Theoretical and Applied Climatology (2019) 137:1529–1539
https://doi.org/10.1007/s00704-018-2683-2

ORIGINAL PAPER

Determination of drought limit water level of importing reservoir in inter-basin water transfer project under changing environment

Jiezhao Wu[1] · Fawen Li[1] · Yong Zhao[2] · Runxiang Cao[1]

Received: 4 June 2018 / Accepted: 15 October 2018 / Published online: 31 October 2018

Abstract
Drought occurrence and its related impacts are a major concern in many basins throughout the world. Reservoirs play a very important role in drought resistance. Compared with the reservoir flood limit water level, the drought limit water level belongs to a new concept. This paper took the Yuqiao reservoir as the study area and proposed a new method to determine the drought limit water level under changing environment. Firstly, the Mann-Kendall (M-K) method and cluster analysis method were employed to test the trend and change point of the series based on the runoff series of Yuqiao reservoir. On this basis, the runoff frequency curve and design runoff process under current condition were obtained by Pearson-III frequency analysis. Secondly, copula function was used to analyze the synchronous-asynchronous encounter probability of rich-poor runoff of Yuqiao reservoir and Panjiakou reservoir. The available transferred volume of Yuqiao reservoir in dry year was analyzed. Finally, according to the runoff and available transferred volume, the total inflow of Yuqiao reservoir in dry season was calculated. Combining water demand and total inflow of Yuqiao reservoir, the drought limit water level was calculated by month to month. The study results can provide necessary technique support for reservoir drought emergency management.

1 Introduction

In recent decades, intense drought events have been observed on all continents with high economic and social costs (Mishra and Singh 2010). Droughts are the world's costliest natural disasters, causing an average US$ 6–US$ 8 billion in global damages annually and collectively affecting more people than any other form of natural disaster (Wilhite and Svoboda 2000). Dams are important tools for managing water resources under scarcity conditions because they increase water availability during drought periods (Oweis and Hachum 2006; Wisser et al. 2010). Therefore, reservoirs play a key role in modifying the distribution of water over space and time (Wurbs 1993; Nandalal and Sakthivadivel 2002), guaranteeing a more regular streamflow distribution (Komatsu et al. 2010).

The characteristic levels of reservoir include dead water level, normal water level, flood limit water level, and design flood level. The various water levels undertake different tasks in different periods. The key level for control flood is the flood limit water level, about which there are many research achievements at present (Zhou et al. 2009; Li et al. 2010; Chen et al. 2013; Ding et al. 2013; Zhou et al. 2014; Jiang et al. 2015). However, among reservoir characteristic levels, there is no key control level for drought resistance. The drought control water level was first proposed as a new concept by China Flood Control and Drought Relief Headquarters Office in 2012. The new concept of drought control water level is called the drought limit water level. When reservoir water level continues to be low and inflow continues to be less than normal, urban and rural life, industrial and agricultural production, and ecological environment are affected by the water shortage in the water supply zone of the reservoir. That is, there is a potential drought threat, and the early warning limit water level for initiating drought relief is taken as drought limit water level. At present, the research on drought limit water level is still in the initial stage with few

---

✉ Fawen Li
lifawen@tju.edu.cn

✉ Yong Zhao
zhaoyong@iwhr.com

[1] State Key Laboratory of Hydraulic Engineering Simulation and Safety, Tianjin University, Tianjin 300072, People's Republic of China

[2] State Key Laboratory of Simulation and Regulation of Water Cycle in River Basin, China Institute of Water Resource and Hydropower Research, Beijing 100038, People's Republic of China

achievements. Liu (2014) proposed the hydrological index system of drought early warning based on analysis cause and process of drought, and put forward the concept and determination method of drought limit water level. Sun (2014) analyzed the changes of inflow and water consumption (including industry, agriculture, life, and ecology water use) based on the data of Shimen reservoir station, and discussed the drought limit water level under the condition of meeting the water demand. Han et al. (2015) determined the drought limit water level of Changma reservoir based on the water level corresponding to the sum of the dead capacity and the maximum of monthly water supply. Liu et al. (2015) discussed the principles, steps, and methods of drought limit water level determination, and determined the drought limit water level of Dahuofang reservoir in Liaoning Province. Zhang (2016) discussed the determination method of the drought limit water level of Chaihe reservoir based on the survey data of inflow and water supply. Peng et al. (2016) established an optimal control model of drought limit water level for multi-year regulating storage reservoir to achieve the greatest benefit of multi-year water supply.

The above studies on the determination of drought limit water level were mainly based on the concept of the drought limit water level proposed by China Flood Control and Drought Relief Headquarters Office and ignored the influence of reservoir environment change on the inflow. Meanwhile, these researches were mainly aimed at a single reservoir, and researches on inter-basin reservoirs have not been reported. However, with the rapid development of regional socio-economy, inter-basin water transfer projects will be more and more, which have become an important means to alleviate regional water shortage all over the world (Jain et al. 2005; Wan et al. 2018). After the inter-basin water transfer, the inflow condition of the importing reservoir will change, and when calculating the inflow, the transferred water should be taken into account.

The paper selected Yuqiao reservoir as the typical study area. Yuqiao reservoir is an important water supply source for Tianjin city and is crucial to its social and economic development. As the water output from Yuqiao reservoir basin cannot meet the water supply of Tianjin, the water from Panjiakou reservoir is transferred into Yuqiao reservoir through water diversion project. At the same time, with the change of environment, the runoff into Yuqiao reservoir changed significantly. Therefore, Yuqiao reservoir basically covers all the conditions that the general reservoir faces in the process of water supply. So, Yuqiao reservoir as a case is suit to analyze the water supply problems in the changing environment.

This paper analyzed the trend and variability of the long-series runoff of Yuqiao reservoir, and obtained the runoff frequency curve and design runoff process under the current situation. Besides, the paper analyzed the transferable water volume based on the synchronous-asynchronous encounter probability of rich-poor runoff and calculated the total inflow of Yuqiao reservoir. On this basis, combined with water demand, the drought limit water level was calculated by month to month.

2 Study area

Tianjin city is located in east longitude 116° 42′ 05″~118° 03′ 31″ and north latitude 38° 33′ 57″~40° 00′ 07″. It is 172 km from the south to north and 104 km from east to west. Yuqiao reservoir is located in Ji County of northern Tianjin (Fig. 1), where the average annual precipitation is 750 mm and the average annual evaporation is 1000 mm. Yuqiao reservoir is the largest reservoir in Tianjin with a total storage capacity of 15.6×10^8 m^3, a flood control storage capacity of 12.6×10^8 m^3, an active storage capacity of 3.85×10^8 m^3, a dead storage capacity of 0.36×10^8 m^3, a flood limit water level of 19.87 m, and a normal water level of 21.16 m at the end of the flood season. Since the Luanhe-Tianjin Diversion Project was put into operation in 1983, Yuqiao reservoir has played an important role in adjusting and storing water, and also undertakes the water supply for domestic and production use in Tianjin. The Panjiakou reservoir, located in Hebei Province of Northern China, was built at the outlet of the mountainous region of the Luanhe River Basin, which is part of the Haihe River Basin. Panjiakou reservoir has a capacity of 29.3×10^8 m^3, where the flood control storage is 9.7×10^8 m^3 and the active storage capacity is 19.5×10^8 m^3. Yuqiao reservoir imports water from Panjiakou reservoir in Hebei Province and supplies 10×10^8 m^3 water to Tianjin every year. The cumulative water supply to Tianjin is more than 220×10^8 m^3 since 1983.

3 Data and methods

3.1 Data

Annual discharge was available from 1960 to 2006 in both Yuqiao and Panjiakou reservoir watersheds. Annual runoff data were respectively recorded at Yuqiao reservoir and Panjiakou reservoir hydrological stations. The runoff data of Panjiakou reservoir was provided by the Hydrology and Water Resource Survey Bureau of Hebei Province. The runoff data, characteristic water levels, and water level-capacity relation curve of Yuqiao reservoir were obtained from the Yuqiao Reservoir Management Agency. The average monthly water consumption data comes from Tianjin Water Resources Bulletin.

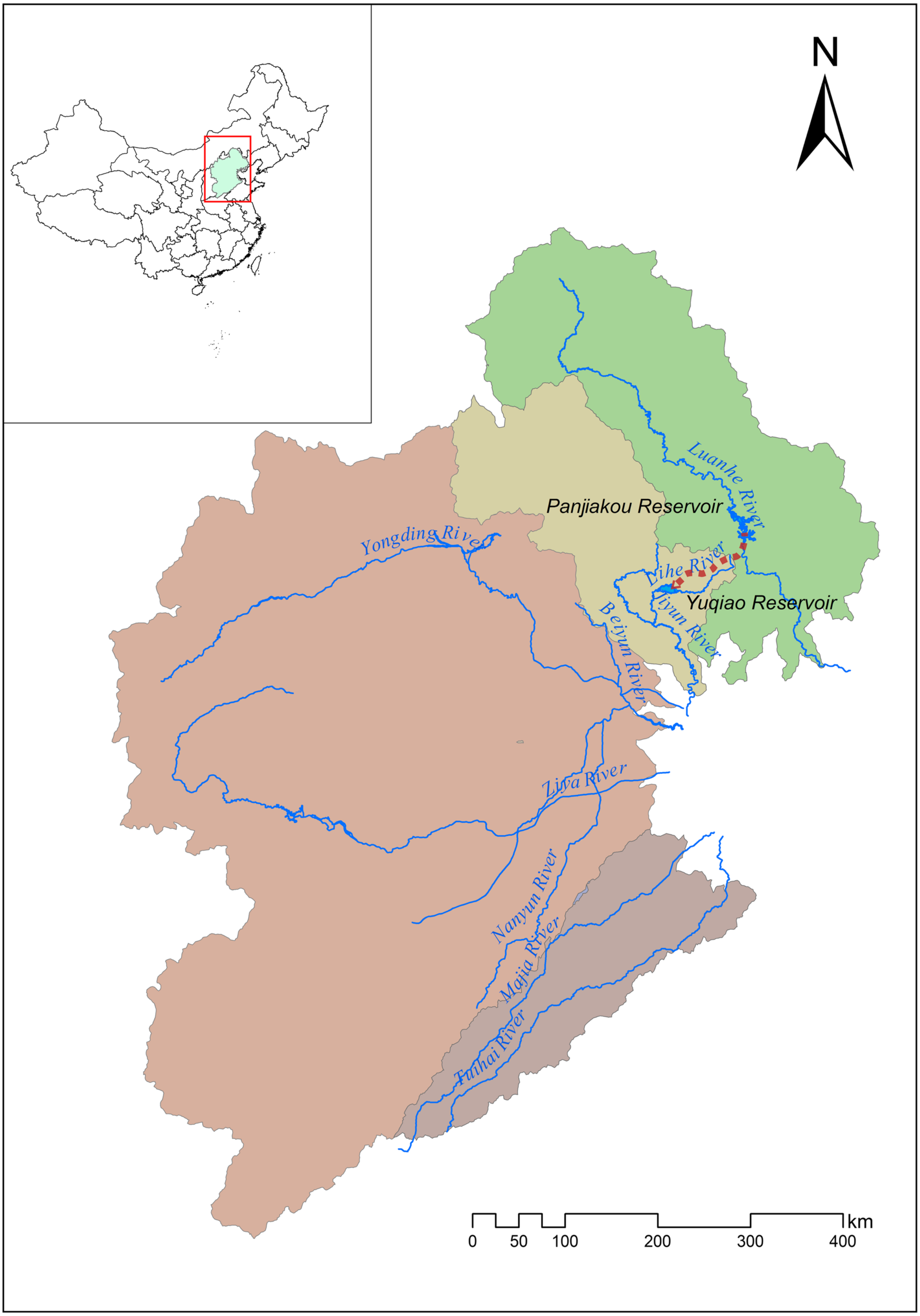

Fig. 1 The location of Yuqiao reservoir and Panjiakou reservoir

3.2 Determination method of drought limit water level

The drought limit water level is determined traditionally based on the water level corresponding to the sum of the dead capacity and the maximum of monthly water supply. The maximum of monthly water supply can be computed by comparisons of the design inflow and water demand (Liu et al. 2012).

The key to the determination of drought limit water level is to ascertain the process of design inflow and water demand. The water demand can be obtained from the statistical data of water users of the reservoir, while there is a large uncertainty in the inflow process. For importing reservoirs, when calculating the inflow, not only the runoff from importing reservoir basin, but also the available transferred water volume from exporting reservoir should be considered. As climate changes and human activities intensified, runoff series in Yuqiao reservoir basin does not meet the consistency requirement anymore, and it is necessary to carry out consistency test on runoff. In addition, for a reservoir importing water from other basins, the synchronous-asynchronous encounter probability of rich-poor runoff of the inter-basin reservoirs needs to be calculated to get the most adverse water transfer situation.

3.2.1 Analysis of the consistency of runoff

As runoff series of Yuqiao reservoir does not meet the consistency requirement (Feng et al. 2011), the traditional runoff frequency analysis cannot be satisfied (Gado and Nguyen 2016; Liang et al. 2018). If the derivation of design runoff does not consider the consistency of runoff, the reliability of drought limit water level will be reduced. Therefore, it is necessary to carry out consistency test on runoff.

The consistency test is to judge whether there are trend and change point components in the series and separate these components from the series (Xie et al. 2005). In this paper, the annual runoff series is divided into consistent random components and inconsistent deterministic components:

$$X_t = Y_t + S_t \tag{1}$$

where Y_t is deterministic aperiodic components (including trend C_t, change point B_t), S_t is random components (including stationary or nonstationary random components), and t is time.

Mann-Kendall (M-K) test is employed to identify the trend of deterministic components (Li et al. 2007). The number of pairs number $x_i < x_j$ $(i < j)$ in time series $x(t)$ is determined first. Then, the variance $\sigma^2_{x_n}$ and statistics U_n of the series are calculated:

$$\sigma^2_{x_n} = \mathrm{var}(x_n) = n(n-1)(2n+5)/72 \tag{2}$$

$$U_n = \frac{x_n - \overline{x_n}}{\sqrt{\mathrm{var}(x_n)}} \tag{3}$$

where n is the sample size.

$$x_n = \sum_{t-1}^{n} x_t; \overline{x_n} = E(x_n) = n(n-1)/4 \tag{4}$$

If $U_n > 0$, there is an upward trend; conversely, there is a downward trend. If $|U_n| > U_{1-\alpha/2}$, the trend is significant; conversely, the trend is not significant. For 5% significant level, the value of $U_{1-\alpha/2}$ is 1.96.

If there is a trend in the runoff series, the trend items should be deducted, and cluster analysis method should be utilized to test the change point of remaining items to find the significant disturbance point τ of the hydrological series (Lei et al. 2007). The mathematical description is as follows:

$$V_r = \sum\left(x_i - \overline{x}_\tau\right)^2, V_{n-r} = \sum\left(x_i - \overline{x}_{n-\tau}\right)^2 \tag{5}$$

where $\overline{x}_\tau$ and $\overline{x}_{n-\tau}$ are the mean of pre-sequence and post sequence of the disturbance point τ respectively.

The sum of squares of deviations is:

$$S_n(\tau) = V_\tau + V_{n-\tau} \tag{6}$$

When $S^*_n(\tau) = min|S_n(\tau)|$ and $1 \leq \tau \leq n$, τ is the optimal segmentation point. That is the disturbance point.

The decomposition of inconsistent hydrological series is mainly to facilitate analyzing the rule of various components, while the ultimate goal is series synthesis. The inconsistent hydrological series is synthetized by utilizing distribution synthesis method (Xie et al. 2009). The Monte Carlo method is used to generate pure stochastic series that can meet the rule of randomness (Lombardo et al. 2017; Sirangelo et al. 2017; Whateley et al. 2016). The stochastic components and deterministic components are numerically synthetized to obtain the sample series. The sample series can be used to deduce the design runoff under current condition by hydrological frequency method (Xie et al. 2005).

3.2.2 Analysis of synchronous-asynchronous encounter probability of rich-poor runoff of inter-basin reservoirs

For importing reservoirs, when calculating the inflow, the transferred water volume should be considered. The actual transferred water volume can be calculated according to the established water diversion ratio and the water storage of the exporting reservoir. Therefore, the synchronous-asynchronous encounter probability of rich-poor runoff of inter-basin reservoirs has directly impact on the available transferred water volume.

The copula method is an effective method to deal with nonlinear correlation variables (Nelson 2006). It has been widely applied to determine reservoir status and future water regime (Chang et al. 2016; Wan et al. 2018). Assuming that X and Y are continuous random variables, their edge distribution functions are respectively $F_X(x)$ and $F_Y(y)$, and the joint distribution function is $F(x, y)$. If $F_X(x)$ and $F_Y(y)$ are both continuous, there is a unique copula function $C_\theta(u, v)$ that makes:

$$F(x,y) = C_\theta(F_X(x), F_Y(y)), \quad \forall x, y \tag{7}$$

where $C_\theta(u, v)$ is a copula function and θ is an undetermined parameter. Among copula functions, three types of Archimedes functions are most widely used, as shown in Table 1 (Liu et al. 2013).where τ is the Kendall rank correlation coefficient which is calculated utilizing the following formula:

$$\tau = \left(C_n^2\right)^{-1} \sum_{i<j} sign\left[\left(x_i - x_j\right)\left(y_i - y_j\right)\right] \tag{8}$$

where sign (*) is the symbolic function. When $(x_i - x_j)(y_i - y_j) > 0$, sign = 1; when $(x_i - x_j)(y_i - y_j) < 0$, $sign = -1$; when $(x_i - x_j)(y_i - y_j) = 0$, sign = 0.

The edge distributions of the reservoir runoff $F_X(x)$ and $F_Y(y)$ employ Pearson-III distribution, whose probability density function $f(x)$ is:

$$f(x) = \frac{b}{\Gamma(a)}(x - a_0)^{\alpha-1} e^{-\beta(x-a_0)} \tag{9}$$

where $\Gamma(a)$ is gamma function and α, β, and a_0 are respectively shape, scale, and location parameters of Pearson-III distribution, $\alpha > 0$, $\beta > 0$.

The parameters of copula function can be estimated by the maximum likelihood method (Liu et al. 2013). In this paper, the fitting test on copula function employs K-S test method, with OLS (sum of squares of deviations) as the evaluation index of goodness-of-fit (Yan et al. 2007). The formulas of the K-S test statistic D and OLS are shown in (10) and (11):

$$D = \max_{1 \le i \le n}\left\{\left|F(x_i, y_i) - \frac{m(i)-1}{n}\right|, \left|F(x_i, y_i) - \frac{m(i)}{n}\right|\right\} \tag{10}$$

where $F(x_i, y_i)$ is the joint distribution of (x_i, y_i) and $m(i)$ is the number of joint observations in the sample that satisfy the conditions of $x \leqslant x_i$ and $y \leqslant y_i$.

$$OLS = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(Pe_i - P_i\right)^2} \tag{11}$$

where P_i and Pe_i are respectively the theoretical frequency and empirical frequency of the joint distribution.

The goodness-of-fit is evaluated by minimum OLS criterion, and the optimal coupling function can be selected out. On this basis, the characteristics of synchronous-asynchronous encounter probability of rich-poor runoff of inter-basin reservoirs are analyzed.

If the annual runoff is divided into wet year, mean year, and dry year by frequency method, there are nine types of synchronous-asynchronous encounter probability of rich-poor runoff of the two reservoirs (Guo et al. 2015). For importing reservoir, the guarantee rate of water supply mainly depends on how much transferred water it can get from exporting reservoir when dry year occurs in importing reservoir. That is:

(1) The two reservoirs are in synchronic situation of rich-poor runoff: This case is adverse to water transfer. The transferred water volume can be calculated according to the inflow of exporting reservoir in dry year.

(2) The two reservoirs are in asynchronous situation of rich-poor runoff: This case is conducive to water transfer. The transferred water volume can be calculated according to the inflow of exporting reservoir in wet year.

4 Results and discussion

4.1 Modified calculation of the design inflow in Yuqiao reservoir

According to formulas (2) and (3), the trend of the annual runoff series of Yuqiao reservoir from 1960 to 2006 is tested. Statistic $U_n = -9.41$ and $U_{1-\alpha/2} = 1.96$, so $|U_n| > U_{1-\alpha/2}$, which indicates that the series has a significant trend of decrease. Figure 2 shows the trend of 5-year moving average annual runoff. From the figure, it can be seen that the trend of runoff is down from the early 1960s to the early 1970s, a sharp rise from the early 1970s to the highest point in the mid-1970s, down dramatically from the mid-1970s to the low point in the early 1980s. The trend of runoff starts to rise from the early 1980s to a higher point in the mid-1990s, then falls, and continues to this day. In general, the runoff is in the trend of decrease, which is consistent with the M-K test results.

According to the result of runoff trend, the overall trend of annual runoff series of Yuqiao reservoir from 1960 to 2006 can be described by a straight line. That is $Y_{t,2} = 131.9366 - 0.0642t$, as shown in Fig. 3.

If the series contains only pure consistent random components, the data should fluctuate up and down on its mean value. That suggests the ideal trend line of the series should be a horizontal line (such as $Y_{t,1}$). This study

Table 1 Three common copula functions

Type	Copula function $C_\theta(u, v)$	Parameter scope	Relationship between τ and θ
Clayton	$(u^{-\theta}+v^{-\theta}-1)^{-1/\theta}$	$\theta > 0$	$\tau = \frac{\theta}{\theta+1}$
Frank	$-\frac{1}{\theta}\ln\left[1+\frac{1}{\theta}\right]$	$\theta > 0$	$\tau = 1-\left[1-\frac{1}{\theta}\int_0^\theta \frac{1}{\theta} dt\right]$
Gumbel-Hougaard	$\exp\{-[(-\ln u)^\theta+(-\ln v)^\theta]^{1/\theta}\}$	$\theta \geqslant 1$	$\tau = 1-\frac{1}{\theta}$

selected annual runoff series from 1960 to 2006, so the trend line is a horizontal line that passes through the starting point of trend line ($t = 1960$).

However, if the runoff series has some trend change, the trend would deviate from the horizontal line. Since a significant decrease trend has been detected in Yuqiao's inflow series, there is a negative slope in the trend line equation. Thus, the deterministic trend component of the annual runoff series can be denoted as Eq. (12). Getting the trend component eliminated, the stochastic components can be obtained. The horizontal line $Y_{t,1} = 6.1046$ shows the average level of the annual runoff series from 1960 to 2006.

$$Y_t = \begin{cases} 0, & t \leqslant 1960 \\ 125.832 - 0.0642t, & 1960 < t \leqslant 2006 \end{cases} \tag{12}$$

The change point test is carried on the remaining items after deducting trend items from the runoff series. The test result shows that the change point is not obvious, so the trend can be used to describe the deterministic components of the runoff series.

According to the decomposition principle of the series X_t, random component $S_t = X_t - Y_t$, so:

$$S_t = \begin{cases} X_t, & t \leqslant 1960 \\ X_t - (125.832 - 0.0642t), & 1960 < t \leqslant 2006 \end{cases} \tag{13}$$

For the random component S_t that meets the consistency, Pearson-III curve can be directly utilized to fit the runoff distribution. The fitting results reflect the frequency distribution of natural runoff unaffected by climate change and human activity. The frequency distribution curve (past) is shown in Fig. 4.

The deterministic components and random components are synthesized by the synthetic method of inconsistent hydrological series. The 1000 sample points (N) of annual runoff consistent with random distribution are generated randomly by Monte Carlo method. The random sample point and the deterministic forecasting value are synthetized to the new sample point of annual runoff. On the basis, the distribution function of synthetic runoff can be fit by Pearson-III curve, and the synthetic hydrological frequency curve (present) consistent with current characteristics is obtained (Fig. 4).

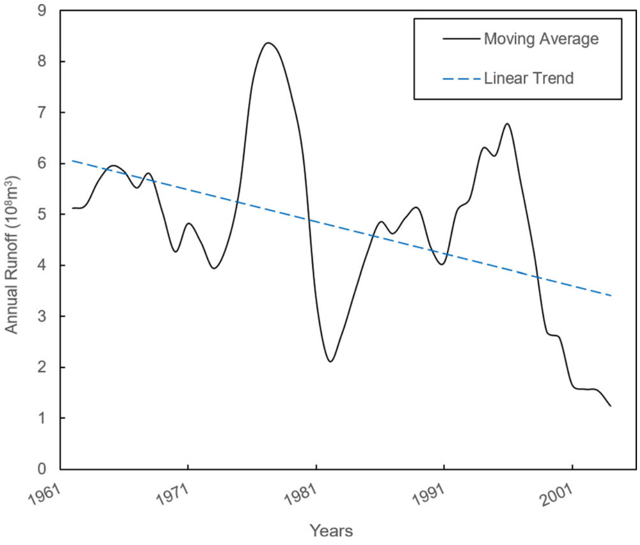

Fig. 2 The trend of 5-year moving average annual runoff

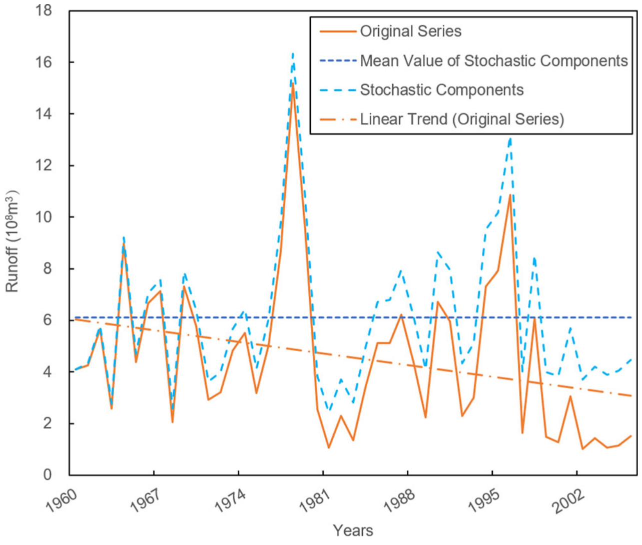

Fig. 3 Trend change of annual runoff of Yuqiao reservoir

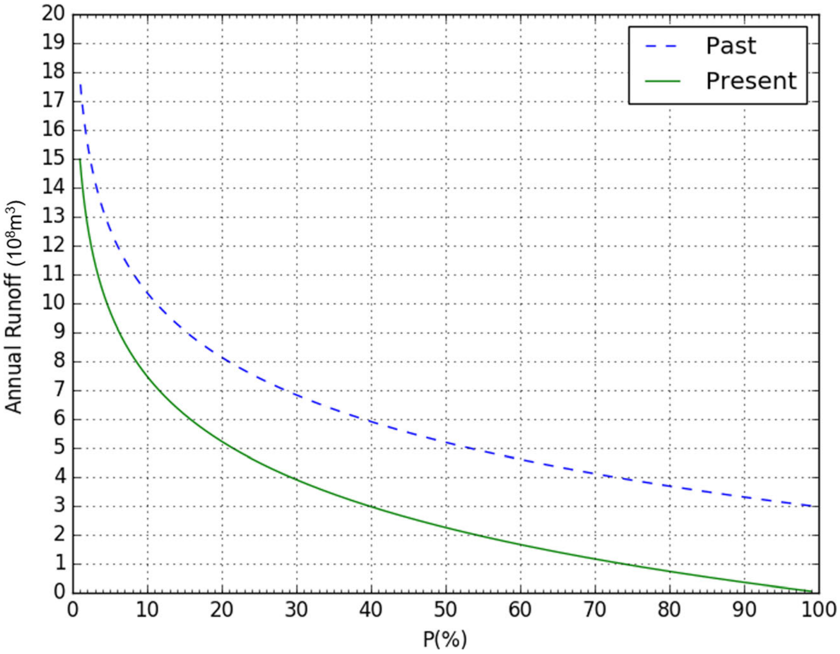

Fig. 4 Frequency curve of Yuqiao reservoir

It can be seen from Fig. 4 that the annual runoff at present is much lower than that in the past. Therefore, when calculating the design runoff, the modified annual runoff data should be utilized. Table 2 shows the modified design runoff process in design dry year ($p = 75\%$).

4.2 Calculation of the transferred water to Yuqiao reservoir

Yuqiao reservoir and Panjiakou reservoir respectively belong to Haihe River Basin and Luan River Basin. According to the water diversion ratio of Tianjin and Hebei, 60% of the discharge of Panjiakou reservoir supplies to Tianjin. Therefore, the actual transferred water volume to Yuqiao reservoir is related to the transferable water volume from Panjiakou reservoir.

By establishing a joint distribution model based on copula function, synchronous-asynchronous encounter probability of rich-poor runoff of Yuqiao reservoir and Panjiakou reservoir is analyzed. The Pearson-III distribution is utilized to represent the edge distribution of the reservoir runoff, and the statistical characteristic parameters $\bar{x}$, C_v, and C_s of the reservoir are estimated by linear moment method (Zhang and Hall 2004), as shown in Table 3.

According to the copula fitting test and optimization theory, statistics D and OLS are computed according to formulas (10) and (11). The calculation results are shown in Table 4. All three copula functions are tested by K-S method, and Clayton with the smallest OLS is selected as the joint function.

The fitting curve of the theoretical frequency and empirical points of the runoff of Yuqiao reservoir and Panjiakou reservoir is obtained by utilizing Clayton coupling function (Fig. 5).

It can be seen from Fig. 5 that the theoretical distribution obtained from Clayton copula is well fitted to the empirical points, so it is reasonable to adopt Clayton as the coupling function. According to the established joint distribution model, the synchronous-asynchronous encounter probability of rich-poor runoff of Panjiakou reservoir and Yuqiao reservoir at different times can be computed.

Table 2 Reservoir design inflow in drought year (10^8 m^3)

Drought year	Oct	Nov	Dec	Jan	Feb	Mar	Year
($p = 75\%$)	0.05	0.03	0.01	0.01	0.01	0.03	
	Apr	May	Jun	Jul	Aug	Sep	
	0.05	0.07	0.12	0.24	0.23	0.09	0.94

Table 3 Statistical characteristic parameters of the annual runoff of Yuqiao reservoir and Panjiakou reservoir

Parameters	Panjiakou reservoir	Yuqiao reservoir
$\bar{x}$	20.18023	4.790973
C_v	0.472646	0.614812
C_s	0.534969	1.20904

Table 4 Copula parameters and calculation results of evaluation indicators

	Clayton	Frank	Gumbel-Hougaard
θ	8.66124	2.672318	3.344
D	0.100952	0.100669	0.105699
OLS	0.029197	0.037295	0.041147

The corresponding joint distribution contour is shown in Fig. 6. The probability of various runoff encounters of Yuqiao reservoir and Panjiakou reservoir can be found out in the figure.

Nine forms of synchronous-asynchronous encounter probability of rich-poor runoff are shown in Table 5.

As can be seen from the table, the synchronous encounter probability is maximum, accounting for 64.4%. Thereinto, the synchronous encounter probability of dry year is 27.15%. According to conditional probability calculation, when Yuqiao encounters a dry year, the probability that Panjiakou reservoir contemporaneously encounters a dry year is 72.43%. This high synchronization is adverse to water transfer. So, it is reasonable to assume that when Yuqiao reservoir is in dry year (p = 75%), Panjiakou reservoir storage is in a similar low level. In this paper, the transferable water volume is calculated in a condition that both the donor and recipient reservoirs are in the same drought year degree (p = 75%). The result is relatively safe to direct the determination of the drought limit water level.

Table 6 shows the design runoff process of Panjiakou reservoir in dry year (p = 75%). According to the established water diversion ratio of Hebei and Tianjin, the water transferred to Yuqiao reservoir is 6.37×10^8 m^3 in dry year (p = 75%).

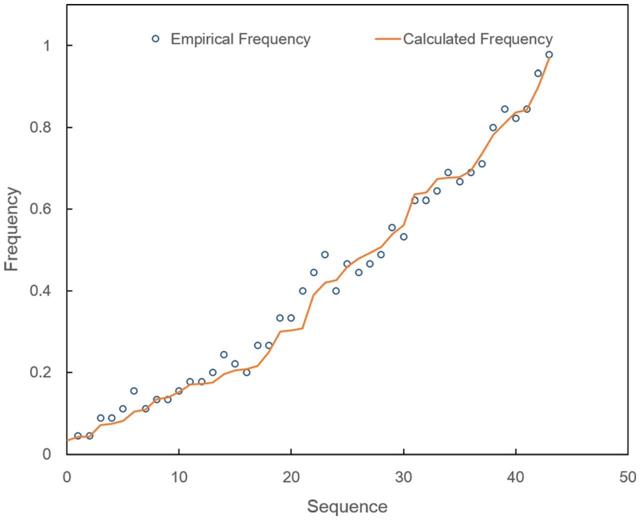

Fig. 5 The fitting curve of the theoretical frequency and empirical points of the runoff of Yuqiao reservoir and Panjiakou reservoir

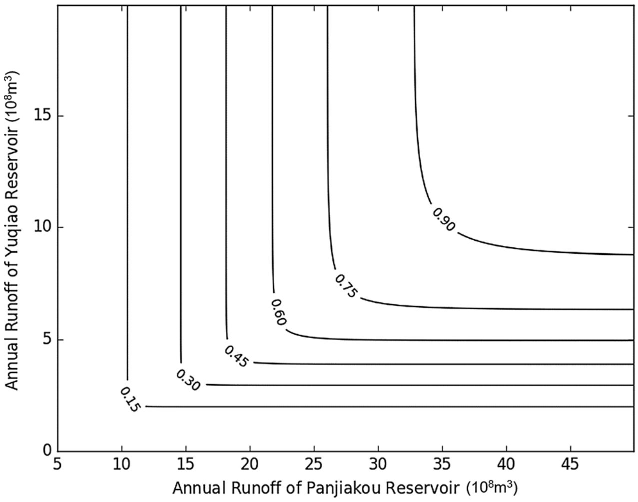

Fig. 6 Joint distribution contour of the annual runoff of Yuqiao reservoir and Panjiakou reservoir

According to the proportion of the monthly transferred water accounting for that of the whole year in Yuqiao reservoir (Tianjin Water Conservancy Bureau), the water transfer process in dry year (p = 75%) is shown in Table 7.

4.3 Determination of water demand in the water supply area of Yuqiao reservoir

At present, water supply to Tianjin is mainly composed of water transferred from Luanhe River, surface water, and groundwater. Yuqiao reservoir supplies most water for urban life and industrial production in Tianjin. Its water supply area covers almost the entire Tianjin. In recent years, the average annual water consumption of the users in water supply area of Yuqiao reservoir is 8.16×10^8 m^3. Besides, the overall trend of water consumption is relatively stable with little fluctuation throughout the year, and the average monthly water consumption is 0.68×10^8 m^3 (Tianjin Water Resources Bulletin).

Table 5 Synchronous-asynchronous encounter probability of rich-poor runoff of Yuqiao reservoir and Panjiakou reservoir (%)

Yuqiao	Panjiakou	Wet year	Mean year	Dry year
Wet year		27.56	7.46	2.49
Mean year		7.47	9.69	7.85
Dry year		2.48	7.85	27.15

Table 6 Design runoff of Panjiakou reservoir in drought year (10^8 m^3)

Drought year ($p = 75\%$)	Oct	Nov	Dec	Jan	Feb	Mar	Year
	1.01	0.67	0.33	0.27	0.27	0.57	
	Apr	May	Jun	Jul	Aug	Sep	
	0.72	0.44	0.98	1.98	3.11	1.94	12.29

4.4 Determination of drought limit water level of Yuqiao reservoir

The runoff of Yuqiao reservoir has remarkable rich-poor changes throughout the year, and the dry season is from November to May each year. At the same time, it is the water supply period. So, the drought limit water level must be set to alleviate water scarcity in the period. The drought limit water level is determined based on the water level corresponding to the sum of the dead capacity and the maximum of monthly water supply. The maximum of monthly water supply can be computed by comparisons of the total inflow and water demand, with the calculation process carried on by month to month. The modified design runoff plus the transferred water in dry year is taken as the total inflow. The calculation results are shown in Table 8.

The sum of the dead capacity and the maximum of monthly water supply is 0.89×10^8 m^3, and the corresponding water level is 16.65 m. Therefore, the drought limit water level is set to 16.65 m. That is, in early warning period, if the water level is lower, a drought resistance mechanism will be initiated.

The determination of the drought limit water level has taken into account the influence of environmental change on the inflow as well as the most adverse situation of water transfer that the two reservoirs encounter dry year synchronously. Therefore, the determination of the drought limit water level can help to supply water flexibly in drought period and serve as an important index for drought resistance and reservoir management; it has potentially broad application prospects.

5 Conclusions

The drought limit water level of a recipient reservoir in an inter-basin water transfer project has been determined considering the environment changing effects in this paper. The design inflow of the drought year is one of key elements to calculate reservoir drought limit water level, while the trend and change point of the runoff series caused by environment change can significantly impact the result of design inflow. A consistency modification of the inflow series has been conducted to better estimate the available water for a drought year. In addition, the synchronous-asynchronous encounter probability of rich-poor runoff of donor and recipient reservoirs has been analyzed, and the greater possible encounter situation has been chosen to calculate the transfer water in the design drought year, which is more reasonable. As climate changes and inter-basin water transfer is becoming a long-term option to correct the spatial and temporal mismatch of water availability and demand all over the world, to establish a key reservoir control level for drought resistance is significantly important to water-deficient regions.

Table 7 Water transfer process of Yuqiao reservoir in drought year (10^8 m^3)

Drought year ($p = 75\%$)	Oct	Nov	Dec	Jan	Feb	Mar	Year
	0.52	0.35	0.17	0.14	0.14	0.30	
	Apr	May	Jun	Jul	Aug	Sep	
	0.37	0.23	0.51	1.03	1.61	1.00	6.37

Table 8 Calculation of the drought limit water level of Yuqiao reservoir

Items (10^8 m^3)	Water demand	Runoff	Transferred water	Total inflow	Water supply
Jan	0.68	0.01	0.14	0.15	0.53
Feb	0.68	0.01	0.14	0.15	0.53
Mar	0.68	0.03	0.30	0.33	0.35
Apr	0.68	0.05	0.37	0.42	0.25
May	0.68	0.07	0.23	0.30	0.38
Jun	0.68	0.12	0.51	0.63	0.05
Jul	0.68	0.24	1.03	1.27	0
Aug	0.68	0.23	1.61	1.84	0
Sep	0.68	0.09	1.00	1.09	0
Oct	0.68	0.05	0.52	0.57	0.10
Nov	0.68	0.03	0.35	0.38	0.30
Dec	0.68	0.01	0.17	0.18	0.49

(1) The environmental change of Yuqiao reservoir has been remarkable, especially since the Luanhe-Tianjin Diversion Project was completed in 1983. Therefore, when determining the drought limit water level of Yuqiao reservoir, it needs to consider the influence of environmental change and the inter-basin water transfer.

(2) According to the annual runoff data of Yuqiao reservoir from 1960 to 2006, the trend and change point of the runoff data are tested. It is found that there is a significant trend of decrease without apparent change point. The random runoff and synthetic runoff series were obtained by utilizing decomposition and synthesis method. The Pearson-III curve of runoff between the last and the present exists with significant differences. The design runoff

must be modified, and the modified annual runoff is 0.94×10^8 m^3 in dry year ($p = 75\%$).

(3) The paper uses the copula function to analyze the synchronous-asynchronous encounter probability of rich-poor runoff of the two reservoirs. The synchronous encounter probability is maximum, accounting for 64.4%. Thereinto, the synchronous encounter probability of dry year is 27.15%. This situation is most adverse to water transfer. According to the established water diversion ratio of Hebei and Tianjin, the water transferred to Yuqiao reservoir is 6.37×10^8 m^3 in dry year ($p = 75\%$).

(4) According to the determination method of drought limit water level, the sum of the dead capacity and the maximum of monthly water supply is 0.89×10^8 m^3, and the corresponding water level is 16.65 m. Therefore, the drought limit water level of Yuqiao reservoir is set to 16.65 m.

Acknowledgements We thank Huifeng Liu for proofreading the paper and the task of revising the figures and tables.

Funding information The authors would like to acknowledge the financial support for this work provided by the National Natural Science Foundation of China (grant no. 51579169 and 51879181), the National Key R&D Program of China (grant no. 2016YFC0401407), and the Ministry of Water Resources Special Funds for Scientific Research on Public Causes (201401041).

References

Chang JX, Li YY, Wang YM, Yuan M (2016) Copula-based drought risk assessment combined with an integrated index in the Wei River Basin, China. J Hydrol 540:824–834

Chen J, Guo S, Li Y, Liu P, Zhou Y (2013) Joint operation and dynamic control of flood limiting water levels for cascade reservoirs. Water Resour Manag 27:749–763

Ding W, Liang GH, Zhou HC (2013) Real-time dynamic control of limited water level of reservoir based on flood forecast information. J Hydroelec Eng 32(5):41–47 (in Chinese)

Feng P, Niu JY, Zhang W (2011) Evolution characteristics of hydrological time series based on s-transform. J Basic Sci Eng 19(1):1–8 (in Chinese)

Gado TA, Nguyen V-T-V (2016) An at-site flood estimation method in the context of non-stationarity I. A simulation study. J Hydrol 535: 710–721

Guo AJ, Huang Q, Chang JX, Li YY, Sun JN, Wang YM (2015) Variation of relationship between runoff and sediment based on copula function in the Jinghe River Basin. J Nat Resour 30(4):673–683

Han DA, Zhang BZ, Wang XH (2015) Analysis and determination of drought limit water level for Changma Reservoir. Gansu Agric 9: 61–62 (in Chinese)

Jain SK, Reddy NSRK, Chaube UC (2005) Analysis of a large inter-basin water transfer system in India. Hydrol Sc J 50(1):125–137

Jiang ZQ, Sun P, Ji CM, Zhou JZ (2015) Credibility theory based dynamic control bound optimization for reservoir flood limited water level. J Hydrol 529(3):928–939

Komatsu H, Kume T, Otsuki K (2010) Water resource management in Japan: forest management or dam reservoirs? J Environ Manag 91: 814–823

Lei HF, Xie P, Chen GC, Li J (2007) Comparison and analysis on the performance of hydrological time series change-point testing methods. Water Resour Power 25(4):36–40

Li LJ, Zhang L, Wang H (2007) Assessing the impact of climate variability and human activities on streamflow from the Wuding river basin in China. Hydrol Process 21(25):3485–3491

Li X, Guo S, Liu P, Chen G (2010) Dynamic control of flood limited water level for reservoir operation by considering inflow uncertainty. J Hydrol 391:124–132

Liang Z, Yang J, Hu Y, Wang J, Li B, Zhao J (2018) A sample reconstruction method based on a modified reservoir index for flood frequency analysis of non-stationary hydrological series. Stoch Env Res Risk A 32:1561–1571

Liu N (2014) Studies on hydrologic drought warning in China. Adv Water Sci 25(3):444–451 (in Chinese)

Liu P, Li L, Wu R, Li K (2012) Necessity and methods for reservoir seasonal drought control water level. J Water Resour Res 1:52–56

Liu Z, Tian Z, Qiao CL, Jia ZF (2013) Analysis on coincidence characteristics of high and low streamflow in central Shaanxi based on copula function. Agric Res Arid Areas 31(4):245–248 (in Chinese)

Liu HP, Yang X, Wang SG, Li S, Liang FG (2015) Determination of drought-alarming water level at Dahuofang reservoir in Liaoning Province, China. Flood Drought Manag 25(4):72–75 (in Chinese)

Lombardo F, Volpi E, Koutsoyiannis D, Serinaldi F (2017) A theoretically consistent stochastic cascade for temporal disaggregation of intermittent rainfall. Water Resour Res 53(6):4586–4605

Mishra AK, Singh VP (2010) A review of drought concepts. J Hydrol 391:202–216

Nandalal KDW, Sakthivadivel R (2002) Planning and management of a complex water resource system: case of Samanalawewa and Udawalawe reservoirs in the Walawe river, Sri Lanka. Agric Water Manag 57:207–221

Nelson RB (2006) An introduction to copulas. Springer, New York

Oweis T, Hachum A (2006) Water harvesting and supplemental irrigation for improved water productivity of dry farming systems in West Asia and North Africa. Agric Water Manag 80(1–3):57–73

Peng SM, Wang Y, Zhang YY, Jiang GQ (2016) Optimal control of drought limit water level for multi-year regulating storage reservoir. J Hydraul Eng 47:552–559 (In Chinese)

Sirangelo B, Caloiero T, Coscarelli R, Ferrari E (2017) A stochastic model for the analysis of maximum daily temperature. Theor Appl Climatol 130(1–2):275–289

Sun WW (2014) Analysis of drought limit water level (flow) for Shimen reservoir, Jilin. Water Resour 11:39–41 (in Chinese)

Wan F, Yuan W, Li Q, Lü S (2018) Research on risk and early warning system of inter-basin multi-reservoir water transfer-supply operation with consideration of uncertain factors. Irrig Drain 67:461–470

Whateley S, Steinschneider S, Brown C (2016) Selecting stochastic climate realizations to efficiently explore a wide range of climate risk to water resource systems. J Water Resour Plan Manag 142(6): 06016002

Wilhite DA, Svoboda MD (2000) Drought early warning systems in the context of drought preparedness and mitigation, in early warning systems for drought preparedness and drought management. World Meteorological Organization, Geneva, pp 1–16

Wisser D, Frolking S, Douglas EM, Fekete BM, Schumann AH, Vörösmarty CJ (2010) The significance of local water resources captured in small reservoirs for crop production—a global-scale analysis. J Hydrol 384:264–275

Wurbs RA (1993) Reservoir system simulation and optimization models. J Water Resour Plan Manag (ASCE) 119(4):455–472

Xie P, Chen GP, Xia J (2005) Hydrological frequency calculation principle of inconsistent annual runoff series under changing environments. Eng J Wuhan Univ 38(6):6–9 (in Chinese)

Xie P, Chen GC, Lei HF (2009) The assessment method of water resources based on trend analysis of changing environments. J Hydroelec Eng 28(2):14–19 (in Chinese)

Yan BW, Guo SL, Xiao Y (2007) Synchronous-asynchronous encounter probability of wetness dryness precipitation between water source area and water receiving areas in the middle route of south-to-north water transfer project. J Hydraul Eng 38(10): 1178–1185

Zhang J (2016) Study on determination method of drought limited water level in Liaoning River reservoir. Water Sci Eng Technol 3:26–28 (in Chinese)

Zhang JY, Hall MJ (2004) Regional flood frequency analysis for the Gan-Ming River basin in China. J Hydrol 296(1):98–117

Zhou HC, Li W, Zhang C (2009) Research on schemes optimization of dynamic flood control limited water level of a reservoir. J Hydroelec Eng 28(4):27–32 (in Chinese)

Zhou Y, Guo S, Liu P, Xu C (2014) Joint operation and dynamic control of flood limiting water levels for mixed cascade reservoir systems. J Hydrol 519:248–257