, groundwater table, riverbed conductance, and aquifer properties (Zhan et al., 2015; Zhang et al., 2020), and thus varies with reaches and seasons. In addition, Liu et al. (2016) reported that river damming could increase river water recharge for groundwater. However, the precipitation amount is relatively scarce and the Dagu River is overall dry during most of the time. Hence, the recharge of groundwater by river is limited (Zhang et al., 2019; Yin, 2019). Groundwater isotopes were more negative than the volume-weighted mean isotopic compositions of precipitation, suggesting that groundwater was sourced from some other water with more depleted heavy isotopes. Earlier studies showed that the lateral underground inflow was one of groundwater recharge source for the study area, but its contribution was relatively small (Yang, 2012; Xiong et al., 2020). Some researchers reported that in some regions of North China (e.g., Hexi Corridor, Erdos basin, Inner Mongolia plateau, Erenhot wasteland), groundwater was mainly sourced from the interbasin deep groundwater circulation rather than atmospheric precipitation (Chen et al., 2004; Chen and Wang, 2009; Zhan et al., 2017; Wang et al., 2017). However, the interbasin deep groundwater circulation has not been found in the study area based on previous studies on groundwater recharge source of the Dagu River (e.g., Yang, 2012; Liu, 2012; Yin, 2019; Xiong et al., 2020; Zhang et al., 2019; Zhang et al., 2020), but it is still needed to be verified in future studies. Overall, the depletion of heavy isotopes in groundwater should be attributed to the supplement of atmospheric precipitation in the wet year and the heavy rainfall during the wet season (accounting for 94% of the whole year) as well as the lateral underground inflow (Yin, 2019; Hu, 2019; Xiong et al., 2020). It was estimated that 23% of the annual precipitation can be converted into groundwater and the precipitation recharge can account for more than half of the total groundwater recharge in the Dagu watershed (Liu, 2012). Therefore, it is feasible and beneficial to increase precipitation recharge for groundwater to alleviate the water shortage of the Dagu River.

4.3. What is the impact of drought on river water cycles?

The drought in 2019 was mainly caused by the precipitation scarcity in spring and early summer (Fig. S1). The dry climate enhanced the sub-cloud secondary evaporation and led to heavy isotopes more enriched in precipitation (Table 2), which has been reported in other regions subject to the East Asian monsoon (Cai et al., 2017). In specific, the average δD and δ^{18}O of precipitation were −59.6‰ and −8.1‰ in 2018, while they were −31.5‰ and −3.4‰ in 2019, respectively (Table 2).

The drought effect on precipitation in turn influenced river water isotopic enrichment and water cycle dynamics through increased evaporation signals (Saranya et al., 2020). Correspondingly, the average δD

Table 2
Isotopic compositions of precipitation, river water and groundwater between August 2018 and August 2019.

Parameter	Year	δD (‰)				$\delta^{18}O$ (‰)				d-excess (‰)					$\Delta^{18}O_{RIV/GW-PPT}$ (‰)
		Mean	Max	Min	SD	Mean	Max	Min	SD	Mean	Max	Min	SD	Var (%)	
Precipitation	2018	−59.6	−34.9	−89.1	16.2	−8.1	−4.6	−12.4	2.4	+5.4	+12.5	−4.1	5.1	−175.1	–
($n = 16$)	2019	−31.5	−25.8	−40.3	6.0	−3.4	−1.8	−5.4	1.4	−4.1	+3.1	−12.7	7.3		–
River water	2018	−50.3	−35.9	−71.0	9.4	−5.8	−3.2	−9.8	1.9	−3.6	+7.7	−13.7	6.1	−246.4	+1.2
($n = 20$)	2019	−31.3	−20.3	−59.7	9.3	−2.3	+0.5	−7.1	1.9	−12.5	−3.0	−26.5	7.8		+2.7
Groundwater	2018	−66.5	−60.8	−71.3	4.5	−9.4	−8.2	−10.1	0.8	+8.4	+10.2	+4.9	2.4	−215.8	−2.3
($n = 5$)	2019	−54.9	−45.8	−63.5	6.4	−5.6	−3.6	−7.3	1.9	−9.7	+1.3	−24.6	11.1		−0.6

Max, maximum value; Min, minimum value; SD, standard deviation; Var, the variation of d-excess between August 2018 and August 2019; for δD, $\delta^{18}O$ and d-excess, differences between August 2018 and August 2019 in precipitation, river water and groundwater were all significant at $p < 0.05$, differences between precipitation and river water as well as between river water and groundwater were all significant at $p < 0.05$, but not significant for differences between precipitation and groundwater.

and $\delta^{18}O$ of river water were −50.3‰ and −5.8‰ in 2018, and −31.3‰ and −2.3‰ in 2019, respectively (Table 2, Fig. S4). The differences in isotopes between these two years highlighted the significant effect of drought on river water isotopes and water cycle dynamics, which was consistent with earlier studies (e.g., Marchina et al., 2017; Chiogna et al., 2018; Wu et al., 2018; Saranya et al., 2020). For example, Wu et al. (2018) found that the Changjiang River presented more positive δD and $\delta^{18}O$ isotopes under the extreme drought conditions. Saranya et al. (2020) concluded that the drought not only stimulated evaporative fractionation but also reduced the altitude effect and continental effect along the tropical Periyar basin. Therefore, river water was commonly enriched in heavy isotopes in the arid climate region (Kendall and Coplen, 2001; Hillel et al., 2015).

Compared with precipitation, the d-excess signature of river water in August 2019 presented a greater reduction (246.4%) relative to August 2018 (Table 2). The more positive $\Delta^{18}O_{RIV-PPT}$ in August 2019 was also observed relative to that of August 2018 (Table 2). This result illustrated that river water isotope signals had a stronger response to drought than those of precipitation. After replenished by the atmospheric precipitation, the Dagu River experienced strong evaporation jointly affected by river damming and drought, and thus exhibited abnormally negative d-excess (−12.5 ± 7.8‰) in August 2019. This effect overall appeared to be more prominent towards the downstream (Fig. S4). A few researches have reported similar results. For instance, Vanplantinga et al. (2017) concluded that peak drought conditions could highlight anthropogenic reservoir dominance in river flows. In the lower Jordan River, the lowest $\delta^{18}O$ signature was no less than −4.5‰ for all river water samples and the d-excess was lower than 0 for 60% of river water samples owing to the combined effects of the aridity and damming regulation (Hillel et al., 2015).

No flow in the Dagu River and the drying up at most river reaches (Fig. S2) were the most obvious results of drought, which contributed to the complete loss of longitudinal connectivity and land-sea connectivity in the “river-estuary-offshore” system. Further, the role of potential water pollution and river water-groundwater exchange in river water cycles became more prominent, which changed the amplitude of river water isotopes (Lambs et al., 2005; Reckerth et al., 2017). For example, significant evaporation and sodium pollution led to lower d-excess in the Krishna River than other rivers in India (Table S1). Earlier studies reported that the Dagu River has almost become canals of sewage discharge (Li et al., 2008). Especillay, the $\delta^{18}O$ of the Dagu River was found to be significantly positively correlated with water temperature, Cl^- concentration and EC respectively ($p < 0.05$) (Fig. S5), suggesting that water pollution had potential influences on river water cycles.

For groundwater, more positive $\delta^{18}O$ and more negative d-excess were observed in August 2019 than those of August 2018 (Table 2). Moreover, $\Delta^{18}O_{GW-PPT}$ was higher in August 2019 (−0.6‰) than that of August 2018 (−2.3‰) despite of negative values. This implied that groundwater was also impacted by the 2019 drought in direct or indirect ways. The drought not only can enhance groundwater evaporation but also can aggravate groundwater over-exploitation, thereby influencing the interaction between river water and groundwater. The drying up of the river accelerated by drought could also alter the exchange between river water and groundwater. Thus, the drought seemed to highlight the complicated relationship between river water and groundwater. It is expected that more groundwater samples will be supplied to explain the potential connectivity between river water and groundwater, better if combined with the application of radon and radium isotopic tracers.

In general, the combined effects of river damming and drought, together with river water-groundwater exchange and potential water pollution, could greatly change water cycle dynamics and further exacerbate water shortage and related ecological problems for the Dagu River. Our survey strongly supported this assumption (Fig. S2) as mentioned above. In view of this, the combined effects should be paid more attention for water resource management, particularly in regions with water-limited but heavily-regulated rivers. And anyway, the strategy for emergency water supply, especially in groundwater management and protection, should be planned and prepared to prevent the adverse effect of drought and damming on river ecosystem and water resources.

5. Conclusions

In this study, water cycle dynamics associated with river damming and drought over the Dagu River, an ephemeral river in Jiaodong Peninsula of North China, have been explored based on the D and ^{18}O isotopes for the period 2018–2019. The results showed that river water isotopes significantly varied either temporally or spatially. Precipitation was the main factor controlling the temporal variations in river water isotopes, but their relationship was affected by river damming, river water-groundwater exchange and potential water pollution. Spatially, a single dam did not present an obvious impact on river water isotopes. However, the accumulative effects of cascade dams greatly increased hydraulic residence time and water evaporation, resulting in river water enriched in heavy isotopes towards the lower reaches. The drought in 2019 further aggravated evaporative fractionation and highlighted the inter-annual variations of river water isotopes. Overall, the combined effects of river damming and drought greatly changed water cycle dynamics and further exacerbated water shortage, which should thus be considered together for water resource management, especially in regions with water-limited but heavily-regulated rivers. Future long-term and high-frequency investigation is also required to more systematically understand the spatial-temporal variations in river water isotopes and to provide more detailed explanation pertaining to water cycle dynamics in ephemeral rivers.

CRediT authorship contribution statement

Dejuan Jiang: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Validation, Writing - original draft. **Zhi Li:** Methodology, Writing - review & editing. **Yongming Luo:** Supervision, Writing - review & editing. **Yun Xia:** Data curation, Investigation.

Declaration of competing interest

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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Appendix A. Supplementary data

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