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Research papers

The effects of reservoir storage and water use on the upstream–downstream drought propagation

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A R T I C L E I N F O

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Downstreamness

A B S T R A C T

Temporal aspects (e.g., response time and propagation rate) of drought propagation have been explored extensively by many studies, yet much less is revealed about the spatial characteristics of drought propagation. In our case study region the Shaying River basin with two major reservoirs, the effects of reservoir storage and water use on drought propagation, especially the upstream–downstream drought propagation, are closely investigated. It is found that meteorological droughts propagate to reservoir droughts in the river basin with drought pooling and lengthening. How hydrological droughts propagate from upstream to downstream is closely related to drought severity. Mild and moderate upstream reservoir droughts usually did not propagate to the downstream reservoir, but severe upstream reservoir droughts could propagate to the downstream reservoirs with delayed occurrence, prolonged duration, and increased severity. Severe reservoir droughts could lead to severe streamflow droughts, even after the end of reservoir droughts as an aftermath. During the period of drought propagation from upstream to downstream, the downstreamness of stored volume (Dsv) typically keeps going down from above the downstreamness of storage capacity (Dsc) at the beginning of drought occurrence, indicating relatively more water is stored in the downstream reservoir, to below Dsc at the end of drought, indicating relatively more water stored in the upstream reservoir. Although the increase of water uses aggravated hydrological drought in the long-term, the typical exacerbating effect of water use on hydrological droughts is not observed during 2013–2018 because most human water use was industrial and domestic which was generally stable over time. In the 2013–2018 period, upstream reservoir's drought was driven by inflow variability, while downstream reservoir's drought conditions were predominantly shaped by mainly the variation of the outflow from the upstream reservoir. These findings offer crucial implications for policymakers, aiding in the formulation of robust drought and water management strategies that consider upstream–downstream dynamics, providing essential insights for river-basin scale water resource management and drought mitigation.

1. Introduction

Drought, defined as a deficit in available water compared to the normal conditions, where "normal" is based on an average established over a certain period or a specified level, is a climate-related phenomenon that evolves at different time scales impacting the hydrological cycle (Rangecroft et al., 2019). There are multiple types of droughts, such as meteorological drought, agricultural drought and hydrological drought, each having their particular spatiotemporal features. Hydrological drought is a type of drought that can be explained as a lack of water in the hydrological system, leading to low streamflow in rivers, canals, or reservoirs (van Loon, 2015). Hydrological drought lags the occurrence of meteorological drought, and the development of hydrological droughts is more complex and uncertain than meteorological drought because many factors such as meteorological conditions, catchment properties and human activities play key roles in affecting hydrological drought (Wu et al., 2018; Liu et al., 2023). Drought propagation became a hot issue in the drought research community in the last decade (Wang et al., 2016), and previous studies mainly focused on the propagation time, the propagation probability, the change of

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drought characteristics, and factors controlling propagation processes at different spatiotemporal scales (Haslinger et al., 2014; Ma et al., 2022; Shi et al., 2022; Wang et al., 2021; Xu et al., 2019; Zhu et al., 2019). Many studies showed that human activities such as reservoir operation and water uses for agriculture, industry, and domestic purposes played important roles in hydrology drought development (Van Loon et al., 2022; Veldkamp et al., 2017; Wang et al., 2019); Wu et al., 2021; Yu et al., 2019; Zhang et al., 2015), and the effects of reservoirs operation could be different in space or time (Di Baldassarre et al., 2018; Veldkamp et al., 2017). Uneven distribution of water resources can impact the hydrological cycle so that the duration and severity of hydrological drought are reduced in some areas, while in other regions is intensified, consequently disrupting the hydrological cycle in the area (Di Baldassarre et al., 2018; He et al., 2017). Currently, as human pressures remain to increase, there is an urgent need to improve our understanding about the interrelationship between human activities (e.g., reservoir operations, groundwater abstraction, and irrigation) and the occurrence of drought (Cheng et al., 2021; Rangecroft et al., 2019; Van Oel et al., 2018; Di Baldassarre et al., 2018; Veldkamp et al., 2017; Wang et al., 2016). Understanding how the reservoir operations could affect hydrological drought differently in space or time (e.g., in upstream and downstream areas) could inform more effective reservoir operation strategies (Veldkamp et al., 2017).

The objective of this study is to assess the impact of reservoir storage and water use on the spatial distribution of hydrological drought in upstream and downstream areas taking the Shaying River basin in China as an example. To reach this objective the study includes three parts: (i) identifying meteorological and hydrological drought using the standardized indices, such as the Standardized Precipitation Index (SPI), the Standardized Precipitation Evapotranspiration Index (SPEI), the Standardized Streamflow Index (SSI), and the Standardized Reservoir Storage Index (SRSI); (ii) assessing the effect of reservoir storage on hydrological drought, using the concept of "downstreamness" (Van Oel et al., 2018) to analyse the spatial distribution of stored volumes of water in reservoirs throughout the river basin over time; and (iii) assessing the impact of water use on the occurrence hydrological drought.

2. Materials and methods

2.1. Study area

The case study area is the upper part of a tributary of the Huai River, called the Shaying River, located in the Henan province in China. The Shaying River originates from the Funiu mountain and has a total length of 624 km. The river flows through several major cities, such as Pingdingshan and Luohe of Henan Province (Fig. 1). The Shaying River Basin has a warm temperate climate with the annual average temperature around 15 °C. The climate is dominated by monsoons, with most precipitation falls in the period from June until September.

This study focuses on the drainage area above the city of Luohe, with an area of 12,150 km^2 (Fig. 1). The area has a very dense population, especially in the city of Pingdingshan, and is highly developed in terms of industrial and agricultural activities. In the upper Shaying River, many dams and reservoirs of various sizes are located for the purposes of flood control, hydropower generation, domestic and industrial water supply, and irrigation. Two major reservoirs above Luohe are the Baiguishan and the Zhaopingtai reservoirs. The cumulative storage capacity of the two reservoirs almost equal to the average annual runoff at Luohe gauging station, which is 1.57 billion m^3 during 1990–2018. Information of the Zhaopingtai and Baiguishan reservoir is presented in Table 1.

Both reservoirs are annual regulation reservoir and play key roles in flood control, water supply, and irrigation. The water-receiving areas of both reservoirs are located below the reservoirs (Fig. 1). Specifically, Zhaopingtai reservoir supplies water to Lushan and Shilong (with a total population of 0.4 million) for industrial water use, and to Lushan for domestic water use, and to the Zhaopingtai Irrigation district (covering Lushan, Ye, Pingdingshan and Baofeng) for agricultural water use.

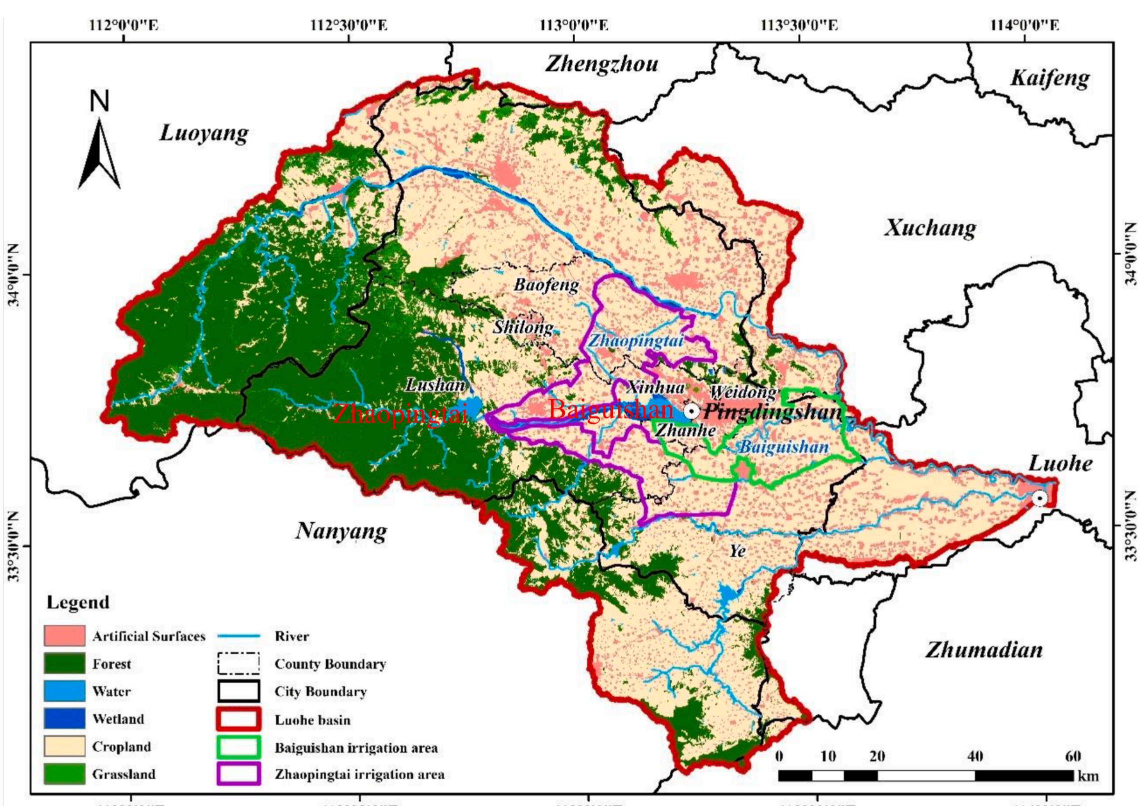

Fig. 1. Shaying River basin above Luohe and locations of reservoirs, irrigation areas and counties.

Table 1
Information of the Zhaopingtai and Baiguishan reservoirs.

Features	Zhaopingtai	Baiguishan
Total storage capacity (million m^3)	685	922
Inpoundment year	1959	1966
Drainage area (km^2)	1430	2744
Maximum lake area (km^2)	25	67
Main functions	Flood control, irrigation, water supply, hydropower	Flood control, irrigation, water supply
Design irrigation area (km^2)	667	333
Annual average precipitation 1990–2018 (mm)	797	777
Annual average pan evaporation 1996–2018 (mm)	799	809
Annual average outflow 1996–2018 (million m^3)	414	483

According to the operation rule, when the water level of Zhaopingtai goes below 159.6 m, the water in the reservoir is allocated only for industrial and domestic water use, with no water supply for the agricultural water use. When the water level further goes down below 159 m (i.e., the dead water level), water supply stops for any use. Due to the extreme drought condition in the region in 2014 and the water shortage afterwards, little water was supplied for the agricultural water use during 2014–2018. The Baiguishan reservoir is the largest one in region which supplies water to Pingdingshan city (including three districts, i.e., Xinhua, Weidong and Zhanhe, with a total population of 0.7 million) for industrial and domestic water use, and to the Baiguishan Irrigation District (covering the city of Pingdingshan and Ye county) for agricultural water use. When the water level of Baiguishan goes below 98.6 m, the water in the reservoir is allocated for only industrial and domestic water use, with no water for the agricultural water use. When the water level further goes down below 97.5 m (i.e., the dead water level), the reservoir will stop supplying water for any use.

Between 2000 and 2018 the area of cropland decreased from 9335 km^2 to 8784 km^2 in the Shaying River basin above Luohe, while the built-up areas increased from 121 km^2 up to 680 km^2 according to the satellite images (Copernicus Climate Change Service, 2019). The bulletins of the Water Resource Bureau in Pingdingshan show that, the industry was the major water user with an annual average of 532 million m^3 in the catchments of both reservoirs over the period from 2013 to 2018, whereas the annual average for the agriculture was 117 million m^3 and for the domestic sector 93 million m^3. Main agricultural practices in the area include wheat, paddy, corn, soybeans, potato, cotton, oil (peanut, rapeseed, and sesame), tobacco leaves, vegetables, and fruits such as watermelons. The population in the catchments of the Baiguishan and Zhaopingtai reservoirs stayed relatively stable in the period between 2000 and 2020.

2.2. Datasets

Hydrological data is collected for the period between 1990 and 2018 (Table 2). The reservoir storage and outflow data were available on the 1st, 11th, and 21st of each month. As this study focused on the monthly flow, storage data on the 1st of each month *t* is used as the monthly storage in the month *t*-1. In the reservoir outflow data collected from the Bureau of hydrology and water resources of Henan Province there were some data gaps between 1990 and 1996. Therefore, outflow data between 1996 and 2018 is used in this study to have a consistent comparison (Fig. 2a).

The monthly and annual areal precipitation over the drainage area of both reservoir watersheds are calculated using the gridded near-surface China Meteorological Forcing Dataset (CMFD) (He et al., 2020), which is a combined dataset of remote sensing products, in-situ observation data of weather stations, and reanalysis datasets. It has a temporal resolution of three hours and a spatial resolution of 0.1°. Observed daily pan evaporation at two reservoirs between 1996 and 2018 is obtained from the Bureau of hydrology and water resources of Henan Province. The monthly areal average precipitation over the catchment and monthly pan evaporation are displayed in Fig. 2b.

Table 2
Overview datasets used in this study.

Data	The available timespan of data	Data source
Digital elevation model (DEM)	N.A.	Shuttle Rader Topography Mission (SRTM) from NASA (https://www2.jpl.nasa.gov/srtm/)
Monthly discharge at Luohe	1990–2018	Bureau of hydrology and water resources of Henan Province
Storage volumes of the Zhaopingtai and Baiguishan reservoirs	1990–2018	Bureau of hydrology and water resources of Henan Province
Outflow from the Zhaopingtai and Baiguishan reservoirs	1996–2018	Bureau of hydrology and water resources of Henan Province
Gridded precipitation	1979–2018	The China Meteorological Forcing Dataset (CMFD) (He et al., 2020)
Pan evaporation at Zhaopingtai and Baiguishan	1996–2018	Bureau of hydrology and water resources of Henan Province
Water use	2013–2018	Pingdingshan Water Resource Bulletin 2013–2018

2.3. Estimating reservoir inflows and water use

There is no measurement available about inflows to the two reservoirs. The monthly inflow (Q^t_{inflow}) to a reservoir during 2013–2018 is derived using the following water balance equation:

$$Q^t_{inflow} = \frac{\Delta V}{\Delta t} + Q^t_{outflow} + Q^t_{seepage} + E^t + W^t_{supply} - W^t_{transfer} - P^t \tag{1}$$

where $\frac{\Delta V}{\Delta t}$ (m^3/month) is the monthly reservoir storage change; P^t (m^3/month) and E^t (m^3/month) are the precipitation and eporation on and from the lake surface in month *t*, respectively; $Q^t_{seepage}$ (m^3/month) is the amount of reservoir seepage; W^t_{supply} is the amount of water withdraw for domestic/industrial water supply to the reservoir water receiving counties in month *t*; $W^t_{transfer}$ (m^3/month) is the amount of water transferred to the reservoir by the South-to-North Water Diversion Project; $Q^t_{outflow}$(m^3/month) is the observed outflow via the spillway and irrigation canals.

$Q^t_{seepage}$ is one of the most important losses from reservoirs which changes with the reservoir storage. In this study, $Q^t_{seepage}$ is estimated roughly as 1% of the reservoir storage in each month according to a technical report by the Baiguishan reservoir management authority.

The lake evaporation E^t is estimated based on lake surface area and pan evaporation observed at the two reservoirs. The lake surface areas of two reservoirs are estimated using the NDWI (Normalized Difference Water Index) based on https://scihub.copernicus.eu/dhus/#/home Sentinel-2 satellite images at different dates, so as to establish the relationship between the lake surface area and reservoir storage. Then the relationship is used to derive lake surface area at each month based on monthly storage data. Finally, the lake surface evaporation in each month is estimated as the multiplication of the lake surface area and pan evaporation.

Water use from the reservoirs refers to the portion of all types of water use in the reservoir water receiving area. For the Zhaopingtai Reservoir, water uses include industrial/domestic water use in Lushan and Shilong, and agricultural water use in the Zhaopingtai Irrigation

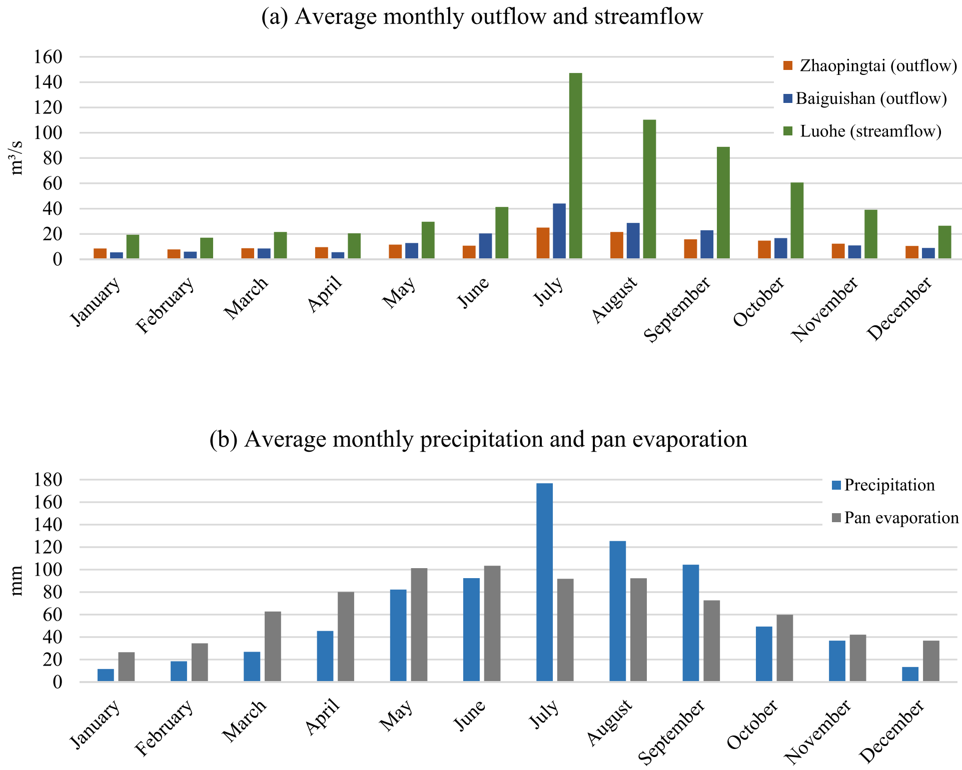

Fig. 2. Monthly (a) outflow and streamflow, and (b) the areal precipitation in the watershed and the average pan evaporation at Zhaopingtai and Baiguishan (1996–2018).

district. For the Baiguishan Reservoir, water use is estimated as the sum of the industrial/domestic water use in Pingdingshan city (including three districts, i.e., Xinhua, Weidong and Zhanhe) and agricultural water use in Baiguishan Irrigation District (Fig. 1). Annual water use data of each county is available from the Pingdingshan Water Resource Bulletin between 2013 and 2018, and the water uses are integrated to estimate the water use from two reservoirs respectively. To better understand the impact of water use on hydrological drought evolution, the yearly water use data of two reservoirs is downscaled to monthly time scale based on the seasonal variation of water use. Domestic and eco-environmental water use present strong seasonality and can be disintegrated using monthly temperature (Wada et al., 2014). The yearly industrial use is equally allocated to each month. Due to severe water shortage during the 2014 drought, little water was supplied to the Zhaopingtai irrigation district during 2014–2018 according to the information from the reservoir management authority, therefore irrigation water use is not considered for the Zhaopingtai Reservoir during that period.

Water availability refers to the available water that could be used for reservoir water supply, which is estimated as the difference between the sum of the inflow, water transfer volume and the change of reservoir storage, and the water loss (including evaporation and reservoir seepage). Water availability is greater than the amount of water supplied to the receiving area of the reservoir.

2.4. Standardized drought indices

The Standardized Precipitation Index (SPI) (McKee et al., 1993) and the Standardized Precipitation Evapotranspiration Index (SPEI) (Beguería et al., 2014) are used to identify meteorological droughts. Hydrological droughts are investigated from two aspects in the present study, i.e. streamflow droughts and reservoir droughts. The Standardized Streamflow Index (SSI) (Vicente-Serrano et al., 2012) is used to identify streamflow drought. To calculate the Standardized Reservoir Storage Index (SRSI), the same method is applied as for the SPI, with the sole difference being the usage of monthly reservoir storage data instead of precipitation. All four drought indices (i.e., SPI, SPEI, SSI, and SRSI) are calculated at a time scale of 3 months on monthly basis (referred to as SPI-3, SPEI-3, SSI-3 and SRSI-3, respectively). The meteorological drought and hydrological drought events start when respectively the SPI, SPEI, SSI and SRSI values are continuously below −1, and end when the index is above −1. The severity of the drought event is a sum of the monthly drought index (i.e., SPI, SPEI, SSI, or SRSI for meteorological drought, streamflow drought and reservoir drought, respectively) during a drought period. The intensity of meteorological drought and hydrological drought is indicated by four different levels. Namely, mild (0 to −0.99), moderate (−1.00 to −1.49), severe (−1.50 to −1.99), and extreme (≤−2.00) (McKee et al., 1993).

2.5. Downstreamness

Van Oel et al. (2011) proposed the concept of “downstreamness” to analyse the impact of a reservoir network on the streamflow in a river catchment over time. The concept helps understand how water availability develops throughout the reservoir network and advances the understanding of where the water is stored in the basin during and following the periods of drought. The downstreamness of drainage area for any location x (D_x) is the ratio of the upstream catchment area to the entire river basin (Van Oel et al., 2011):

$$D_x = \frac{A_{up,x}}{A_{tot}} \times 100\% \qquad (2)$$

where $A_{up,x}$ is the area upstream of location x (km^2), and A_{tot} is the total area of the catchment (km^2).

In addition, the spatial distribution of water stored in reservoirs throughout the river basin can be indicated using the downstreamness of reservoir storage capacity (D_{SC}) in a basin, and the actual volume of water in those reservoirs, expressed as the downstreamness of stored volume (D_{SV}). For a basin with n reservoirs, D_{SC} and D_{SV} are given by

(Van Oel et al., 2011):

$$D_{SC} = \frac{\sum_{x=1}^{n} SC_x D_x}{\sum_{x=1}^{n} SC_x} \quad (3)$$

$$D_{SV} = \frac{\sum_{x=1}^{n} SV_x D_x}{\sum_{x=1}^{n} SV_x} \quad (4)$$

where *SCx* (m^3) is the storage capacity of reservoir *x*, *SVx* (m^3) is the volume of water stored in reservoir *x*. The value of D_{SC} is fixed for a given basin, and it only changes when new reservoirs been built. The value of D_{SV} varies over time depending on the inflows and outflows of water in the reservoirs over time. By calculating D_{SC} and D_{SV}, it is possible to determine where the water is stored over time in upstream and downstream areas. If D_{SV} is larger than D_{SC}, more water is relatively stored downstream. If D_{SV} is smaller than D_{SC}, more water is relatively stored upstream. In that situation, more water stays upstream than it would have been without the upstream reservoir. If the reservoir filling rates are equal for all reservoirs, D_{SV} equals D_{SC}. The situations are schematically illustrated using an hourglass in Fig. 3.

2.6. Trend analysis

The Mann-Kendall test is a commonly used statistical method in detecting trends in climate and hydrological data (Hirsch et al., 1982). Two statistics were used to characterize these trends, namely, Kendall's correlation coefficient (τ) to illustrate the trend direction (i.e., upward, or downward), and the *p*-value which is the probability of getting a result that is either the same or more extreme than the actual observations. The null hypothesis (H_0) of no trend is discarded if *p*-value is less than the significance level α (usually, $\alpha = 0.05$).

3. Results

3.1. Temporal variation of hydrometeorological factors

Trends in different hydrometeorological variables (precipitation, evaporation, reservoir outflow and streamflow) in the study area are detected using the Mann-Kendall test (Table 3). The results indicate no significant upward or downward patterns in annual precipitation and pan evaporation, but the reservoir outflow significantly decreased for both reservoirs. The major reason of the decrease of outflow is that the outflow is the aggregated discharge via the spillway and irrigation canals, not including water supply for industrial and domestic water use. On the one hand, during the period 1990–2018, there is no much change of irrigation area, therefor no increase of water discharge for irrigation. On the contrast, water use for irrigation from the reservoirs was often cut off to guarantee the water supply for industrial and domestic water supply after the severe drought in 2014. On the other hand, water abstraction for water supply to reservoir water receiving areas increased during this period due to the increase of population and economy. Although the reservoir outflow from Baiguishan significantly decreased, however Baihuishan only controls 22.6% of the total drainage area at Luohe, hence we only observe a non-significant decrease of streamflow at Luohe (Table 3).

The stored volumes in the Baiguishan reservoir significantly decreased throughout the studied period, whereas the Zhaopingtai reservoir does not show any significant trend in reservoir volumes. Therefore, we can infer that the storage of upstream Zhaopingtai reservoir did not significantly change because, on the one hand, there is no significant precipitation and evaporation change, consequently, the inflow to Zhaopingtai did not change significantly; on the other hand, the decrease of outflow compensated for the increased water withdrawal for the reservoirs water supply area. Meanwhile, the storage of downstream Baiguishan reservoir decreased significantly because the decrease of its outflow cannot compensate for the decrease of its inflow (which mainly comes from the outflow of the upstream Zhaopingtai reservoir) and the increase of the water withdrawal for water supply.

Due to the data availability, we calculated inflow only for the period during 2013–2018. Reservoir variables, namely inflow, outflow, and reservoir storage during the period 2013–2018 are displayed in Fig. 4. Evidently, inflow rates exceed the outflow rates greatly in both the Zhaopingtai and Baiguishan reservoirs due to the joint effects of reservoir water retention, reservoir water supply, and water loss by seepage and evaporation over time. The difference between inflow and outflow is smaller in the upstream Zhaopingtai reservoir, indicating a relatively less disturbance by water withdraw and water loss compared to the Baiguishan reservoir. The outflow of Zhaopingtai peaks in May for increasing the effective flood defence capacity of reservoir before the coming flood season, whereas the outflow of Baiguishan peaks a month later in June, indicating that the Zhaopingtai reservoir plays a heavier role than Baiguishan in flood defence. Peak storage months also differ between the two reservoirs. Specifically, the Zhaopingtai reservoir reaches its peak in reservoir storage in November, whereas the Baiguishan reservoir reaches its peak a month earlier in October. That means that Baiguishan starts to impound water approximately one month earlier than Zhaopingtai after the flood season, although according to the operating rules, both reservoirs have the highest flood limit water levels in the same period during August 26 - September 15. Since 2014, the Baiguishan reservoir has received water transfers annually through the middle route of the South-to-North Water Diversion Project.

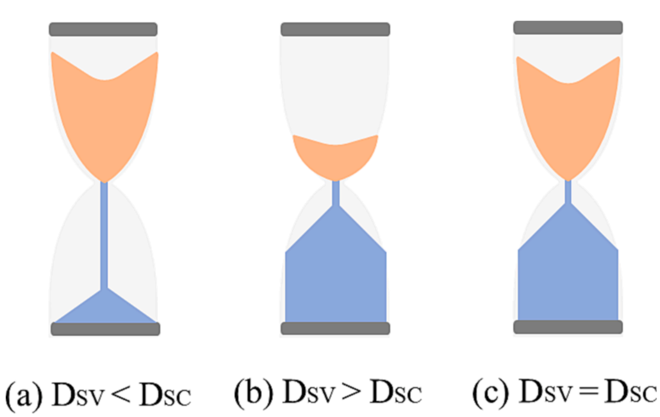

Fig. 3. Downstreamness situations schematically illustrated using an hourglass for a basin with two reservoirs (Note: orange represents the filling portion of the upstream reservoir, and blue represents the filling portion of the downstream reservoir). For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.

3.2. Drought identification and drought propagation

For the Zhaopingtai and Baiguishan reservoirs, meteorological droughts (according to the SPI-3, and SPEI-3) and hydrological droughts (according to SRSI-3) are identified over the period from 1990 until 2018 (Fig. 5 & Table 4). Also, hydrological droughts are identified according to SSI-3 at Luohe (Fig. 5b).

Overall, it appears that the temporal variation patterns of meteorological drought were the same for both reservoir catchments, especially according to the SPI-3, with only slight differences in magnitude and duration (Fig. 5a & Table 4). The SPEI-3 shows more differences between both reservoirs, especially considering the number of drought periods identified (31 for the Zhaopingtai reservoir, and 25 for the Baiguishan reservoir) (Fig. 5a & Table 4). In the drainage areas of both reservoirs, the meteorological drought episodes that have been identified are predominantly brief, lasting only one to two months. In contrast, between 1997 and 2000, an exception to the typical short meteorological droughts was observed, with four major meteorological droughts occurring that lasted for extended periods. These longer-duration

Table 3
Kendalls's τ of Mann-Kendall test for hydrometeorological variables in the watershed.

Location	**Storage** (1990–2018)	**Outflow** (1996–2018)	**Precipitation** (1990–2018)	**Pan evaporation** (1990–2018)	**Streamflow** (1990–2018)
Zhaopingtai	−0.02	−0.44*	−0.08	0.01	
Baiguishan	−0.31*	−0.42*	0.06	−0.11	
Luohe					−0.20

Note: * indicates a significant trend at the significance level of 0.05.

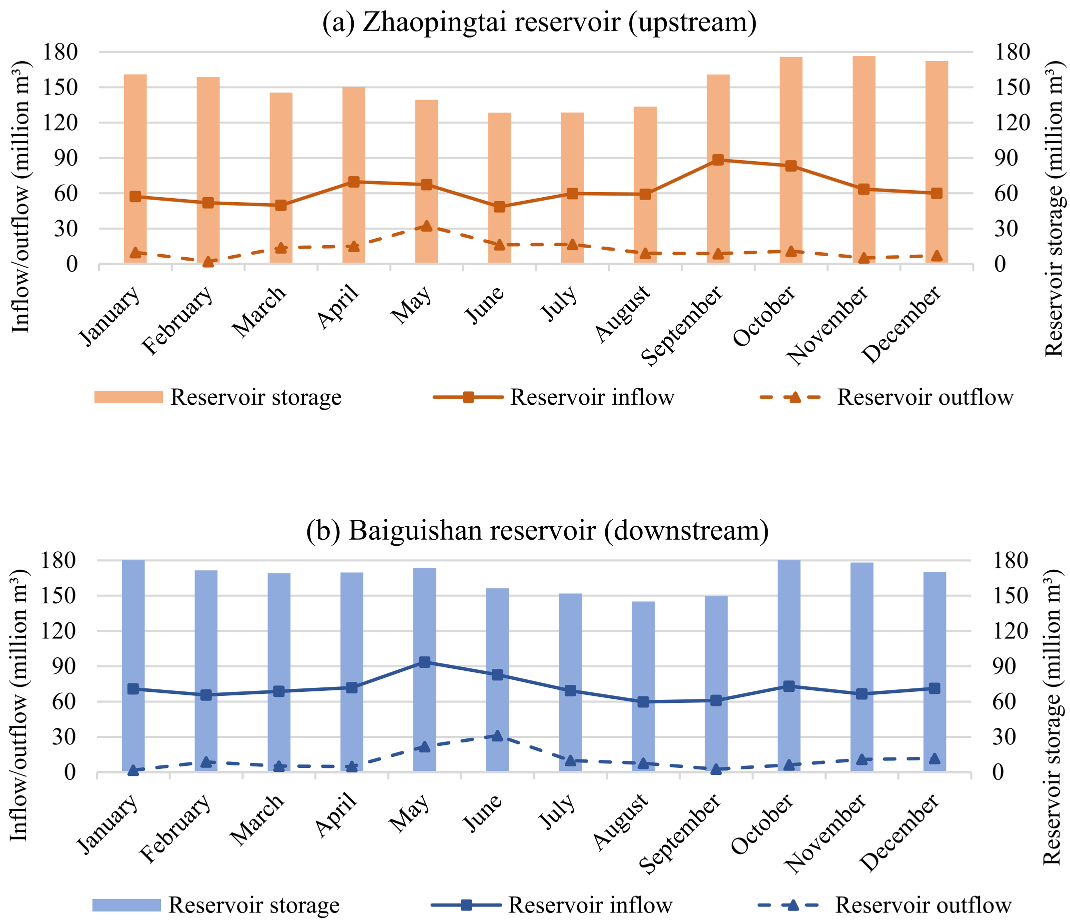

Fig. 4. Mean monthly reservoir storage, inflow, and outflow (2013–2018) of (a) Zhaopingtai; and (b) Baiguishan.

meteorological droughts had a substantial impact, resulting in two instances of reservoir drought in Zhaopingtai and one instance in Baiguishan from August 1999 to June 2000. Each of these reservoir droughts persisted for a period exceeding 6 months. An additional period that stands out is from December 2010 to April 2013, during which several meteorological droughts occurred. However, despite the multiple meteorological droughts, only one extended reservoir drought was recorded in each of Zhaopingtai and Baiguishan. This phenomenon is a reflection of typical features of drought propagation from meteorological drought to hydrologic drought, i.e., drought pooling and lengthening (van Loon 2015).

The reservoir droughts indicated by SRSI-3 show significant differences between the Zhaopingtai and Baiguishan reservoirs (Fig. 5b) in terms of the frequency, duration, timing and severity (Fig. 5b & Table 4). Reservoir droughts at upstream Zhaopingtai with a short duration of less than 6 months (e.g., May 1995 – June 1995, April 2000 - May 2000, February 2003 - July 2003; March 2005 - June 2005; August 2006 - September 2006; February 2009 - July 2009) mostly did not propagate to downstream Baiguishan reservoir. The possible reason is that during these mild and moderate droughts, the Zhaopingtai reservoir authority operate the reservoir in its usual way, which means no reduction of the tail water from the Zhapintai. That helps to avoid hydrological drought events in Baiguishan. All three reservoir droughts at Zhaopingtai with a duration longer than 6 months (i.e., August 1997 - April 1998, August 1999 - January 2000, and September 2013 - September 2014) match a reservoir drought at Baiguishan (i.e., October 1997 - April 1998, October 1999 - June 2000, and October 2013 - Febuary 2015) respectively. For the overlapping reservoir droughts, the onset is one or two months earlier at the upstream Zhaopingtai that advances towards the downstream Baiguishan. Moreover, among two of the three overlapping droughts, the duration of the downstream reservoir droughts got longer and the severity got stronger (especially the 2014 mega-drought with duration from 13 months to 17 months, and severity from 19.78 to 39.41). An opposite phenomenon was observed in reservoir drought during July 2016 - September 2017, when only the Baiguishan reservoir experienced a reservoir drought, and the drought was not preceded by a reservoir drought at Zhaopingtai. Such an abnormal is an effect of a special reservoir operation strategy after the 2014 mega-drought for preventing possible near future mega-droughts, that is, Zhaopingtai reservoir released very small amount of water it received from the

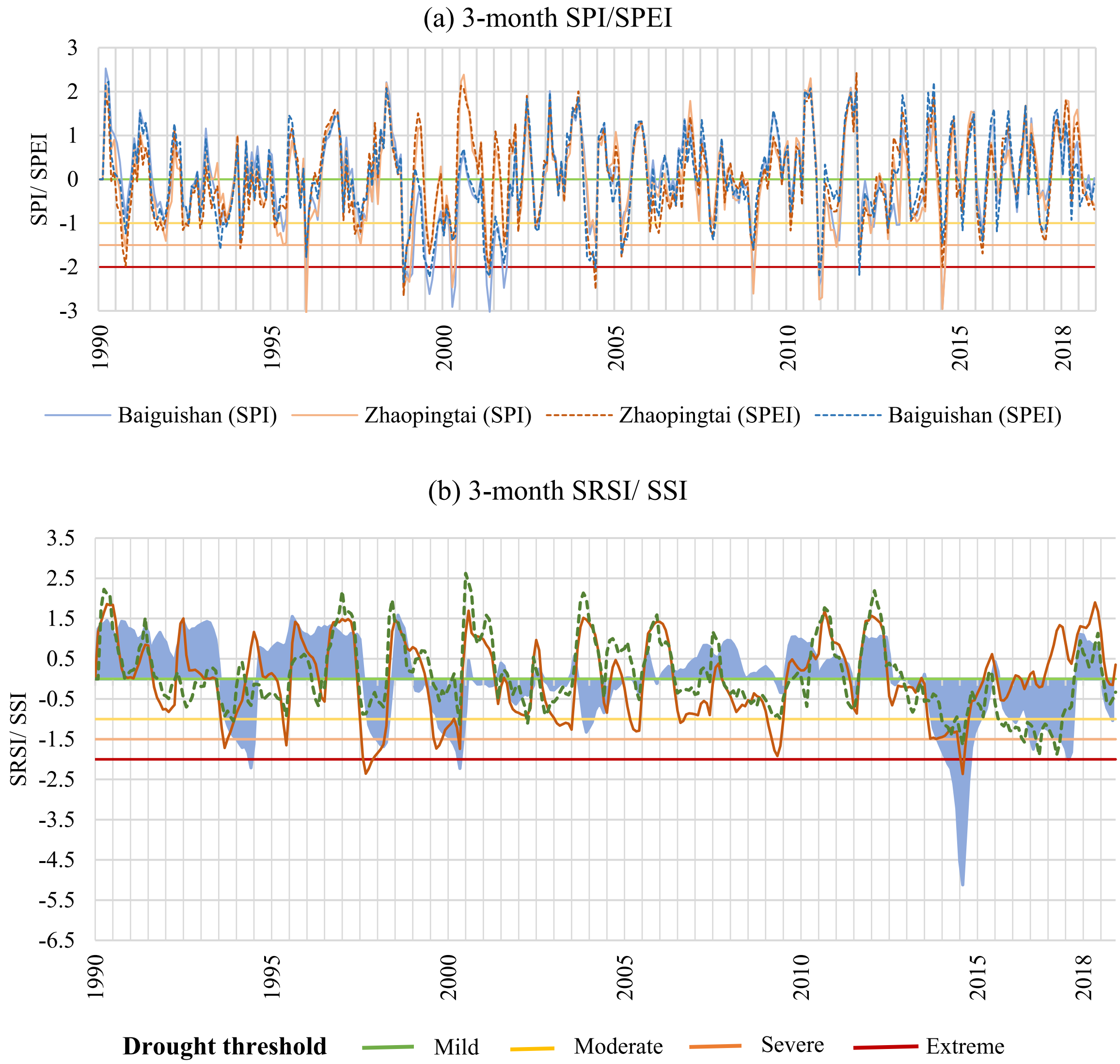

Fig. 5. Temporal evolution of meteorological and hydrological drought using (a) SPI-3 and SPEI-3 at the Zhaopingtai and Baiguishan reservoirs; and (b) SRSI-3 of the Zhaopingtai and Baiguishan reservoirs; and the SSI-3 at the Luohe gauging station.

upstream drainage area, leading to very little replenishment to the downstream Baiguishan reservoir. In a word, moderate droughts at the upstream reservoir did not propagate to the downstream reservoir, indicating a reduction of drought frequency in the drought propagation, while severe droughts tend to propagate to the downstream reservoir with a 1 ~ 2 months time lag of drought occurrence, an increase of drought severity and an increase of drought duration. Additionally, such kind of reservoir drought propagation may be interrupted by storing more water in the upstream reservoir for drought mitigation purpose.

There are only three moderate streamflow droughts at Luohe identified in terms of SSI between 1990 and 2013 (Fig. 5b & Table 4). Although several reservoir droughts occurred in the two upstream major reservoirs during 1990 and 2013, they have little effects on streamflow observed at Luohe. This pattern changed in 2014 when the long-duration mega reservoir droughts occurred in September 2013 - September 2014 in Zhaopingtai and in Ocotober 2013 - February 2015 in Baiguishan. From 2014 onward, the streamflow was impacted by a decrease in outflows from both reservoirs, because both reservoirs barely released any water. An explanation of this could be the reservoir authorities were more cautious with releasing water after the devastating impacts of the drought in September 2013 - February 2015 in the Shaying River basin (China Daily, 2014). As a consequence, the streamflow drought in 2014 (composed of two period, i.e. January 2014 – May 2014, and July 2014 – September 2014) occurred three months after the occurrence of reservoir droughts at Zhaopingtai and Baiguishan, which was the direct effect of the drought propagation from reservoir drought to streamflow drought. Another major streamflow drought took place between September 2015 - May 2017, with a duration of 21 months and a magnitude of −28.18, even there was no major meteorological droughts (Fig. 5 & Table 4). Overall, because the two reservoirs control only about 22.6% of the total catchment area above Luohe despite of their huge storage capacities, moderate reservoir droughts often dissipated when they propagate to downstream river flows. But when severe reservoir droughts occurred, the outflow from reservoirs to downstream will be cut off, consequently leading to severe streamflow droughts. Moreover, long-duration severe streamflow droughts may follow even when in the case of normal years, such as the streamflow drought during September 2015 - May 2017, due to water management measures as well as the depletion of water storage in the catchment during the preceding mega drought period.

Table 4
Overview of drought indicators SPI-3, SPEI-3, SRSI-3 and SSI-3, including the drought severity and the drought duration in months.

SPI-3				SPEI-3				SRSI-3				SSI-3	
Zhaopingtai		Baiguishan		Zhaopingtai		Baiguishan		Zhaopingtai		Baiguishan		Luohe	
Duration (start month)	Severity	Duration (start month)	Severity	Duration (start month)	Severity	Duration (start month)	Severity	Duration (start month)	Severity	Duration (start month)	Severity	Duration (start month)	Severity
2 (1990–09)	−2.76	1 (1991–12)	−1.11	3 (1990–09)	−4.58	1 (1990–10)	−1.24	5 (1993–08)	−6.83	10 (1993–10)	−15.99	1 (1993–12)	−1.05
2 (1991–11)	−2.54	1 (1993–07)	−1.09	1 (1991–09)	−1.15	1 (1992–08)	−1.01	2 (1995–05)	−2.76	7 (1997–10)	−10.36	1 (2000–05)	−1.13
2 (1992–06)	−2.07	1 (1993–09)	−1.04	1 (1991–11)	−1.17	2 (1993–06)	−2.67	9 (1997–08)	−16.92	9 (1999–10)	−14.07	1 (2002–04)	−1.12
1 (1994–02)	−1.28	1 (1995–05)	−1.19	3 (1992–06)	−3.23	1 (1993–09)	−1.09	7 (1999–08)	−9.88	4 (2003–11)	−4.60	5 (2014–01)	−5.91
4 (1995–03)	−5.46	1 (1996–01)	−2.18	1 (1992–12)	−1.12	1 (1994–02)	−1.40	2 (2000–04)	−2.95	17 (2013–10)	−39.41	3 (2014–07)	−4.03
1 (1996–01)	−3.11	1 (1997–08)	−1.25	1 (1993–07)	−1.04	1 (1996–01)	−1.77	6 (2003–02)	−6.86	1 (2016–02)	−1.08	21 (2015–09)	−28.18
2 (1997–07)	−2.68	4 (1998–11)	−8.88	2 (1994–02)	−2.74	3 (1998–11)	−5.18	4 (2005–03)	−4.87	15 (2016–07)	−22.40		
4 (1998–11)	−8.54	5 (1999–06)	−10.03	1 (1995–02)	−1.11	6 (1999–06)	−10.21	2 (2006–08)	−2.14	1 (2018–11)	−1.04		
3 (1999–07)	−4.05	1 (2000–01)	−1.29	1 (1996–01)	−1.76	1 (2000–01)	−1.28	6 (2009–02)	−9.02				
1 (2000–01)	−1.04	3 (2000–03)	−6.52	3 (1997–06)	−3.49	2 (2000–04)	−2.70	13 (2013–09)	−19.78				
2 (2000–04)	−4.39	8 (2001–04)	−15.68	3 (1998–11)	−5.54	4 (2001–03)	−7.45						
2 (2001–04)	−3.87	1 (2002–10)	−1.08	3 (1999–07)	−4.17	4 (2001–08)	−6.12						
2 (2001–10)	−2.95	1 (2004–04)	−1.26	1 (2000–01)	−1.16	2 (2002–09)	−2.30						
1 (2002–03)	−1.01	1 (2004–06)	−1.38	2 (2000–04)	−2.45	4 (2004–03)	−7.30						
1 (2002–09)	−1.06	1 (2005–03)	−1.05	2 (2001–04)	−3.80	3 (2005–03)	−4.42						
1 (2004–04)	−1.09	1 (2007–11)	−1.04	2 (2001–10)	−2.51	2 (2007–10)	−2.50						
1 (2004–06)	−1.44	2 (2009–01)	−3.73	1 (2002–03)	−1.20	2 (2008–12)	−2.78						
1 (2005–03)	−1.40	2 (2010–12)	−4.64	1 (2002–09)	−1.10	2 (2010–12)	−3.81						
1 (2007–11)	−1.02	3 (2011–05)	−3.84	4 (2004–03)	−7.04	1 (2012–02)	−2.18						
3 (2008–12)	−5.09	1 (2012–02)	−1.48	3 (2005–03)	−4.24	1 (2012–12)	−1.12						
1 (2010–02)	−1.06	2 (2012–06)	−2.12	1 (2006–01)	−1.20	1 (2014–07)	−1.47						
2 (2010–12)	−5.44	1 (2012–12)	−1.10	2 (2006–03)	−2.27	1 (2015–02)	−1.16						
4 (2011–04)	−4.86	2 (2013–03)	−2.08	2 (2007–10)	−2.35	1 (2015–09)	−1.42						
1 (2012–02)	−1.39	2 (2014–07)	−4.83	2 (2008–12)	−2.86	1 (2016–02)	−1.19						
1 (2012–06)	−1.23	1 (2015–09)	−1.28	1 (2010–02)	−1.17	3 (2017–05)	−3.31						
1 (2012–12)	−1.37			2 (2010–12	−3.84								
2 (2014–07)	−4.87			2 (2012–02)	−2.93								
1 (2015–09)	−1.42			1 (2012–12)	−1.22								
				2 (2014–07)	−3.15								
				2 (2015–08)	−2.99								
				2 (2017–06)	−2.71								

3.3. Relationship between downstreamness of reservoir storage and upstream–downstream drought propagation

To understand how the variation of reservoir storage between upstream and downstream reservoirs affects reservoir drought, the periods of reservoir drought identified in the previous section are more closely analysed to see how the reservoir droughts of the upstream Zhaopingtai reservoir and downstream Baiguishan reservoir changed with the change of downstreamness of stored volume (*Dsv*) during those periods.

Downstreamness of drainage areas (D_x) of reservoirs relative to the Luohe gauging station is 22.4% for the Baiguishan reservoir and 11.5% for the Zhaopingtai reservoir. The downstreamness of stored volume (*Dsv*) and downstreamness of storage capacity (*Dsc*) for the Baiguishan and Zhaopingtai reservoirs during 1990–2018 are illustrated in Fig. 6. D_{SC} is a constant value of 17.7% during the study period. Therefore, if $D_{SV} > 17.7\%$, more water is relatively stored downstream; else if $D_{SV} < 17.7\%$, more water is relatively stored upstream. The variation of monthly reservoir volumes and the timeline of identified periods of meteorological and hydrological drought are also illustrated in Fig. 6.

According to the operating rules, the two reservoirs have the highest flood limit water levels during August 26 - September 15, after which both reservoirs start to save water for dry months in winter and spring. Consequently, both reservoirs reached their peaks in stored volumes in November (Zhaopingtai) and October (Baiguishan) (Fig. 4). The volumes stored in the Baiguishan reservoir, compared to the Zhaopingtai, were relatively more stable throughout the study period (Fig. 6a) because of the buffering effect of the Zhaopingtai reservoir. That is, as shown in Fig. 2a, the outflows of the Zhaopingtai are lower than Baiguishan in wet months (May ~ October) to store more flood flow, but are relatively higher during dry months (November ~ April) to provide more low flow to Baiguishan, so that Zhaopingtai acts as a buffer for the Baiguishan.

The identified periods of reservoir drought (in terms of SRSI-3) (Table 4) when droughts occurred in both upstream and downstream reservoirs are more closely examined in relation to the changes in D_{SV}, to understand how water storage has impacted the propagation of hydrological droughts. These are the identified periods:

(1) **August 1993 – July 1994:** During this first identified period of hydrological drought, the upstream Zhaopingtai reservoir stored comparatively more water, with an average Dsv of 17.2% (Fig. 6c). The drought hit Zhaopingtai in August 1993 and Baiguishan in October 1993. Notably, the period of hydrological drought ended seven months earlier in the Zhaopingtai reservoir and surpassed the Baiguishan in reservoir volumes (May 1994 - September 1994). When the reservoir drought started in Zhaopingtai, D_{SV} was much higher than D_{SC} about 19.2, indicating a higher relative storage in the downstream Baiguishan reservoir. Then D_{SC} kept going down, land remained lower than D_{SC} until the end of Baiguishan's drought in July 1994, indicating a higher relative storage in the Zhaopingtai reservoir (Fig. 6c). After the drought, D_{SC} kept going up, up to 20.8 in July 1995.

(2) **August 1997 - April 1998:** Prior to the second identified phase of hydrological drought, both reservoirs' watersheds experienced the onset of a meteorological drought in the summer of 1997. This progressed into a hydrological drought within the reservoirs, initially impacting the Zhaopingtai reservoir (August 1997 - April 1998) and subsequently impacting the Baiguishan reservoir (October 1997 - April 1998). At the beginning of this drought, the downstream Baiguishan reservoir hold a higher water storage, with an average D_{SV} of 20.3%. Then steadily went down to 17.1 at the end of the drought, indicating a relatively higher water storage in Zhaopingtai reservoir. In April/May 1998 it started raining again, contributing to the restoration of water storage in the two reservoirs. Then the D_{SV} went up several month later, indicating relative more water was stored in the downstream reservoir than the upstream reservoir.

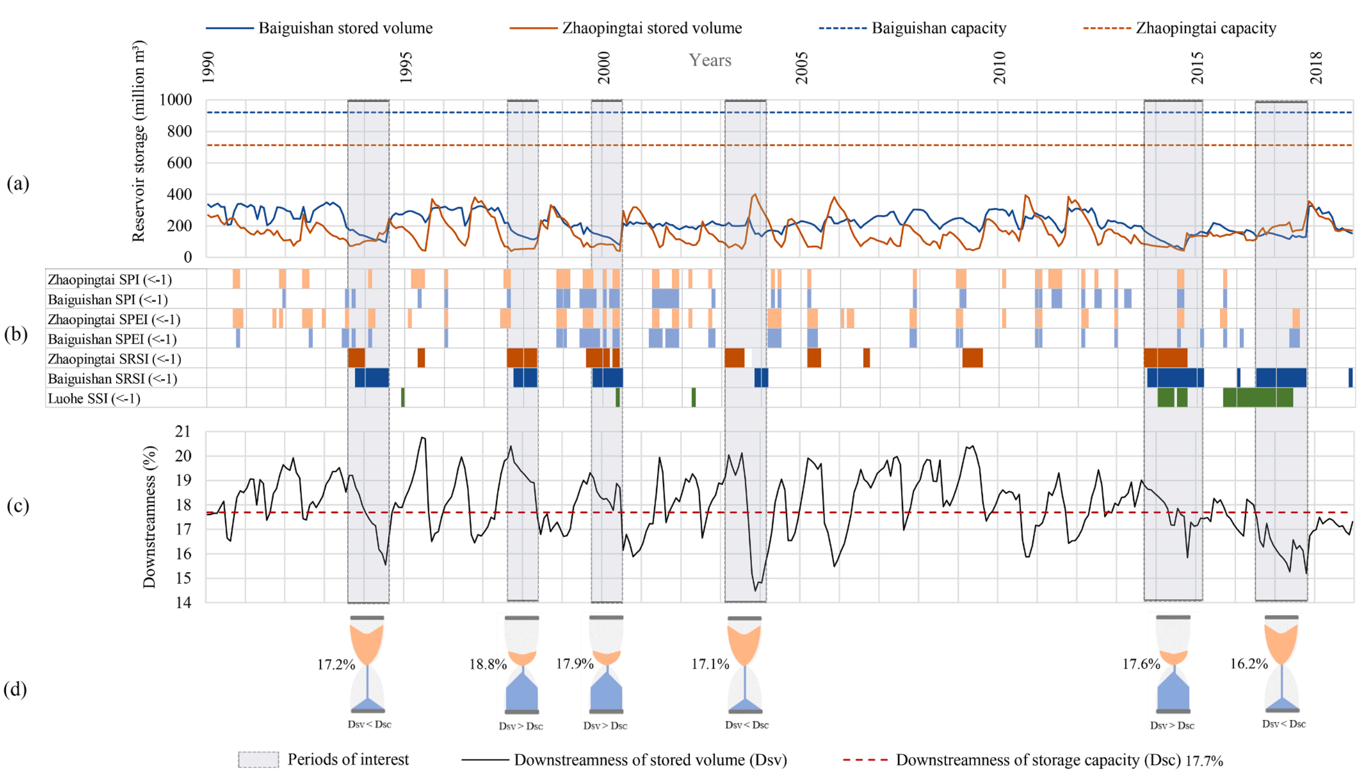

Fig. 6. Comparing downstreamness and reservoir storages, with meteorological and hydrological drought in the Baiguishan and Zhaopingtai reservoirs for six periods: (a) Reservoir volumes over time in both reservoirs; (b) Timeline, illustrating the development of meteorological (SPI and SPEI) and hydrological drought (SRSI and SSI); (c) Downstreamness of stored volume (Dsv) and Downstreamness of storage capacity (Dsc); (d) Average Dsv for the six time periods.

(3) **August 1999 - June 2000:** The drought started in the Zhaopingtai reservoir in August 1999, two months prior to the Baiguishan reservoir. The drought also started with D_{SV} high above D_{SC}. Then D_{SV} kept going down to 16.2 at the end of the reservoir drought in Baiguishan in June 2000. The drought concluded in summer 2000 with heavy rainfall replenishing both reservoirs' volumes. The Zhaopingtai reservoir recovered first. The Baiguishan reservoir did not surpass Zhaopingtai's volume until March 2001, consequently D_{SV} went above D_{SC} afterwards.

(4) **February 2003 - February 2004**: From February to July 2003, hydrological drought was identified in the Zhaopingtai reservoir. During that period, Dsv was mostly larger than 19.0, indicating relatively more water was stored in the downstream reservoir. But during the later period from August 2003 to February 2004, the upstream Zhaopingtai reservoir stored more water, Dsv dropped far beneath Dsc, with an average of 16.3. Subsequently, a reservoir drought solely impacted the downstream Baiguishan reservoir from November 2003 to February 2004.

(5) **September 2013 - February 2015**: During this prolonged period of reservoir hydrological drought, the storage volumes of both the Zhaopingtai reservoir (September 2013-September 2014), and Baiguishan reservoir (October 2013 - February 2015) were low (by average, 90 million m^3 in Zhaopingtai, 113 million m^3 in Baiguishan), which was the result of multiple periods of meteorological drought (December 2010 - December 2012). It is noteworthy that this major drought event also started with Dsv much larger than Dsc, indicating relatively more water was stored in the downstream reservoir, then Dsv kept going down, dropped below Dsc in the later half period of drought. It started raining again at the end of 2014, which led to the recovery of the reservoir volumes in both the Zhaopingtai and Baiguishan to some extent. But the tendency of the decline of Dsv remained, until September 2017. As a result, July 2016 - September 2017 witnessed reservoir drought only in the Baiguishan reservoir (Fig. 6b) with a monthly average of 138 million m^3 water stored, which is much lower than its average during 1990–2018 (Fig. 6a). In

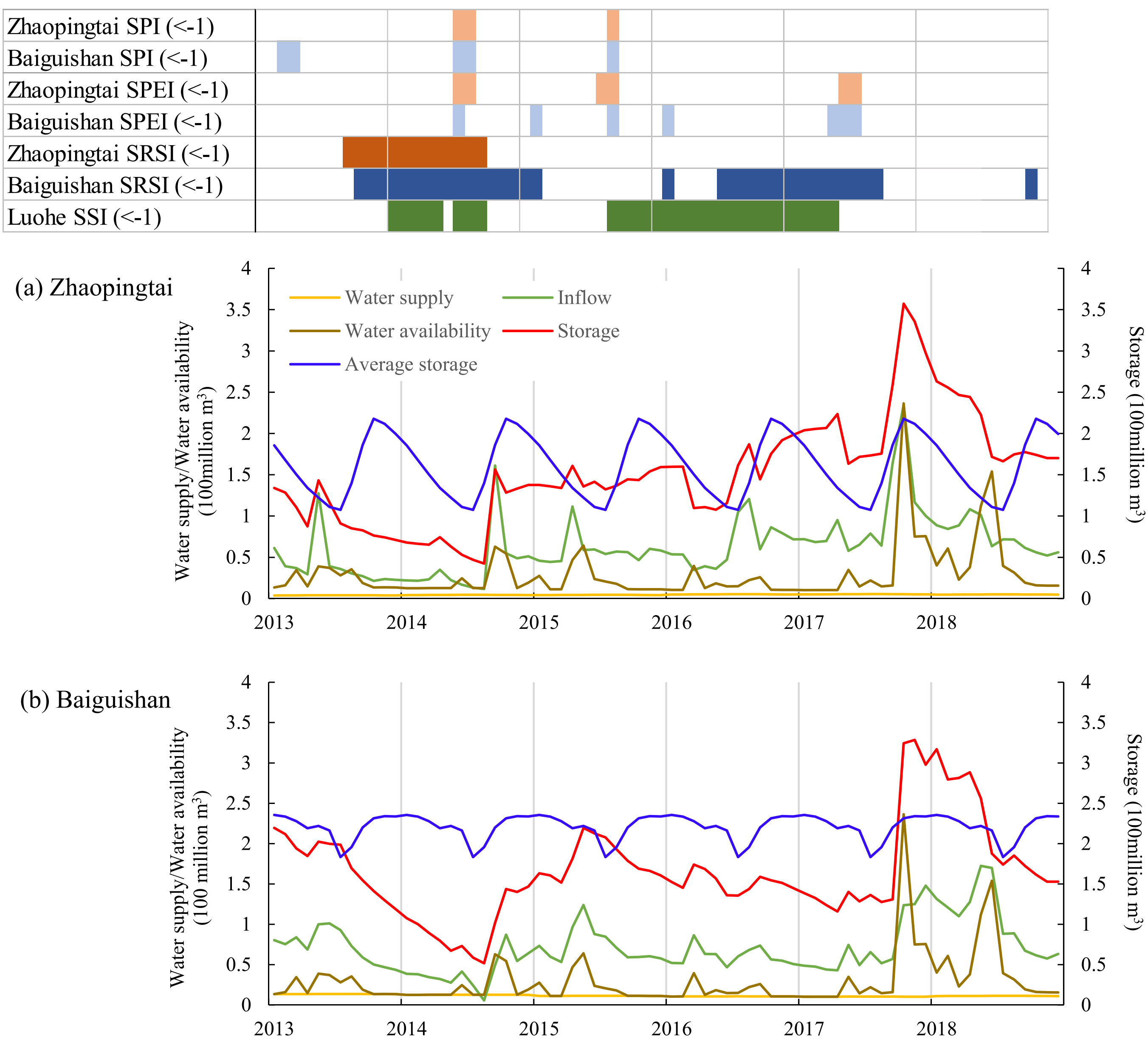

Fig. 7. Comparison of the monthly meteorological (SPI and SPEI), hydrological drought (SRSI and SSI); and monthly water supply, water availability, inflow, and reservoir storage.

comparison, during July 2016 - September 2017, relatively more water was stored in the upstream Zhaopingtai reservoir, with an average *Dsv* of 16.2% (Fig. 6d).

Generally, because the downstream Baiguishan reservoir plays a bigger role in the regional water supply, normally more water stored in the Baiguishan with a slightly larger *Dsv* than *Dsc*. During drought periods, little water was released to the downstream reservoir from the upstream reservoir, and the depletion of the downstream reservoir is faster than the upstream reservoir. Consequently, *Dsv* keeps going down during the period of upstream–downstream drought propagation. When the drought period ended, usually relatively more water was stored in the upstream reservoir than in the downstream reservoir, leading to a smaller *Dsv*.

3.4. The effects of water use on hydrological droughts

The study about the impacts of water use on hydrological drought in the present study is based on water supply data from the reservoirs, because during the period of heavy drought, agricultural water use is stopped from the two reservoirs according to the reservoir operation rules (Qiao and Liu, 2022). Monthly storage, the amount of water supply, inflow, and the amount of water availability for both upstream and downstream reservoirs are plotted in Fig. 7. Fig. 7 also includes the timeline of the identified meteorological and hydrological drought periods using SPI, SPEI, SRSI, and SSI (Fig. 5 and Table 4).

During the period from 2013−2017, the variation of water supply was not significant (3.7–5.5 million m^3 in Zhaopingtai and 10.2–13.6 million m^3 in Baiguishan); meanwhile, the water availability varied significantly in both reservoirs throughout this period, due to the variation of inflow and the reservoir storage. During the time of the extreme drought between September 2013 - February 2015, the water supply in the water-receiving area exceeded the inflow in the downstream Baiguishan reservoir. At that time reservoir storage played a key role in supplying water, except for August 2014 when water level reached below the dead level.

From May 2015 - September 2017, the Baiguishan reservoir underwent a predominantly consistent decline in water levels, as represented by the decline of the reservoir storage (red line in Fig. 7b). The cause of the reduction in reservoir storage, consequently a severe reservoir drought, is the decrease of the inflow to the reservoir (green line in Fig. 7b), while the amount of water supply (orange line) in the water receiving area of the reservoir did not change much. Between July 2016 and September 2017, the Baiguishan reservoir experienced another significant reservoir drought, as shown in Fig. 5 and Table 4. This particular period of reservoir drought that unfolded solely in the downstream Baiguishan reservoir did not result from a propagating meteorological drought, because during the same period the upstream Zhaopingtai reservoir's storage volumes appeared to increase. By September 2017, a noticeable recovery in water availability had become evident in both reservoirs. This rebound in the Zhaopingtai reservoir can be largely related to an increase in inflow, directly resulting from an increase in precipitation as indicated by the increase of SPI (Fig. 5). At the same time, the water availability in the Baiguishan reservoir also showed signs of improvement. This was facilitated by the excess water flowing downstream from the Zhaopingtai reservoir, complemented by water replenishment provided by the South-to-North Water Diversion Project.

Human water use has been widely viewed as a major role in the aggravation of hydrological drought in many regions. However, when the condition of water use becomes a climate normal, as in our case study area during 2013–2018, particularly when a significant proportion of the total water use is attributed to industrial usage, the aggravating effect of human water use is not evident. In our case, the major role in the development of upstream reservoir drought at Zhaopingtai during 2013–2018 was the inflow, whereas in the development of downstream reservoir drought at Baiguishan is also the inflow which was composed of mostly the outflow from upstream Zhaopingtai reservoir.

4. Discussion

4.1. Spatial difference of reservoir effects on hydrological drought

This study applied the concept of downstreamness to examine the influence of reservoir water storage on the occurrence of hydrological drought. Fig. 6 displays the downstreamness alongside meteorological and hydrological drought data for the Baiguishan and Zhaopingtai reservoirs during six periods of interest, to illustrate how the variation of water storage was associated with hydrological drought. September 2017 examined, from July 2016 to September 2017, was particularly noteworthy. During this period, more water was stored in the Zhaopingtai reservoir, located upstream, while the Baiguishan reservoir experienced a prolonged hydrological drought. Retaining more water in the upstream Zhaopingtai reservoir, bolstered water availability in that region, consequently leading to a reduction in water availability downstream. This scenario differed from prior periods, specifically 2005–2009, when the downstream Baiguishan reservoir held more water.

Results from the Mann-Kendall test do not indicate a significant downward trend in the storage of the Zhaopingtai reservoir. In contrast, they reveal a declining trend in the storage volume rates in the downstream Baiguishan reservoir, as detailed in Table 3. Following the drought from September 2013 to February 2015, the water storage in the Zhaopingtai reservoir substantially contributed to exacerbating the hydrological drought experienced in the Baiguishan reservoir between July 2016 and September 2017. Meanwhile, the precipitation and evaporation do not show any significant downward or upward trend indicates that natural factors have limited impact on the spatial hydrological drought.

Many studies showed that reservoirs played an important role in controlling the characteristics of hydrological drought (Di Baldassarre et al., 2018; Wu et al., 2018, 2021; Yu et al., 2019). The reservoir operation always results in lower peak flows and higher low flows (Wang et al., 2011; van Oel et al., 2018). This leads to more severe streamflow droughts in reservoir impounding season and less in reservoir water release season in the downstream river reaches (López-Moreno et al., 2009; Yu et al., 2019). Furthermore, reservoir operations may significantly alter the process of drought propagation (Van Oel et al., 2017; Wang et al., 2019), and the effects of reservoir operation on the intensification of hydrological droughts may be different in different catchments on different spatial scales. Zhang et al. (2015) showed that reservoir regulations extend the time lags between the meteorological and hydrological anomalies in the same catchment as the present study, and upstream and downstream reservoirs have different effects on drought severity of their outflows. He et al. (2017) showed that reservoirs helped alleviate drought conditions during the 2014 drought in California, USA. Veldkamp et al. (2017) used an ensemble of five global hydrological models to examine how human interventions affected monthly river water availability and water scarcity, showed that human activities often caused water scarcity to travel downstream on a global scale. Meanwhile, the hydrologic model simulation by Cheng et al. (2021) on a basin scale showed that reservoirs alleviated hydrological droughts in downstream water-receiving regions because of the water diverted from upstream reservoirs. Previous studies about drought propagation mostly focused on how meteorological droughts propagate to hydrologic droughts over time (e.g., Ma et al., 2022; Wang et al., 2021; Wu et al., 2018; Xu et al., 2019; Zhang et al., 2022; Zhu et al., 2019). However, how the upstream reservoir affects the downstream reservoir drought, and further on affect the downstream streamflow droughts has not been reported in the literature as far as we know. Our study shows not only how meteorological droughts propagate to different types of hydrological droughts (i.e., reservoir drought and streamflow drought) under the impacts of reservoir operation, but also how the hydrological droughts propagate in space, that is, from upstream reservoir drought to downstream reservoir drought, then from reservoir droughts to downstream streamflow droughts. The results improved our understanding about drought propagation in space under human interventions. However, we need to further explore how the allocation policies can mitigate hydrological droughts in the future research for helping reservoir authorities to make reservoir operation decisions.

4.2. Effects of water use

Global drought intensities heavily increased due to human water consumption in the past few decades (Wada et al., 2013). The simulation by Cheng et al. (2021) showed that the effects of different types of water use on hydrological drought differed in different parts of the Huaihe river basin in China. Wang et al. (2021) demonstrated that reservoir operation had a significant effect on alleviating the duration and severity of extreme downstream streamflow drought, but increased streamflow drought during the period of reservoir impoundment. Using 28 empirical case studies globally, Van Loon et al. (2022) showed that human activities both aggravated and alleviated streamflow drought, with more cases of aggravation than alleviation. In our case, as shown in Section 3.1, the increase of industrial and domestic water use led to the long-term decreasing trend in outflows of both reservoirs, and the decreasing trend in the storage of Baiguishan reservoir, consequently aggravated hydrological drought. But during several drought periods during 2013–2018, the major portion of the total water usage is industrial and residential which is generally stable over time, indicating little effects of water use on drought conditions. Therefore, this study indicates that while human water use can aggravate hydrological drought in the long term (e.g., several decades) because of the expansion of irrigation area and the increase of human population, when water use is basically stable in a comparative short period of time (like 6 years during 2013–2018 in our case), the water availability dominated by the variation of inflow to the reservoir plays a major role in reservoir drought severity; and, spatial differences in water storage and inflow played significant roles in the onset and severity of upstream/downstream droughts. This underscores the importance of effective water management strategies that consider these spatial differences. The development of region-specific water management strategies is crucial for mitigating such droughts in the future.

For future research, it is recommended to collect more accurate spatial and temporal data regarding different types of water use, possibly with the help of remote sensing techniques. Also, to understand the relationship between the reservoirs and other water sources (particularly groundwater) additional analysis is required. Di Baldassarre et al. (2018) also mentioned that studying changes of human activities during water shortages is essential to understand the causality of water availability and demand and how they mutually affect one another. One way to understand this causality is to investigate where the water users get their water from and what their motivations are in choosing where to get their water from. This allows to gain knowledge about the human-water interactions at a specific location in the watershed and could help policymakers make more tailor-made policies supporting the water-users to be more adaptive against drought.

5. Conclusions

Understanding drought propagation is important for effective water resources management and drought mitigation. While many studies have explored the temporal aspects (e.g., response time and propagation rate) of drought propagation at different spatiotemporal scales, there have been limited studies into the spatial characteristics of drought propagation. In our case study for the Shaying River basin which has two major reservoirs, we differentiate between two types of hydrological droughts, that is, reservoir drought (i.e., deficit in reservoir storage) and streamflow drought (i.e., deficit in streamflow discharge), and assess how reservoir storage and water use affect drought propagation in both space and time.

Drought pooling and lengthening are demonstrated in the drought propagation from meteorological drought to reservoir drought in the river basin. How hydrological droughts propagate from upstream to downstream is closely related to drought severity. Mild and moderate upstream reservoir droughts usually did not propagate to the downstream reservoir, but severe upstream reservoir droughts could propagate to the downstream reservoir with delayed occurrence, prolonged duration, and increased severity. Mild and moderate upstream reservoir droughts often dissipate when they propagate to downstream river flows as reservoirs do not contribute most runoff to the river. But severe reservoir droughts could lead to severe streamflow droughts, even after the end of reservoir droughts as an aftermath.

The change of spatial water distribution between upstream and downstream areas in the reservoir drought propagation can be clearly illustrated through the application of the downstreamness concept. Because the downstream Baiguishan reservoir plays a bigger role in the regional water supply, normally more water stored in the Baiguishan with a downstreamness of stored volume (*Dsv*) larger than the downstreamness of storage capacity (*Dsc*). During drought propagation, little water was released to the downstream reservoir from the upstream reservoir, and the depletion of the downstream reservoir is faster than the upstream reservoir. Consequently, during the period of upstream–downstream drought propagation, *Dsv* typically keeps going down from above *Dsc* at the beginning of drought occurrence, indicating relatively more water is stored in the downstream reservoir, to below *Dsc* at the end of drought, indicating relatively more water stored in the upstream reservoir.

The increase of industrial and domestic water use led to the long-term decreasing trend in outflows of both reservoirs, and the decreasing trend in the storage of Baiguishan reservoir, consequently aggravated hydrological drought. But during 2013–2018, the major portion of the total water usage was industrial and residential which was generally stable over time, the typical exacerbating effect of human water use on hydrological droughts is not observed. In the 2013–2018 period, upstream Zhaopingtai reservoir's drought was driven by inflow variability, while downstream Baiguishan reservoir's drought conditions were predominantly shaped by mainly the variation of the outflow from the upstream Zhaopingtai reservoir.

These findings highlight the importance of developing effective water management strategies that account for spatial differences upstream and downstream. A particular focus should be placed on optimizing water storage and distribution systems to mitigate the impacts of hydrological drought. While this research is specific to one highly regulated river basin with two reservoirs, the knowledge gained has broader implications and can be beneficial for other artificially managed river basins worldwide facing similar challenges regarding drought.

Author contributions

M. Schilstra: Investigation, Formal analysis, Visualization, Writing – orginial draft, reviewing & editing, W. Wang: Funding acqusition, Conceptualization, Investigation methodology, Formal analysis, Validation, Writing – reviewing & editing; P. R. van Oel: Conceptualization, Writing – reviewing & editing; J. Wang and H. Cheng: Data curation, Writing – reviewing & editing.

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.

Data availability

Data will be made available on request.

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References

Beguería, S., Vicente-Serrano, S.M., Reig, F., Latorre, B., 2014. Standardized precipitation evapotranspiration index (SPEI) revisited: parameter fitting, evapotranspiration models, tools, datasets and drought monitoring. Int. J. Climatol. 34 (10), 3001–3023.

Cheng, H., Wang, W., van Oel, P.R., Lu, J., Wang, G., Wang, H., 2021. Impacts of different human activities on hydrological drought in the Huaihe River Basin based on scenario comparison. J. Hydrol.: Reg. Stud. 37, 100909.

China Daily., 2014. Drought persists in Central China's Henan province. China Daily. http://usa.chinadaily.com.cn/china/2014-08/05/content_18252310.htm.

Copernicus Climate Change Service, Climate Data Store., 2019. Land cover classification gridded maps from 1992 to present derived from satellite observation. Copernicus Climate Change Service (C3S) Climate Data Store (CDS). doi: 10.24381/cds.006f2c9a (Accessed on 29-03-2023).

Di Baldassarre, G., Wanders, N., AghaKouchak, A., Kuil, L., Rangecroft, S., Veldkamp, T.I.E., Garcia, M., van Oel, P.R., Breinl, K., van Loon, A.F., 2018. Water shortages worsened by reservoir effects. Nat. Sustain. 1 (11), 617–622.

Haslinger, K., Koffler, D., Schöner, W., Laaha, G., 2014. Exploring the link between meteorological drought and streamflow: effects of climate-catchment interaction. Water Resour. Res. 50 (3), 2468–2487.

He, X., Wada, Y., Wanders, N., Sheffield, J., 2017. Intensification of hydrological drought in California by human water management. Geophys. Res. Lett. 44 (4), 1777–1785.

He, J., Yang, K., Tang, W., Lu, H., Qin, J., Chen, Y., Li, X., 2020. The first high-resolution meteorological forcing dataset for land process studies over China. Sci. Data 7 (1), 25. https://doi.org/10.1038/s41597-020-0369-y.

Hirsch, R.M., Slack, J.R., Smith, R.A., 1982. Techniques of trend analysis for monthly water quality data. Water Resour. Res. 18 (1), 107–121.

Liu, Q., Yang, Y., Liang, L., Yan, D., Wang, X., Li, C., Sun, T., 2023. Shift in precipitation-streamflow relationship induced by multi-year drought across global catchments. Sci. Total Environ. 857, 159560.

López-Moreno, J.I., Vicente-Serrano, S.M., Beguería, S., García-Ruiz, J.M., Portela, M.M., Almeida, A.B., 2009. Dam effects on droughts magnitude and duration in a transboundary basin: the Lower River Tagus, Spain and Portugal. Water Resour. Res. 45 (2).

Ma, L., Huang, Q., Huang, S., Liu, D., Leng, G., Wang, L., Li, P., 2022. Propagation dynamics and causes of hydrological drought in response to meteorological drought at seasonal timescales. Hydrol. Res. 53 (1), 193–205.

McKee, T.B., Doesken, N.J., Kleist, J., 1993. The relationship of drought frequency and duration to time scales. Proc. 8th Conf. Appl. Climatol. 17 (22), 179–183.

Pingdingshan Water Resource Bureau., n.d. Pingdingshan Water Resources Bulletin.

Qiao, Q., Liu, W., 2022. Early warning period and water level limit for droughts in Zhaopingtai Reservoir. Water Sci. Technol. 1, 12–14 in Chinese.

Rangecroft, S., van Loon, A.F., Maureira, H., Verbist, K., Hannah, D.M., 2019. An observation-based method to quantify the human influence on hydrological drought: upstream–downstream comparison. Hydrol. Sci. J. 64 (3), 276–287.

Shi, H., Zhou, Z., Liu, L., Liu, S., 2022. A global perspective on propagation from meteorological drought to hydrological drought during 1902–2014. Atmos. Res. 280, 106441.

Van Loon, A.F., 2015. Hydrological drought explained. Wiley Interdiscip. Rev. Water 2 (4), 359–392.

Van Loon, A.F., Rangecroft, S., Coxon, G., Werner, M., Wanders, N., Di Baldassarre, G., Tijdeman, E., Bosman, M., Gleeson, T., Nauditt, A., 2022. Streamflow droughts aggravated by human activities despite management. Environ. Res. Lett. 17 (4), 044059.

Van Oel, P.R., Martins, E.S.P.R., Costa, A.C., 2017. The effect of reservoir networks on drought propagation.

Van Oel, P.R., Krol, M.S., Hoekstra, A.Y., 2011. Downstreamness: a concept to analyze basin closure. J. Water Resour. Plan. Manag. 137 (5), 404–411.

Van Oel, P.R., Martins, E.S.P.R., Costa, A.C., Wanders, N., van Lanen, H.A.J., 2018. Diagnosing drought using the downstreamness concept: the effect of reservoir networks on drought evolution. Hydrol. Sci. J. 63 (7), 979–990.

Veldkamp, T.I.E., Wada, Y., Aerts, J., Döll, P., Gosling, S.N., Liu, J., Masaki, Y., Oki, T., Ostberg, S., Pokhrel, Y., 2017. Water scarcity hotspots travel downstream due to human interventions in the 20th and 21st century. Nat. Commun. 8 (1), 1–12.

Vicente-Serrano, S.M., López-Moreno, J.I., Beguería, S., Lorenzo-Lacruz, J., Azorin-Molina, C., Morán-Tejeda, E., 2012. Accurate computation of a streamflow drought index. J. Hydrol. Eng. 17 (2), 318–332. https://doi.org/10.1061/(asce)he.1943-5584.0000433.

Wada, Y., Van Beek, L.P.H., Wanders, N., Bierkens, M.F.P., 2013. Human water consumption intensifies hydrological drought worldwide. Environ. Res. Lett. 8 (3), 034036.

Wada, Y., Wisser, D., Bierkens, M.F.P., 2014. Global modeling of withdrawal, allocation and consumptive use of surface water and groundwater resources. Earth Syst. Dyn. 5 (1), 15–40.

Wang, W., Ertsen, M.W., Svoboda, M.D., Hafeez, M., 2016. Propagation of drought: from meteorological drought to agricultural and hydrological drought. Adv. Meteorol. 2016.

Wang, Y., Li, J., Zhang, T., Wang, B., 2019. Changes in drought propagation under the regulation of reservoirs and water diversion. Theor. Appl. Climatol. 138, 701–711.

Wang, J., Wang, W., Cheng, H., Wang, H., Zhu, Y., 2021. Propagation from meteorological to hydrological drought and its influencing factors in the Huaihe River Basin. Water 13 (14), 1985.

Wang, W., Wang, X., Zhou, X., 2011. Impacts of Californian dams on flow regime and maximum/minimum flow probability distribution. Hydrology Research 42 (4), 275–289.

Wu, J., Liu, Z., Yao, H., Chen, X., Chen, X., Zheng, Y., He, Y., 2018. Impacts of reservoir operations on multi-scale correlations between hydrological drought and meteorological drought. J. Hydrol. 563, 726–736.

Wu, J., Yuan, X., Yao, H., Chen, X., Wang, G., 2021. Reservoirs regulate the relationship between hydrological drought recovery water and drought characteristics. J. Hydrol. 603, 127127.

Xu, Y., Zhang, X., Wang, X., Hao, Z., Singh, V.P., Hao, F., 2019. Propagation from meteorological drought to hydrological drought under the impact of human activities: a case study in northern China. J. Hydrol. 579, 124147.

Yu, M., Liu, X., Li, Q., 2019. Impacts of the Three Gorges Reservoir on its immediate downstream hydrological drought regime during 1950–2016. Nat. Hazards 96, 413–430.

Zhang, R., Chen, X., Zhang, Z., Shi, P., 2015. Evolution of hydrological drought under the regulation of two reservoirs in the headwater basin of the Huaihe River, China. Stoch. Env. Res. Risk A. 29, 487–499.

Zhang, X., Hao, Z., Singh, V.P., Zhang, Y., Feng, S., Xu, Y., Hao, F., 2022. Drought propagation under global warming: characteristics, approaches, processes, and controlling factors. Sci. Total Environ. 838, 156021.

Zhu, Y., Liu, Y., Wang, W., Singh, V.P., Ma, X., Yu, Z., 2019. Three-dimensional characterization of meteorological and hydrological droughts and their probabilistic links. J. Hydrol. 578, 124016.