

Evolution of hydrological drought under the regulation of two reservoirs in the headwater basin of the Huaihe River, China

Runrun Zhang · Xi Chen · Zhicai Zhang · Peng Shi

Published online: 27 November 2014
© Springer-Verlag Berlin Heidelberg 2014

Abstract Reservoir regulation has a significant effect on streamflow regimes and thus hydrological drought characteristics. The impacts of two or more cascade reservoirs on upstream and downstream droughts may be different due to various geographical and topographical characteristics and water management activities. In this study, evolution of hydrological drought features, such as duration and magnitude, under the regulation of two cascade reservoirs in the Shahe River basin of the Huaihe River of China is analyzed as an example. The effect of the two reservoirs regulation on the drought severity is revealed by correlation analysis and comparisons of the standardized streamflow indices (SSI) of the reservoir inflow and outflow, and the standardized reservoir storage indices (SRSI). Additionally, the time lags between the standardized precipitation index and the hydrological drought indices (SSI and SRSI) are analyzed with the purpose of revealing the response of hydrological anomalies to meteorological variations. Results indicate that: (1) the multi-months dependence of streamflow and storage on climatic conditions causes longlasting hydrological anomalies, which reduces hydrological drought frequency; (2) the upstream reservoir leads to a marked decrease in streamflow drought severity, particularly during the severe drought. Although the downstream reservoir leads to an overall increase in the drought severity, it mitigates the severe and extreme

droughts; (3) the reservoir storage functions to smooth streamflow variation in that it reduces the drought frequency and extends the duration.

Keywords Hydrological drought · Reservoir regulation · The standardized precipitation index · The Huaihe River

1 Introduction

Drought is resulted from a long period of precipitation deficit (Dracup et al. 1980; Tallaksen et al. 1997), which affects various hydrologic variables including soil moisture content, groundwater storage, river discharge, reservoir storage and so on. Normally, based on the affected components, droughts are classified into four categories (meteorological, hydrological, agricultural and socio-economic droughts). Hydrological drought is related to a period of inadequate surface and subsurface water resources in a given water resources management system (Mishra and Singh 2011). In view of the close relationship between streamflow and precipitation, the response of hydrological droughts to meteorological droughts has attracted considerable attention of hydrologists.

Hydrological droughts are mainly affected by characteristics of watersheds (Zecharias and Brutsaert 1988; Vogel and Kroll 1992) and hydrological components such as streamflow, its response to precipitation variation is delayed due to land surface regulation (Vicente-Serrano and López-Moreno 2005; López-Moreno et al. 2013). Additionally, human activities, such as dam and reservoir constructions, and water diversion alter relationship between hydrological and meteorological droughts. Because reservoirs are built to reduce flood discharge in the flooding season for flood control and to increase water

R. Zhang · X. Chen (✉) · Z. Zhang · P. Shi
State Key Laboratory of Hydrology-Water Resources and Hydraulic Engineering, Hohai University, Nanjing 210098, China
e-mail: xichen@hhu.edu.cn

R. Zhang · X. Chen · Z. Zhang · P. Shi
College of Hydrology and Water Resources, Hohai University, Nanjing 210098, China

supply for irrigation, ecological flow and other demands in the dry season, reservoir management changes temporal and spatial patterns of streamflow (Liang et al. 2013; Zhang et al. 2013, 2014b) and thus its response to precipitation variation (López-Moreno et al. 2009, 2013; Lorenzo-Lacruz et al. 2010). This alteration is particularly significant in the subtropical monsoon climate areas, where precipitation is characterized by marked seasonality, high inter-annual variability and periodic floods and droughts (Wang 2000). Vicente-Serrano and López-Moreno (2005) analyzed the relationship between the standardized series of hydrological variables (river discharge and reservoir storage) and SPI at different time scales. They found that in the mountainous Mediterranean basin, the surface runoff anomalies closely related to the precipitation variations at a time scale of 1–4 months, whereas the reservoir storages are at a longer time scale of 7–10 months.

The changes of the temporal and spatial patterns of streamflow affect hydrological droughts in varying degrees due to various geographical and topographical characteristics and water management activities. López-Moreno et al. (2009) found that under the effect of Alcántara reservoir on the Tagus River, located close to the border between Spain and Portugal, the Portuguese part of the basin in the downstream has experienced more severe droughts than the upstream part in terms of both magnitude and duration. Li et al. (2011) evaluated the impacts of river regulation and water diversion on the hydrological characteristics in the Murrumbidgee River, Australia. They found that the regulation successfully mitigated the magnitude of hydrologic droughts by ensuring a more reliable water supply for users in downstream of two major dams but the hydrologic benefits of reservoir regulation progressively disappeared along the river course due to water diversion and hydrological drought at regions far from the foot of the reservoirs were augmented progressively.

The Huaihe River basin is of particular interest because of its situation in China's transition terrain of northern climate and southern climate. It belongs to the warm temperate monsoon and sub-humid climate region (Wang 2000). The basin has the highest population density in China. As one of the major agricultural areas, it consumes millions of tons of water in each year. In the Huaihe River, about 5,674 reservoirs and 5,427 sluices have built since 1950s for flood control and water supply (Hu et al. 2008), which have been recognized as a principal reason for the changes of streamflow in the Huaihe River basin (Zhang et al. 2011a; b), particularly in the non-flood season and during the dry years (Zhang et al. 2010). For effective and sustainable water management in the basin, how and to what extent the changes of the streamflow variability due to reservoir regulations affect hydrological droughts in the basin needs to be investigated.

Several drought indices were developed on the basis of different meteorological and hydrological variables and parameters (Heim 2002; Mishra and Singh 2011) for identification of droughts intensity and surface extent (Karl 1986; Heddinghaus and Sabol 1991; Byun and Wilhite 1999; Shukla and Wood 2008). One of the drought indices, the standardized precipitation index (SPI) (McKee et al. 1993) was commonly used to quantify the meteorological anomalies based on the probability of precipitation for any time scales. It can also be used to detect hydrological droughts in terms of the standardized streamflow index (SSI) (Shukla and Wood 2008). The index provides great flexibility for estimating the relationship and effect between different drought elements.

The objectives of this study were to analyze the impacts of reservoir operation on monthly streamflow alteration and drought characteristics, particularly, evolution of the drought severity affected by two cascade reservoirs with hydrological connection in the Shahe River, one of the tributaries in the upstream of the Huaihe River. Such investigation was executed by the correlation analysis and comparison of statistical features of the drought indices in terms of the standardized series of precipitation, and the inflow, outflow and storage of the two cascade reservoirs.

2 Study area and dataset

2.1 Study area

The Shahe River is one of the tributaries of the Huaihe River, located about mid-way between the Yellow River and Yangtze River (Fig. 1). The basin is characteristic of semi-moist continental warm temperate monsoon climate. The annual mean temperature is between 14 and 16 °C. The highest and lowest temperatures are 44 °C in July and –24 °C in February, respectively. More than 75 % of the basin is mountainous area with an average elevation of 1,000 m (the highest elevation is 2,153 m). The terrain of the catchment tilts from northwest to southeast and the mountainous and hilly areas are located in the western part and flat plain areas are in the east (Fig. 1).

These geographical and climatic features result in the extremely uneven distributions of annual and seasonal rainfall. The annual precipitation is between 650 and 1,400 mm, varying from the largest in the south to the smallest in the north. The temporal distribution of rainfall in the watershed is mainly controlled by the monsoonal cycle. More than half of the annual precipitation falls in summer (from June to August), and 20, 21 and 5 % of the annual precipitation appears in spring (March to May), autumn (September to November) and winter (December to February), respectively (Fig. 2). The storm center is

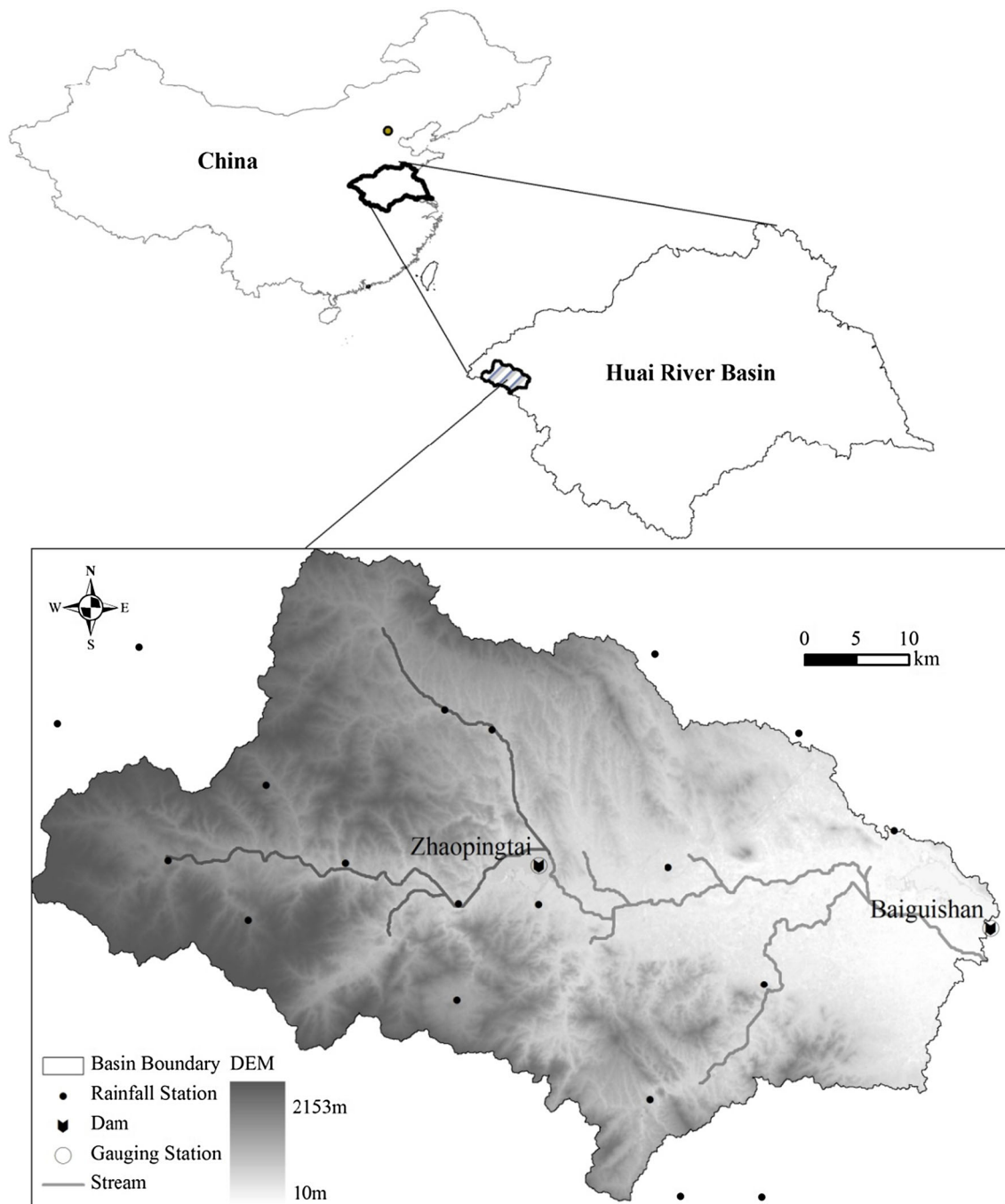


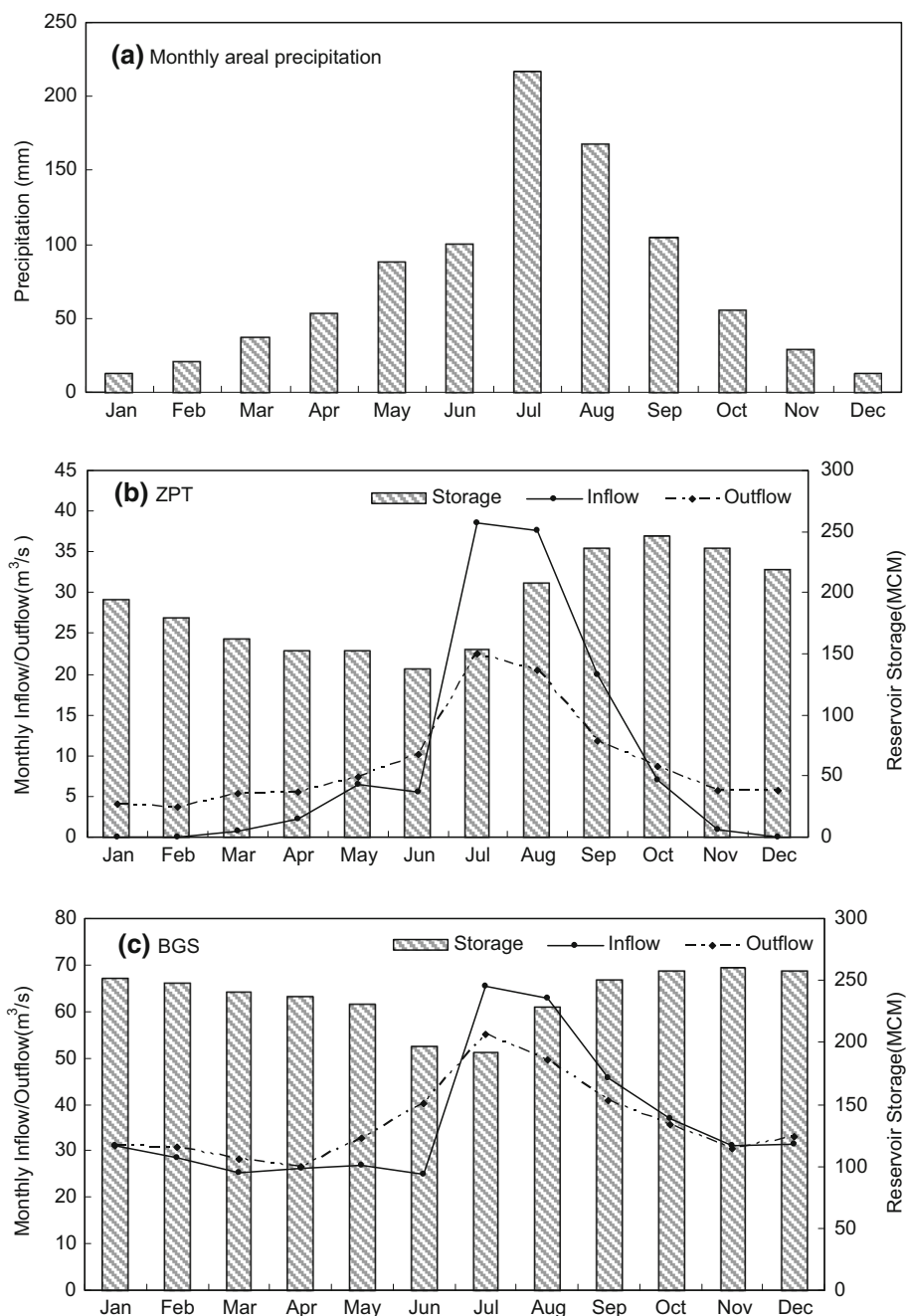
Fig. 1 Location of the study area and spatial distribution of the two reservoirs and gauging stations

located in the upstream of the mountainous area and most floods occur in the summer months. Similar to the rainfall regime, the streamflow of the Shahe River basin is uneven both among months and years. More than half of the annual discharge occurs in wet season from July to September (Fig. 2). The average discharge in the wet year is more than nine times of that in the dry year.

There are two cascade reservoirs located in the main-stream of the Shahe River, where the downstream

BaiGuiShan (BGS) reservoir is 35 km away from the upstream ZhaoPingTai (ZPT) reservoir. ZPT and BGS reservoirs have a gross storage capacity of 713 and 922 million m^3 (MCM), and a draining area of 1,430 and 2,740 km^2 , respectively. Characteristics of the two reservoirs are given in Table 1. The two reservoirs play a large part in the water management for flood control, irrigation, water supply and hydropower generation. Additionally, over 80 small dams and sluices have been built since 1960s

Fig. 2 Average monthly meteorological and hydrological variables from 1967 to 2010 **a** areal precipitation of the basin controlled by BGS reservoir, **b** inflow, outflow and storage of ZPT reservoir, **c** the same as **b** but for BGS reservoir



for storing flood flow for irrigation in the Shahe River basin (Zhang and Zhang 2014a), which significantly influences streamflow processes and the exchange between surface water and groundwater (Zhang et al. 2011c).

2.2 Dataset

Precipitation, reservoir storage and outflow records of the two reservoirs (ZPT and BGS) covering the period from 1967 to 2010 were obtained from the Department of water

resources of Henan Province, China. There are 21 rainfall stations with available daily records in the study area (Fig. 1). Regional precipitation was estimated by the weighted average method of Thiessen polygons in terms of the daily records of all observation stations. Then, monthly precipitation was calculated from the areal average daily value. Based on monthly series of Regional areal precipitation, meteorological variability was analyzed.

Hydrological variations were analyzed based on monthly series of streamflow and reservoir storages. Using the original records of the reservoir outflow and storage,

the reservoir inflow was derived according to the following water balance equations.

$$\begin{cases} (\overline{IQ}_{t,t+\Delta t} - \overline{OQ}_{t,t+\Delta t}) * \Delta t = W_{t+\Delta t} - W_t = \Delta \overline{W}_{t,t+\Delta t} \\ \overline{IQ}_{t,t+\Delta t} = (IQ_t + IQ_{t+\Delta t})/2 \\ \overline{OQ}_{t,t+\Delta t} = (OQ_t + OQ_{t+\Delta t})/2 \end{cases} \quad (1)$$

where, IQ_t and $IQ_{t+\Delta t}$ are the reservoir inflows at time t and $t + \Delta t$, respectively; OQ_t and $OQ_{t+\Delta t}$ are the reservoir outflows at time t and $t + \Delta t$, respectively; $\overline{IQ}_{t,t+\Delta t}$ and $\overline{OQ}_{t,t+\Delta t}$ are the mean values of the inflow and outflow in the period from t to $t + \Delta t$, respectively. Because the time intervals Δt of the recorded reservoir storage and outflow were changed from several minutes to several days, the reservoir storage and outflow records at different time intervals were all transferred into amount in half an hour interval using liner interpolation, and then daily data were further accumulated to monthly scale for inflow derivation and hydrological drought index calculations.

In the inflow calculation, evaporative loss and precipitation recharge into the reservoirs were neglected because the net amount between the annual loss and the annual recharge was only about 0.11 and 0.26 % of the annual storage, or 0.85 and 0.65 % of annual outflow of ZPT and BGS reservoirs, respectively. Note that: this amount was estimated in terms of 1,008 mm of annual potential evaporation in the Huaihe River basin (Rong et al. 2011), 902 mm of annual precipitation in the region controlled by BGS reservoir, and 24 and 70 km² of the maximum areas impounded by ZPT and BGS reservoirs, respectively.

3 Methods

3.1 Calculation of drought index

In this study, the standardized precipitation index (SPI) was used to evaluate meteorological variation; the standardized streamflow index (SSI) of the reservoir inflow and outflow and the standardized reservoir storage index (SRSI) were used for hydrological drought detection.

The SPI, SSI and SRSI are the fits of random variables: precipitation, streamflow and reservoir storage, respectively. Values of these drought indices are influenced by both types of the distribution function and length of the analyzed series. There are a great many literatures about SPI/SSI calculation based on Gamma (McKee et al. 1993; Paulo et al. 2005), lognormal (Zaidman et al. 2002), and Pearson Type III distribution (López-Moreno et al. 2009). In this paper, Gamma distribution was selected for SPI and SSI calculations using a program developed by the US National Drought Mitigation Center at the University of Nebraska-Lincoln (National Drought Mitigation Center

Table 1 Characteristics of the two reservoirs located at the main-stream of the Shahe River

Features	ZPT	BGS
Storage capacity (MCM)	713	922
Annual average flow (MCM)	563	858
Annual average precipitation(mm)	955	903
Dam height (m)	35.5	23.6
Draining area (km ²)	1,430	2,740
Year started to operate	June, 1959	August, 1966
Number of precipitation gauging stations for the reservoir basin	11	21
Number of streamflow gauging stations for the reservoir basin	1	2

UoNL 2000). For SRSI computation, reservoir storage series were normalized using the Box–Cox transformation to obtain standardized series (Box and Cox 1964). For different timescales, moving average series of the analyzed variables at different window widths were used.

(1) The calculation of SPI and SSI

Following three steps were executed to obtain SPI/SSI: First, fit a gamma probability density function to a given frequency distribution of precipitation/streamflow for a specific station. Parameters of the gamma probability density function were estimated for each station at each special time scale of interest and for each month of the year. The maximum likelihood solutions were used to optimally estimate parameters (Thom 1966).

Second, use the optimized parameters to find the cumulative probability of the observed precipitation/streamflow for the given month and timescale for the station in question. Since the gamma function is undefined for $x = 0$, when a precipitation or streamflow contains zeros, the cumulative probability becomes:

$$H(x) = q + (1 - q)G(x) \quad (2)$$

where q is the probability of a zero. If n_0 is the number of zeros in a precipitation/streamflow time series, $q = n_0/n$.

Third, obtain SPI/SSI by the inverse computation using the approach provided by Abramowitz and Stegun (1964).

(2) Calculation of SRSI

The Box–Cox transformation takes the form:

$$Y = \begin{cases} \frac{X^\lambda - 1}{\lambda}, & \lambda \neq 0 \\ \ln(\lambda), & \lambda = 0 \end{cases} \quad (3)$$

where X are the values of the original time series of the reservoir storage, Y are the values of the transformed time

Table 2 Classification of meteorological/hydrological wet and drought states based on SPI/SRI/SRSI interval and the corresponding cumulative probability

State	SPI/SSI/SRSI interval	Cumulative probability
Wet	≥ 1.0	[0.841, 1.0)
Normal	(-1.0, 1.0)	(0.159, 0.841)
Moderate drought	(-1.5, -1.0]	(0.067, 0.159]
Severe drought	(-2.0, -1.5]	(0.023, 0.067]
Extreme drought	≤ -2.0	(0, 0.023]

series, λ is a parameter for the values of the transformed time series.

The transformed values of Eq. (3) were standardized using:

$$Z = \frac{Y - \bar{Y}}{\sigma_Y} \quad (4)$$

where Z is the values of the standardized time series, \bar{Y} is the mean value of the transformed time series, and σ_Y is the standard deviation of the transformed time series. The transformation and the standardization of reservoir storage series in each month were performed. The optimal values of λ for Box–Cox transformation were estimated using the maximum likelihood approach (Press 2007).

3.2 Analysis of drought events

Following the theory of runs, droughts are defined as periods when the drought indices are below a certain threshold (Yevjevich et al. 1967). Each drought event is characterized by its duration, magnitude, time of occurrence and spatial extent. The drought duration (run-length) is the time when the drought index is below the truncation level; drought magnitude (run sum) is the cumulative deviation below the truncation level during that period; the time of drought occurrence is defined as the mean of the onset and the termination date of the drought; the spatial extent is the region suffering from the drought event (Tallaksen et al. 1997; Tallaksen and Van Lanen 2004). For streamflow drought, Zelenhasić and Salvai (1987) defined the truncation level as a certain percentile of the flow duration curve, e.g., 5, 10, or 20 %. McKee et al. (1993) defined the drought triggered by the zero SPI as threshold.

In this paper, two main drought components (drought duration and magnitude) were investigated for measuring drought. Given the objective of the paper, three drought states were defined following McKee et al. (1995), and the thresholds for each meteorological/hydrological drought category and the corresponding cumulative probability were illustrated in Table 2.

Compared with marked variation of meteorological drought, hydrological drought features, particularly after regulation of the reservoirs, show a long and smooth characteristic. Minor droughts with short duration and low magnitude are of little hydrological importance but may disturb the analysis (Fleig et al. 2006). In this paper, SSI and SRSI at a timescale of 6 months were selected for drought event detection. The six months of streamflow and reservoir storage can capture the seasonality variation features well and eliminate the disturbance from the short duration and low magnitude minor droughts.

3.3 Correlation analysis

The outflow series of the two reservoirs represent streamflow regimes after reservoir regulation. The inflow series of the upstream ZPT reservoir represents the natural streamflow regime at the upstream of ZPT reservoir while the inflow of the downstream BGS represents the streamflow regulated by both the upstream reservoir and the local area between the two reservoirs. In this study, the relationship between the standardized reservoir inflow series and outflow series was analyzed by Pearson's correlation coefficient. The correlation coefficient between the continuous monthly series of the standardized inflow and outflow reflects the average impacts of the reservoir operation, and the correlation coefficient between the monthly series of the inflow and outflow at each month reflects the regulation degree in different months.

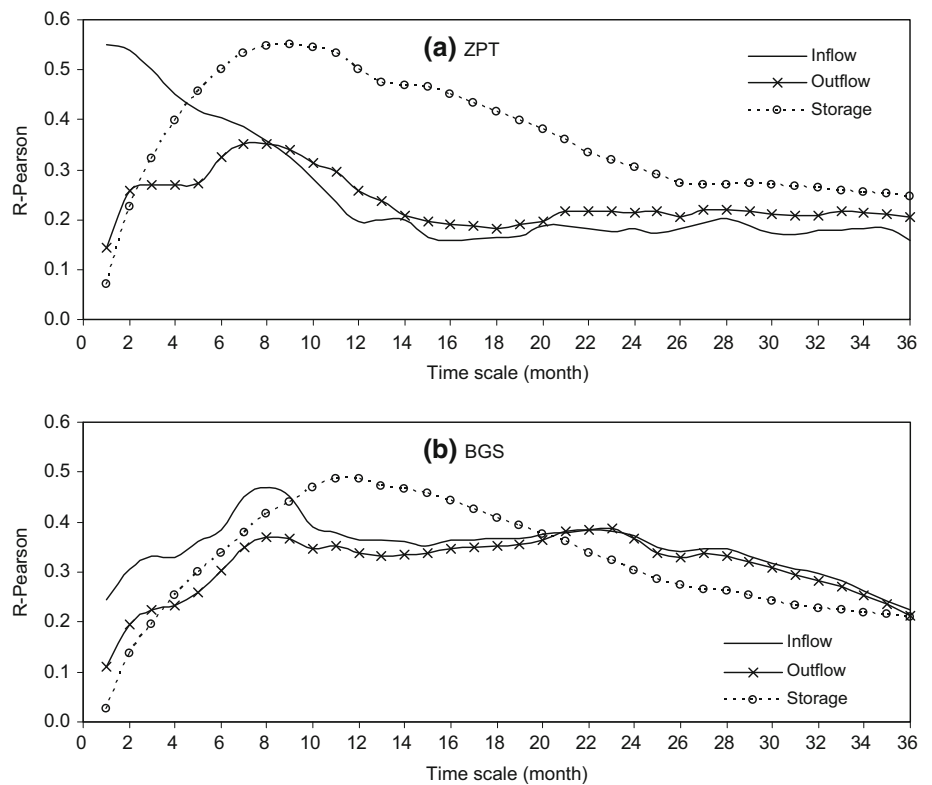
A high level of correlation (approaching 1) indicates that downstream streamflow at the foot of the dam was very similar to that at the reservoir entrance. It implies that the reservoir management did not have a major impact on the river regime. In contrast, a low level of correlation (approaching 0) indicates that the outflow of the reservoir was substantially altered. A negative coefficient indicates an inversion of downstream flow of the reservoir, which is equivalent to a reversal of the natural seasonality of the river (Batalla et al. 2004). Since streamflow variations are related to climate variability, the standardized precipitation series was correlated with the standardized inflow and outflow series to assess response of hydrological variations to meteorological conditions.

4 Results

4.1 Impacts of reservoir operation on monthly average streamflow variations

Since one of the major functions of the reservoirs in the study catchment is flood control, the reservoirs generally diminish the natural seasonal variability of the hydrological

Fig. 3 Correlation between continuous standardized series of hydrological variables (reservoir inflow, outflow and storage) and the standardized series of the regional precipitation at time scales from 1 to 36 months **a** ZPT reservoir, **b** BGS reservoir



regime, leading to a reduction in the high flows in the flood season and an increase in the discharge in the dry season.

Figure 2 shows the average monthly regional precipitation of the basin, and the average monthly inflow, outflow and water storages of ZPT and BGS reservoirs during the period from 1967 to 2010. Generally, the outflow follows the inflow pattern in the seasonal variation, but the outflow is significantly attenuated due to the reservoir regulation. For the upstream ZPT reservoir (Fig. 2b) in months from July to September, the multiyear average monthly inflows exceed outflows, with a 108.3 MCM increase in the reservoir storage from 137.8 MCM at the end of June to 246.1 MCM in October. For the dry and early flood periods from November to next June, outflow exceeds inflow due to release of the storage for irrigation, industrial, ecological and flood control purposes, which leads to decline in reservoir storage.

For BGS reservoir (Fig. 2c), the management pattern is similar to ZPT reservoir but the disparity between inflow and outflow become much smaller, particularly for the flood period during July–September. BGS reservoir refills the storage of 68.9 MCM from 191.6 MCM in July to 260.5 MCM in November, and it is released during the period from December to next June (Fig. 2c). On average, the peak storage of BGS reservoir appears in November, which is delayed for 1 month compared with that of ZPT reservoir. It can be also found that the storage variations of ZPT reservoir are much larger than those of BGS reservoir in

most months of the year except in June, which indicates that the effect of the upstream ZPT reservoir on reducing the natural seasonal variability is more significant than that of the downstream BGS reservoir.

4.2 Response of hydrological anomalies to meteorological variability

A precipitation-based drought index (SPI) was calculated from a regional series of precipitation. The standardized precipitation index (SPI), as well as the standardized streamflow index (SSI) and reservoir storage (SRSI) were commonly used to quantify the meteorological and hydrological anomalies at any time scales. Because monthly streamflow and reservoir storage are commonly related to multi-months precipitation due to catchment regulations and reservoir operations, correlation analysis between monthly SSI/SRSI and SPI at different timescales (from 1 to 36 months) is executed in this study (Fig. 3).

Figure 3 demonstrates the dependence of monthly streamflow and storage on multi-months climatic conditions that may cause longlasting hydrological anomalies. This longlasting effect can be distinguished by the time lag of streamflow anomalies in response to meteorological variability, which is represented by the time scale with the largest correlation coefficient R in Fig. 3. It can be seen that the time lag generally becomes longer for the inflow, outflow and storage series at the downstream BGS in

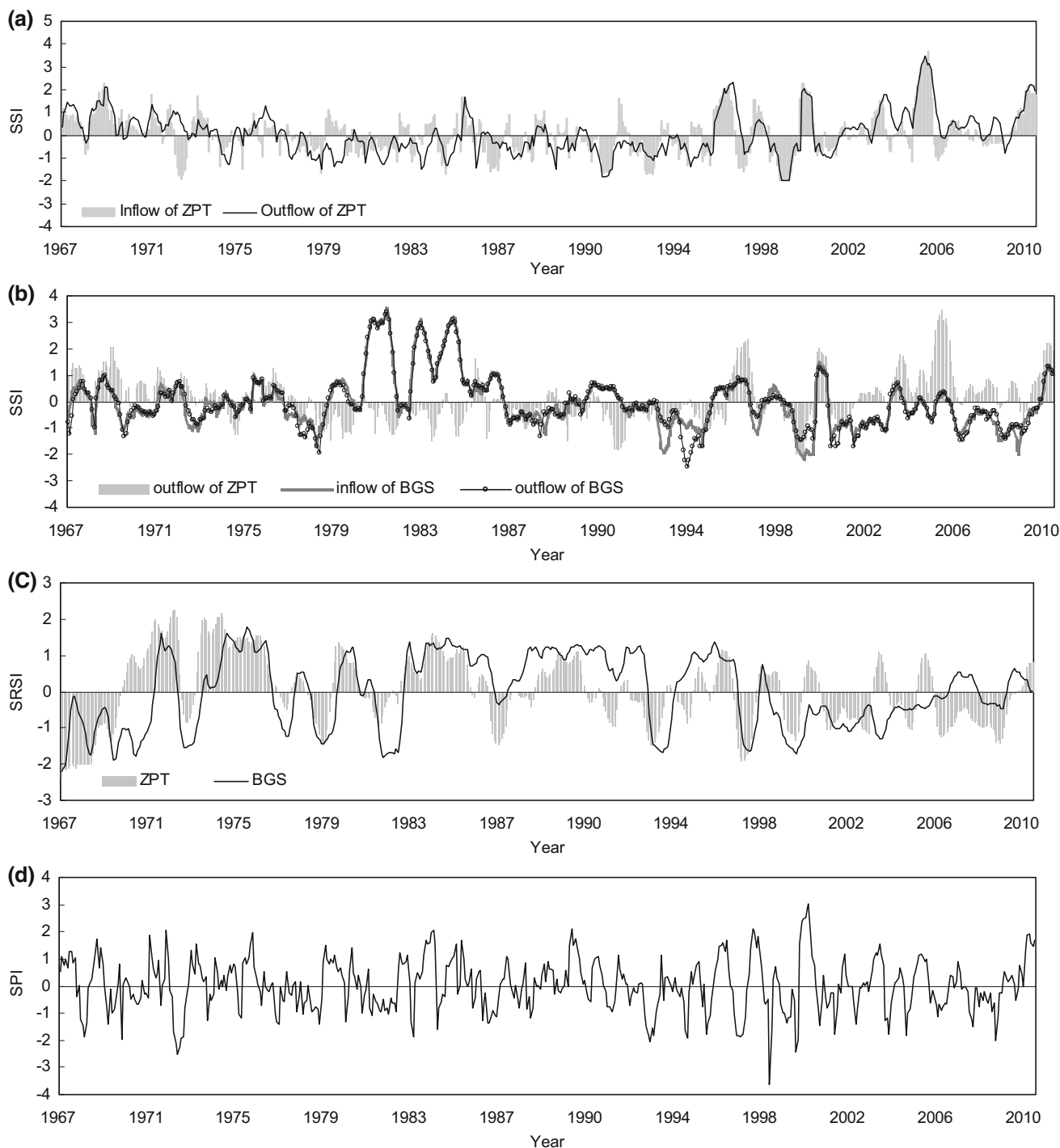


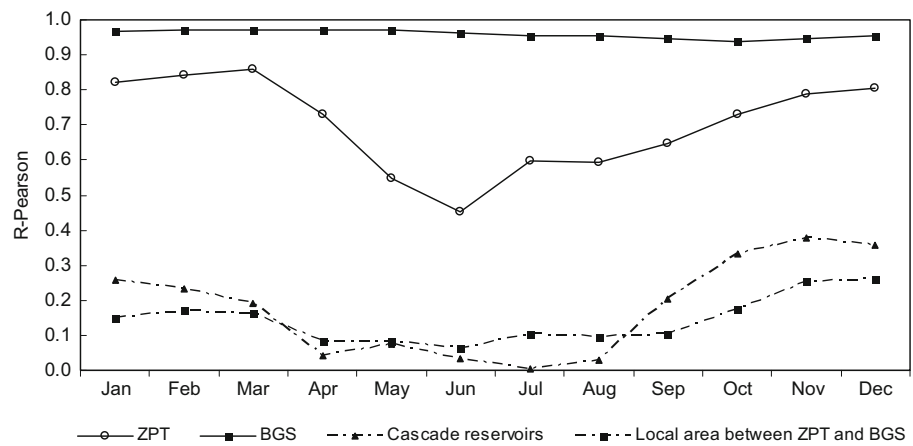
Fig. 4 Evolution of the standardized series of **a** inflow and outflow of ZPT reservoir, **b** outflow of ZPT reservoir and inflow and outflow of BGS reservoir, **c** reservoir storage of ZPT and BGS reservoir, **d** areal

precipitation of the basin controlled by BGS reservoir at a 6-month time scale during 1967–2010

comparison with those of the upstream ZPT (Fig. 3a vs. b). It is also found that the reservoir regulation extends the time lag of the outflows, compared with the time lag of the inflows (inflow vs. outflow in Fig. 3). For the upstream ZPT reservoir, the highest correlation coefficient ($R = 0.55$) is

found at a short timescale of 1 month while the highest correlation coefficients of 0.35 are obtained at a longer timescale of 7–8 months for the outflow (Fig. 3a). The 6–7 months of the outflow lagging behind the inflow SSI are resulted from the ZPT reservoir regulation on significant

Fig. 5 Correlation coefficients between inflow and outflow for ZPT and BGS reservoir, between ZPT inflow and BGS outflow (cascade reservoirs), and between ZPT outflow and BGS inflow (the local area between ZPT and BGS) based on the standardized series (SSI) at a 6-month time scale during 1967–2010



attenuation of the streamflow variations in that it raises the low inflow in the drought period and decreases the high inflow in the wet period (Fig. 2b). However, this longlasting effect is not significant for the downstream BGS reservoir where the monthly inflow and outflow (SSI) are highly correlated with precipitation at time scales at 8 and 8–9 months, respectively (Fig. 3b). The similar pattern of the correlation coefficients for the inflow and outflow SSIs indicates that the regulation of the downstream BGS has little effect on the inflow variations (Fig. 2c) because a large portion of the BGS inflow comes from the regulated outflow by the upstream ZPT reservoir.

The time lags of the storage SRSI in response to meteorological SPI are longest in comparison with the inflow and outflow series. The time lags correspond to the highest correlation coefficient at the time scale of 8–10 months for the storage of ZPT and 11–12 months for the storage of BGS (Fig. 3b). The longest lags relate to anomalies of the monthly distribution between precipitation and the storage (Fig. 2), e.g., storage decrease versus precipitation increase from November to June of next year for ZPT reservoir, and the similar pattern of the monthly distribution between precipitation and the storage for BGS reservoir.

4.3 Effects of reservoir regulation on hydrological drought evolution

The above analysis indicates the multi-months dependence of streamflow on precipitation variability. The evolution of the variations of SPI/SSI/SRSI for the monthly successive series using moving average in 6 months during 1967–2010 is shown in Fig. 4. It indicates that variation of the meteorological drought index (SPI) is most intensive and SRSI is relatively stable among all the drought indices. Additionally, the inflow SSI varies more frequently than the outflow SSI does. Variations of the inflow/outflow SSI

and SRSI for the downstream BGS are reduced, compared to those of the upstream ZPT.

Correlation between the inflow and outflow series is executed to quantify effects of the reservoir regulation on the evolution of hydrological drought indices (Fig. 5). For the upstream ZPT reservoir, the correlation coefficient between the successive series of inflow and outflow (SSI) during 1967–2010 is 0.70 for the mean value (the line of ZPT in Fig. 5). It is lower in the pre-flood and flood period from May to September (Fig. 5) when ZPT reservoir begins operation for flood prevention (Fig. 2). For the downstream BGS reservoir, the evolution pattern of outflow SSI matches that of inflow very well during 1967–2010 (Fig. 4b). The correlation coefficient between the inflow and outflow SSI series is as high as 0.95 and remains relative steady among months (Fig. 5). It indicates that regulation of BGS reservoir has less effect on the inflow processes and the drought evolution. However, for the local area between the two reservoirs, anomalies between the outflow SSI of ZPT and the inflow SSI of BGS reservoir are marked (Fig. 4b), particularly during the successive drought period of 1979–1987 and the successive wet period of 2000–2010. The correlation coefficient between the ZPT outflow and BGS inflow SSI reduces to 0.14 for the monthly mean and 0.26 for the highest in December (Fig. 5). It means that the upstream outflow from ZPT reservoir has been dramatically altered throughout the year as it enters the local area, possibly by numerous small dams and sluice gates, and water consumption for irrigation.

4.4 Effects of reservoir regulation on drought duration and magnitude

Following the status category criteria shown in Table 2, drought events can be detected by the threshold of SSI and SRSI less than -1.0 (including moderate, severe and

Table 3 Statistics of drought events during the period from 1967 to 2010

Drought element	Fre.	Total dur. (months)	Mean dur. (months)	Max. dur. (month)	Total mag.	Mean mag.	Max. mag.
Precipitation	34	71	2.09	7	−108.78	−3.20	−12.29
Inflow of ZPT reservoir	23	60	2.61	9	−87.81	−3.82	−16.21
Outflow of ZPT reservoir	18	48	2.67	7	−65.17	−3.62	−12.97
Inflow of BGS reservoir	17	59	3.47	11	−82.00	−4.82	−20.51
Outflow of BGS reservoir	15	68	4.53	14	−93.51	−6.23	−23.60
Storage of ZPT reservoir	13	80	6.15	20	−119.50	−9.19	−42.50
Storage of BGS reservoir	13	110	8.46	21	−155.66	−11.97	−29.09

Fre. drought frequency, *Total dur.* total drought duration, *Mean dur.* mean drought duration, *Max. dur.* the maximum drought duration, *Total mag.* total drought magnitude, *Mean mag.* mean drought magnitude, *Max. Mag.* the maximum drought magnitude

extreme drought categories). Table 3 lists the statistics of the drought indices during the period from 1967 to 2010: frequency, total duration (number of months of drought events), mean duration (total duration divided by frequency), maximum duration (the maximum duration of drought events), total magnitude (accumulated deficit below the threshold of -1.0), mean magnitude (total magnitude divided by total duration), and maximum magnitude (the maximum magnitude of drought events).

Statistical results in Table 3 show the characteristics of drought elements in terms of precipitation, inflow and outflow and storage. The drought frequencies become lower and lower for the elements in the order of precipitation, inflow and outflow, and reservoir storage (Table 3) because of attenuation effects of the catchment regulation on precipitation and reservoir regulation on streamflow (Fig. 4). However, the regulations significantly extend the mean and maximum drought durations since the reservoirs are maintained at the low flow in a long time period, with a reduction in or even elimination of winter and spring high outflows (López-Moreno et al. 2009) (Fig. 4). In terms of the total durations and the total magnitudes, the precipitation droughts are longer and stronger than the inflow and outflow droughts, but they are shorter and weaker than those of reservoir storage.

For the upstream ZPT reservoir, the droughts for the outflow after the reservoir regulation are significantly mitigated in terms of most statistical values, e.g., lower frequency, shorter (total and maximum) duration, and smaller (total, mean and maximum) magnitude of the outflow than those of the inflow. However, different results are obtained for the downstream BGS reservoir regulation on drought features by comparisons of the BGS inflow and outflow droughts (Table 3). Although the changes between the inflow and outflow are not marked and the frequency of the outflow droughts after the BGS reservoir regulation decreases a little, the outflow drought duration is still extended and the drought magnitude is amplified compared

with drought statistics of BGS inflow. As the reservoir inflow shifts to the outflow, the total drought duration is extended from 59 to 68 months, the mean from 3.47 to 4.53 months and the maximum duration from 11 to 14 months. Meanwhile, the absolute value of the total drought magnitude is amplified from 82.00 to 93.51, the mean from 4.82 to 6.23 and the maximum value from 20.51 to 23.6.

The different behaviors of the drought evolution from the input to the output of the two reservoirs indicate whether the reservoirs mitigate or amplify the drought conditions depends on the extent of the low flow alterations by the reservoir regulation, e.g., mitigating droughts by the upstream ZPT reservoir as it markedly raises the low flow (Fig. 2b) and amplifying droughts by the downstream BGS reservoir as it raises low flow a little (Fig. 2c).

The regulation of the local area between the two cascade reservoirs on drought events are estimated by comparing the drought indices of the ZPT outflow (the third row in Table 3) and the BGS inflow (the fourth row in Table 3). It shows that the drought becomes severe in that the local area regulation extends the drought duration and amplifies the magnitude. The enhanced drought corresponds to a reduction in high flow, particularly after 1990 (Fig. 4b) due to the strong regulation in the local area in which a large portion is occupied by the cultivated plain area and numerical dams have been built for irrigation.

The characteristics of storage drought events are summarized as the sixth and seventh row for the upstream ZPT and the downstream BGS reservoirs, respectively, in Table 3. Both reservoirs in terms of SRSI have suffered from droughts at the same frequency (13 times) in the study period, but droughts of BGS reservoir may be more serious with longer duration and larger magnitude.

According to the classification thresholds in Table 2, moderate, severe and extreme droughts are further detected and total durations of each drought category are shown in Table 4. As the total duration of drought events of the

Table 4 Total duration of each drought category (unit: months) and its proportion to the total duration of drought events (in the brackets) for each drought element during 1967–2010

Drought element	Moderate drought (%)	Severe drought (%)	Extreme drought (%)
Precipitation	40 (56)	24 (34)	7 (10)
Inflow of ZPT reservoir	34 (57)	20 (33)	6 (10)
Outflow of ZPT reservoir	38 (79)	5 (10)	5 (10)
Inflow of BGS reservoir	40 (68)	15 (25)	4 (7)
Outflow of BGS reservoir	54 (79)	11 (16)	3 (4)
Storage of ZPT reservoir	54 (68)	10 (13)	16 (20)
Storage of BGS reservoir	65 (59)	42 (38)	3 (3)

meteorological and hydrological elements are not consistent (Table 3), proportions of each drought category to the total duration for the drought elements are also shown in Table 4 (in the brackets after the drought duration).

Table 4 shows that the catchment and reservoir regulations on precipitation and streamflow alter the drought compositions. Compared with precipitation droughts, the severe and extreme droughts of streamflow (inflows and outflows of the two reservoirs) are reduced, with shorter durations and smaller proportions to the total durations. Compared with the drought duration of the inflow in Table 4, the severe and extreme droughts of the outflow are shortened but the moderate drought is extended after the reservoir regulation. Moreover, regulation of the upstream ZPT reservoir on the reduction of the severe drought is much more significant than that of the downstream BGS reservoir.

For the storage droughts of the two reservoirs (the sixth and seventh rows in Table 4), proportions of extreme droughts are 20 and 3 % for the upstream and downstream reservoir, respectively. Among all these extreme droughts proportions for different drought elements, the upstream reservoir is the highest but the downstream reservoir is the lowest. In the study period (1967–2010), the storage droughts of the upstream reservoir concentrates on the moderate and extreme droughts while the droughts of the downstream reservoir concentrates on the moderate and severe droughts.

5 Conclusions

Reservoir functions generally include flood control, electric power generation and water supply, etc. In the subtropical monsoon climate areas, reservoirs reduce or even eliminate high flows by storing water in reservoir in the flood season, and increase low flows by releasing the stored water for water supply. Such streamflow regulation changes streamflow and thus hydrological drought characteristics.

However, in the case of cascade reservoirs, the impacts of each reservoir may be different due to various geographical and topographical characteristics and water management activities. In this study, two reservoirs in the upper and lower areas of the Shahe River basin, one of the tributaries in the headwaters of the Huaihe River basin, were selected for the investigation. Based on standardized series of regional precipitation, inflow/outflow of the reservoirs and reservoir storage, correlation analysis and comparison of statistical features of the drought indices were conducted.

Relationships between hydrological and meteorological anomalies reflect the response of hydrological variables to climatic variations due to catchment and reservoir regulations. As expected, the reservoir regulation attenuates the outflow and extends the time lags between the hydrological and meteorological anomalies. These effects are particularly more marked for the upstream ZPT reservoir than the downstream ZPT. The results indicate that for the upstream reservoir, the time lag of less than a month between the inflow and the meteorological variability extends to 6–7 months after the reservoir regulation. For the downstream BGS reservoir, the time lag extends to 7 and 7–8 months for the inflow and outflow correlated with precipitation, respectively. Therefore, the longlasting effect of the downstream reservoir regulation on the inflow is not so significant as the upstream reservoir.

The attenuation of the streamflow by the reservoirs significantly reduces drought frequency. However, different extents of the streamflow altered by the upstream and downstream reservoirs behave differently in mitigating or amplifying the drought conditions in terms of index value below -1.0 . Under the regulation of the upstream reservoir, the streamflow drought severity was significantly decreased, with lower frequency, shorter duration and smaller magnitude of the outflow, compared with inflow droughts. On the contrary, the overall drought severity of the streamflow of the downstream reservoir was increased, with extension of the duration and amplification of the magnitude of the outflow. Moreover, regulation of the local area between the two reservoirs significantly increases drought severity, which is indicated by the extended duration and amplified magnitude of the downstream reservoir inflow droughts, compared with the outflow released from the upstream reservoir.

The mitigation/amplification of the overall drought features by the upstream/downstream reservoir does not mean the reservoirs influence drought severity in varying patterns. The results show that the two reservoirs have the same regulation functions in shortening the severe and extreme droughts and expanding the moderate drought. The mitigation of the overall drought features by the upstream reservoir primarily concentrates on reduction in the severe drought while amplification of the overall

drought features by the downstream reservoir concentrates on increase in moderate drought.

Compared with precipitation and streamflow drought indices, reservoir storage droughts show less frequent, longer duration and larger magnitude. These features correspond to the reservoir regulation functions in the seasonal scale, increasing storage in the dry period and decreasing storage in the flood period. However, the varying degrees of the regulation of the two reservoirs lead to different drought features of the storages as well. The stronger regulation of the upstream reservoir on the inflow means larger variations of the storage series, which increases the extreme drought magnitude and duration. On the contrary, the weaker regulation of the downstream reservoir with less variations of the storage decreases the extreme drought and increases the moderate and severe droughts in the meantime.

These analysis results will benefit understanding of the behavior of river flow variability and its effect on hydrological drought severity due to reservoir regulation, particularly for the cascade reservoirs with hydrological connection. They help us make reservoir management strategies in an effective and sustainable view, which will be beneficial for water utilization and flood and drought mitigation in the basin.

Acknowledgments The research is financially supported by the National Natural Science Foundation of China (Grant No. 51190090, 40930635, 51079038). The manuscript was edited by Jiayi Chen. Thanks to the editor and two anonymous reviewers for their constructive comments on the earlier manuscript, which led to a great improvement of the paper.

References

- Abramowitz M, Stegun IA (1964) Handbook of mathematical functions: With formulars, graphs, and mathematical tables, vol 55. DoverPublications. com
- Batalla RJ, Gomez CM, Kondolf GM (2004) Reservoir-induced hydrological changes in the Ebro River basin (NE Spain). *J Hydrol* 290(1):117–136
- Box GE, Cox DR (1964) An analysis of transformations. *J R Stat Soc Ser B (Methodol)*:211–252
- Byun H-R, Wilhite DA (1999) Objective quantification of drought severity and duration. *J Clim* 12(9):2747–2756
- Dracup JA, Lee KS, Paulson EG Jr (1980) On the definition of droughts. *Water Resour Res* 16(2):297–302
- Fleig AK, Tallaksen LM, Hisdal H, Demuth S (2006) A global evaluation of streamflow drought characteristics. *Hydrol Earth Syst Sci* 10(4):535–552
- Heddinghaus TR, Sabol P (1991) A review of the Palmer drought severity index and where do we go from here. In: Proceedings 7th conference on applied climatology, pp 242–246
- Heim RR Jr (2002) A review of twentieth-century drought indices used in the United States. *B Am Meteorol Soc* 83(8):1149–1165
- Hu W-W, G-x Wang, Deng W, S-n Li (2008) The influence of dams on ecohydrological conditions in the Huaihe River basin, China. *Ecol Eng* 33(3):233–241
- Karl TR (1986) The sensitivity of the Palmer drought severity index and Palmer's Z-index to their calibration coefficients including potential evapotranspiration. *J Appl Meteorol Clim* 25(1):77–86
- Li W, Rogers K, Ling J, Saintilan N (2011) The impacts of river regulation and water diversion on the hydrological drought characteristics in the Lower Murrumbidgee River, Australia. *J Hydrol* 405(3):382–391
- Liang K, Liu C, Liu X, Song X (2013) Impacts of climate variability and human activity on streamflow decrease in a sediment concentrated region in the Middle Yellow River. *Stoch Environ Res Risk Assess* 27(7):1741–1749. doi:10.1007/s00477-013-0713-2
- López-Moreno JI, Vicente-Serrano SM, Beguería S, García-Ruiz JM, Portela MM, Almeida AB (2009) Dam effects on droughts magnitude and duration in a transboundary basin: the Lower River Tagus, Spain and Portugal. *Water Resour Res* 45(2):W02405. doi:10.1029/2008WR007198
- López-Moreno JI, Vicente-Serrano SM, Zabalza J, Beguería S, Lorenzo-Lacruz J, Azorin-Molina C, Morán-Tejeda E (2013) Hydrological response to climate variability at different time scales: a study in the Ebro basin. *J Hydrol* 477:175–188
- Lorenzo-Lacruz J, Vicente-Serrano SM, López-Moreno JI, Beguería S, García-Ruiz JM, Cuadrat JM (2010) The impact of droughts and water management on various hydrological systems in the headwaters of the Tagus River (central Spain). *J Hydrol* 386(1–4):13–26
- McKee TB, Doesken NJ, Kleist J (1993) The relationship of drought frequency and duration to time scales. In: Proceedings of the 8th conference on applied climatology, vol 22. American Meteorological Society Boston, MA, pp 179–183
- McKee TB, Doesken NJ, Kleist J (1995) Drought monitoring with multiple time scales. In: Preprints, 9th conference on applied climatology, Dallas, Texas, January 15–20, pp 233–236
- Mishra AK, Singh VP (2011) Drought modeling—A review. *J Hydrol* 403(1):157–175
- National Drought Mitigation Center UoNL (2000) Program to calculate standardized precipitation index. <http://drought.unl.edu/MonitoringTools/DownloadableSPIProgram.aspx>
- Paulo A, Ferreira E, Coelho C, Pereira L (2005) Drought class transition analysis through Markov and Loglinear models, an approach to early warning. *Agr Water Manage* 77(1):59–81
- Press WH (2007) Numerical recipes: the art of scientific computing, 3rd edn. Cambridge University Press, New York
- Rong Y, Zhou Y, Wang W (2011) Analysis of pan evaporation changes in the Huaihe River basin. *Adv water Sci (in Chinese)* 22(1):15–22
- Shukla S, Wood AW (2008) Use of a standardized runoff index for characterizing hydrologic drought. *Geophys Res Lett* 35(2):L02405. doi:10.1029/2007gl032487
- Tallaksen LM, Van Lanen HA (2004) Hydrological drought: processes and estimation methods for streamflow and groundwater, vol 48. Elsevier, Amsterdam
- Tallaksen LM, Madsen H, Clausen B (1997) On the definition and modelling of streamflow drought duration and deficit volume. *Hydrol Sci J* 42(1):15–33
- Thom HCS (1966) Some methods of climatological analysis world meteorological organization (WMO), Geneva
- Vicente-Serrano SM, López-Moreno JI (2005) Hydrological response to different time scales of climatological drought: an evaluation of the standardized precipitation index in a mountainous Mediterranean basin. *Hydrol Earth Syst Sci Dis* 9(5):523–533
- Vogel RM, Kroll CN (1992) Regional geohydrologic-geomorphic relationships for the estimation of low-flow statistics. *Water Resour Res* 28(9):2451–2458. doi:10.1029/92wr01007

- Wang X (2000) Characteristics analysis of rainfall in the upper reaches of the Shaying River Basin (in Chinese with English abstract). *Hydrology* 20(1):53–55
- Yevjevich V, Ingenieur J, Ingénieur Y, Engineer Y (1967) An objective approach to definitions and investigations of continental hydrologic droughts. Colorado State University Fort Collins
- Zaidman M, Rees H, Young A (2002) Spatio-temporal development of streamflow droughts in north-west Europe. *Hydrol Earth Syst Sci Dis* 6(4):733–751
- Zecharias YB, Brutsaert W (1988) The influence of basin morphology on groundwater outflow. *Water Resour Res* 24(10):1645–1650. doi:[10.1029/WR024i010p01645](https://doi.org/10.1029/WR024i010p01645)
- Zelenhasić E, Salvai A (1987) A method of streamflow drought analysis. *Water Resour Res* 23(1):156–168
- Zhang D, Zhang Y (2014) Impacts of urbanization and dams on river runoff in the Shaying river basin. *South North Water Transf Water Sci Technol* 12(4):5–10 (in Chinese)
- Zhang Y, Xia J, Liang T, Shao Q (2010) Impact of water projects on river flow regimes and water quality in Huai River Basin. *Water Resour Manag* 24(5):889–908
- Zhang Q, Singh VP, Sun P, Chen X, Zhang Z, Li J (2011a) Precipitation and streamflow changes in China: changing patterns, causes and implications. *J Hydrol* 410(3–4):204–216
- Zhang Y, Shao Q, Xia J, Bunn SE, Zuo Q (2011b) Changes of flow regimes and precipitation in Huai River Basin in the last half century. *Hydrol Process* 25(2):246–257
- Zhang Y, Xia J, Chen X et al (2011c) Study and application of hydrologic and environmental effects in the highly regulated river basins. China Water Power Press, Beijing (in Chinese)
- Zhang D, Liu X, Liu C, Bai P (2013) Responses of runoff to climatic variation and human activities in the Fenhe River, China. *Stoch Environ Res Risk Assess* 27(6):1293–1301. doi:[10.1007/s00477-012-0665-y](https://doi.org/10.1007/s00477-012-0665-y)
- Zhang Q, Xiao M, Liu C-L, Singh V (2014b) Reservoir-induced hydrological alterations and environmental flow variation in the East River, the Pearl River basin, China. *Stoch Environ Res Risk Assess*:1–13. doi:[10.1007/s00477-014-0893-4](https://doi.org/10.1007/s00477-014-0893-4)