

## Dynamic Regulation of Reservoir Drought Limit Water Level

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**Abstract**—Drought limit water level has been presented to guide reservoir drought resistance for years. However, current static drought limit water levels neglected the water transfer relationship among different periods. In this study, the Yuqiao Reservoir located in Tianjin, China, was taken as the study area. To avoid the excessive subjectivity brought by the conventional typical drought-year selection method, six indicators were used to analyse inflow intra-drought-season distribution characteristics, and a hierarchical agglomeration cluster method was used to propose a classification of the dry season inflow “shape.” To associate with the reservoir inter-month water transfer relationship, a number pair “early warning period/drought limit water level” format was proposed to represent the limit water level. The early warning period turned out to be related to initial water storage, inflow process in dry season and water supply rules. To overcome the uncertainty in inflow process during the dry season, a rolling computation mechanism was applied in determining the drought limit water level, thus dynamic regulation was realized. Finally, the dynamic reservoir drought limit water level was compared with the conventional method. The results suggest that drought limit water level has broad development potential in improving reservoir drought resistance guidance practices.

**Keywords:** drought limit water level, early warning period, rolling computation, dynamic regulation

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### INTRODUCTION

Large-scale and long-lasting droughts can cause more severe damage and influence more people compared to other kinds of natural hazards [8, 19, 25, 30]. Droughts have been thought to be world’s costliest natural disasters, causing an average US\$ 6–8 billion in global damages annually [24].

Generally, a drought plan contains three main parts: monitoring and early warning, risk assessment, and mitigation and response [24]. Among them, early warning is an important non-engineering measure of how to execute drought relief. Several drought indices have been defined for drought warning management, such as the Palmer drought severity index (PDSI), the surface water supply index (SWSI), and the standardized precipitation index (SPI) [5, 7, 28]. No universal index yet exists to handle drought management, and different water users continue to define droughts according to their particular needs [14, 18]. However, there has been little research on the drought alert index of reservoirs.

Huang et al. [16] proposed a drought early warning system (DEWS) for reservoir operation to aid water authorities in the decision-making process while con-

fronting drought threats. On this basis, Huang et al. [15] revised the DEWS for reservoir operation and used reservoir storage (water level) alone to monitor the status of drought. They believed that a single well-defined attribute of storage (water level) was sufficient to quantify the drought water management in this research. DEWS can help the reservoir manager effectively cope with droughts. However, the drought-alert index in the DEWS was not a quantitative value and was inconvenient for reservoir operation. Therefore, it is necessary to present an effective alert index, which is conducive to reservoir operation.

Compared to flood-control scheduling, the flood limit water level was set to guarantee the safety of the dam itself and downstream protection area [2]. Flood limit water level is one of the important parameters in reservoir operation, and it is convenient for reservoir managers to control floods. In drought planning, the drought limit water level refers to the water level of the reservoir required to guarantee the water safety of urban and rural life, as well as industrial and agricultural production during the drought. The drought limit water level was determined traditionally based on the water level corresponding to the sum of the dead

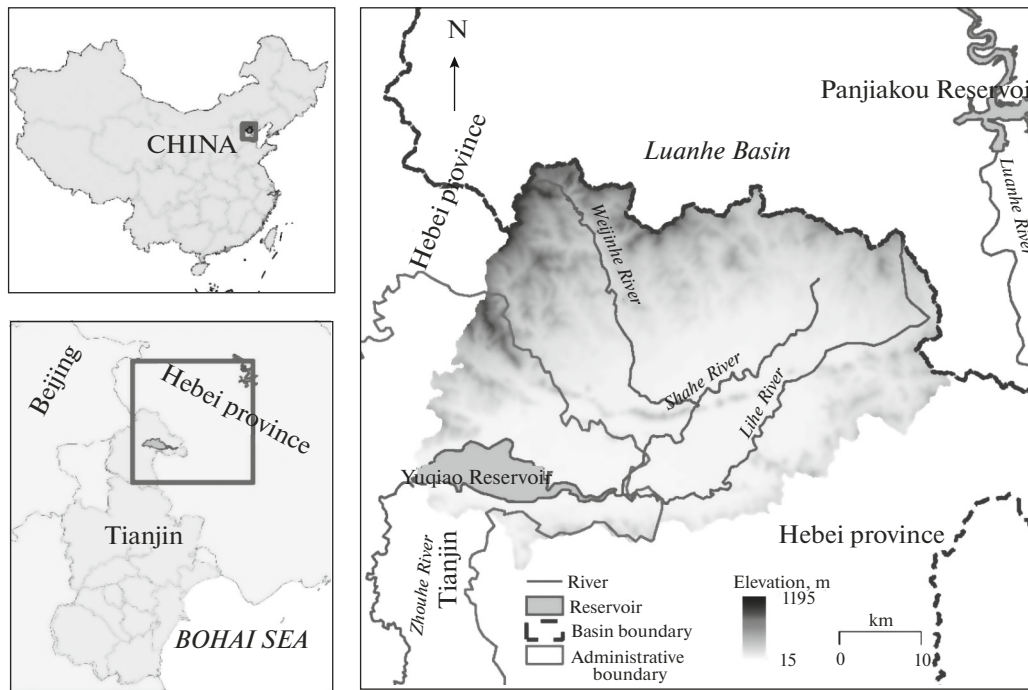


Fig. 1. Location of Yuqiao Reservoir in Tianjin city.

capacity and the maximum of the monthly water supply. The maximum of the monthly water supply could be calculated by comparisons of the designed monthly inflow and monthly water demand [26].

Since the drought limit water level was proposed, it has been widely applied [1, 20, 23, 26]. However, the prevailing determination of reservoir drought limit water level had some problems: (1) adopting a static drought limit water level for complete drought periods, which is not appropriate for most months; (2) neglecting the water transfer relationship among different periods.

Aimed to solving these problems, this paper is based on the Yuqiao Reservoir analysed inflow intra-drought-season distribution characteristics and proposes a classification of the dry season inflow “shape.” The reservoir inter-month storage water transfer relationship was considered, and the dynamic drought limit water level was introduced. To overcome the uncertainty of the inflow process during the dry season and to maintain the continuous early drought warning effectiveness of the drought limit water level, a rolling computation mechanism was added to the determination of drought limit water level.

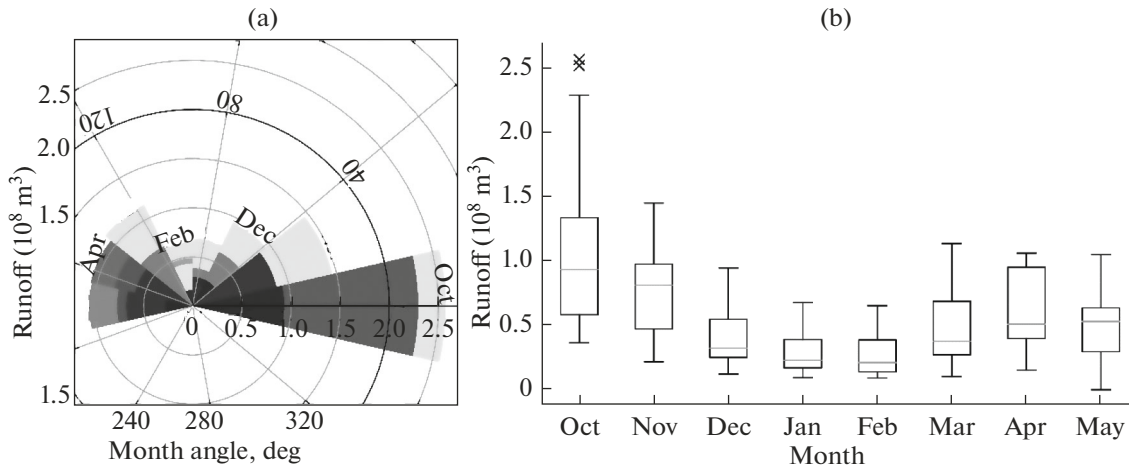
## MATERIALS AND METHODS

### *Description of the Study Area*

Tianjin city is located at east longitude  $116^{\circ}42'05''$  E ~  $118^{\circ}03'31''$  E and north latitude  $38^{\circ}33'57''$  N ~  $40^{\circ}00'07''$  N. It is 172 km from south to north and

104 km from east to west. The Yuqiao Reservoir is located in Ji County in northern Tianjin (Fig. 1), where the average annual precipitation is 750 mm and average annual evaporation is 1000 mm. The precipitation is mainly concentrated in the flood season from June to September, accounting for 67–76% of the annual precipitation, while winter precipitation accounts for less than 2%. Therefore, serious drought occurs most often in winter and spring. Yuqiao Reservoir is the largest reservoir in Tianjin with a total storage capacity of  $1.56 \times 10^9$  m<sup>3</sup>, a flood control storage capacity of  $1.26 \times 10^9$  m<sup>3</sup>, an active storage capacity of  $3.85 \times 10^8$  m<sup>3</sup>, a dead storage capacity of  $0.36 \times 10^8$  m<sup>3</sup>, a flood limit water level of 19.87 m, and a normal water level of 21.16 m at the end of flood season. Since the commencement of the Luanhe-Tianjin Division Project in 1983, water resources in the Luanhe Basin have been diverted into the Yuqiao Reservoir through the main trunk canal. The Yuqiao Reservoir has then undertaken the water supply for domestic and production use in Tianjin by importing water from the Luanhe Basin (Panjiakou Reservoir) and supplying approximately  $10 \times 10^8$  m<sup>3</sup> water to Tianjin every year. According to the water diversion ratio of Tianjin and Heibe, 60% of the discharge of Panjiakou Reservoir supplies Tianjin, while the water conveyance loss is approximately 10% [4].

The natural inflow series data from 1990 to 2015 of Panjiakou Reservoir were obtained from the reservoir station. Design inflow data of the 75% guarantee rate, and water level-capacity relation curve of Yuqiao Res-



**Fig. 2.** (a) Intra-drought-season inflow distribution of Panjiakou Reservoir (1990–2015). The whiskers in (b) have a maximum range of 1.5 IQR.

ervoir were obtained from the Yuqiao Reservoir Management Agency. The water demand data for Yuqiao Reservoir were obtained from the Tianjin Water Conservancy Bureau.

*Research Methods.*

*Intra-Drought-Season Inflow Distribution Characteristics Cluster Analysis*

Streamflow process alteration involves two separate differences in “magnitude” and “shape” [12]. The intra-annual distribution characteristics are shape attributes. The intra-annual distribution of streamflow affected not only the fluvial hydro-systems [13] but also the exploitation and allocation of water resources [22]. Therefore, as the drought limit water level serves as a forewarning characteristic, its determination must be associated with the intra-drought-season inflow distribution characteristics.

In this study, the concentration degree  $C_d$  and concentration period  $C_p$  [3, 22], the non-uniformity coefficient  $C_u$  and the overall adjustment coefficient  $C_r$  [23, 29] and the relative variation in  $C_{\max}$  and  $C_{\min}$  [11] were chosen as the indexes to quantitatively reflect the intra-drought-season distribution feature of the flow.

Specifically, the diversion water from the Panjiakou Reservoir accounted for over 80% of the available water supply of the Yuqiao Reservoir in a  $P = 75\%$  drought year. Whilst, according to the previous studies, the synchronous encounter probability of rich-poor inflow of the Yuqiao and Panjiakou reservoirs is relatively high [26]. Therefore, the Panjiakou Reservoir inflow process was taken as the representative inflow process for the following study, and the Yuqiao Reservoir was assumed to share the same inflow “shape.”

For both the Yuqiao Reservoir and Panjiakou Reservoir, the dry season is 8 months from October to May, with the lowest flow concentrated in January. To reflect the ratio of flow distributed at both ends of the dry season, the starting time of the dry season in October was defined as  $0^\circ$ , and the end time in May was defined as  $180^\circ$ . The other months were equally spaced in-between (shown as Fig. 2a). The concentration degree  $C_d$  was regarded as the ratio between the vector modulus of a certain period of time and the whole dry season inflow volume. The concentration period  $C_p$  is expressed by the direction of the resultant vector.

$$C_d = \frac{\sqrt{R_x^2 + R_y^2}}{R}, \tag{1}$$

$$C_p = \arctan(R_y/R_x), \tag{2}$$

where

$$R_x = \sum_{i=1}^8 r_i \cos \theta_i, \quad R_y = \sum_{i=1}^8 r_i \sin \theta_i, \quad R = \sum_{i=1}^8 r_i, \tag{3}$$

where  $R_x$  and  $R_y$  are the magnitudes of the  $x$  and  $y$  directions,  $10^8 \text{ m}^3$ ;  $R$  is the sum of the inflow in the dry season,  $10^8 \text{ m}^3$ ;  $r_i$ ,  $\theta_i$  ( $i = 1, 2, 3, \dots, 8$ ) are, respectively, the inflow volume and the vector angle of in the  $i$ th time segment, and where 8 is the total months of the dry season.

The non-uniformity coefficient  $C_u$  and overall adjustment coefficient  $C_r$  can be expressed as:

$$C_u = \sigma/\bar{R}, \quad \sigma = \sqrt{\frac{1}{8} \sum_{i=1}^8 (R_i - \bar{R})^2}, \quad \bar{R} = \frac{1}{8} \sum_{i=1}^8 R_i, \tag{4}$$

$$C_r = \frac{\sum_{i=1}^8 \Phi_i (R_i - \bar{R})}{\sum_{i=1}^8 R_i}, \quad \Phi_i = \begin{cases} 0, & R_i < \bar{R} \\ 1, & R_i \geq \bar{R} \end{cases} \tag{5}$$

**Table 1.** Calculation of drought limit water level in the target reservoir

| Item, 10 <sup>8</sup> m <sup>3</sup> | Water demand | Inflow | Water supply | Item, 10 <sup>8</sup> m <sup>3</sup> | Water demand | Inflow | Water supply |
|--------------------------------------|--------------|--------|--------------|--------------------------------------|--------------|--------|--------------|
| JAN                                  | 0.68         | 0.15   | 0.53         | JUL                                  | 0.68         | 1.27   | 0            |
| FEB                                  | 0.68         | 0.15   | 0.53         | AUG                                  | 0.68         | 1.84   | 0            |
| MAR                                  | 0.68         | 0.33   | 0.35         | SEP                                  | 0.68         | 1.09   | 0            |
| APR                                  | 0.68         | 0.42   | 0.26         | OCT                                  | 0.68         | 0.57   | 0.11         |
| MAY                                  | 0.68         | 0.3    | 0.38         | NOV                                  | 0.68         | 0.38   | 0.3          |
| JUN                                  | 0.68         | 0.63   | 0.05         | DEC                                  | 0.68         | 0.18   | 0.5          |

where  $\sigma$  and  $\bar{R}$  are the mean square error and the mean of inflow in a dry season.  $R_i$  is the inflow of the  $i$ th month.

The relative variation can be assessed using  $C_{\max}$  and  $C_{\min}$ .

$$C_{\max} = \frac{R_{\max}}{\bar{R}}, \quad C_{\min} = \frac{R_{\min}}{\bar{R}}. \quad (6)$$

To classify the “shape” of the inflow of Panjiakou (Yuqiao) Reservoir in the dry season, the approach similar to that proposed by Harris et al. [13] was adopted in this study. The intra-drought-season inflow characteristics were first standardized using  $z$ -scores (mean = 0, standard deviation = 1) over the 25-year record. Then, the classifications were obtained using hierarchical cluster analysis. The average linkage technique was chosen for clustering since it was more widely used in climatological applications [17]. Eventually, the structure of the cluster dendrogram and breaks in slope in the agglomeration schedule plot were used to estimate the appropriate number of clusters [13]. Figure 2b shows the intra-drought-season inflow distribution of the Panjiakou Reservoir from 1990–2015.

*Determination Method of Drought Limit Water Level*

The determination of drought limit water level is relatively simple. Assuming the designed monthly inflow and monthly water demand of the target reservoir were as shown in Table 1, the monthly water supply was calculated month-to-month. The maximum of the monthly water supply is  $0.53 \times 10^8 \text{ m}^3$ . The water level corresponding to the maximum water supply plus the dead capacity was defined as the drought limit level [26]. Thus, in the early warning period, if the water level is lower than drought limit level, a drought resistance mechanism will be initiated. However, the drought limit level determined by this method is static and has many problems in reservoir management. So, the dynamic drought limit level is presented in this paper.

*Determination of Drought Early Warning Period*

This paper proposes a number pair “early warning period/drought limit water level” ( $Td, DL$ ) format to represent the drought limit water level, where  $Td$  is the drought early warning period, and  $DL$  is the drought limit water level corresponding to the drought early warning period. The concept of potential drought period is put forward in this paper, which represents the month when drought occurs under a certain water storage  $S$ , the normal water supply rules  $I$  and the inflow  $x$ . The normal water supply rules  $I$  adopts the Standard Operation Policy (SOP) [6, 21] in which reservoir discharge is simplified into a function of the initial reservoir storage and the inflow over the same time [10, 27]. The implementation process of SOP is as follows: if reservoir storage cannot meet the water demand target at the time, in order to meet it as much as possible, the reservoir should fully drain its storage; if the inflow is excessive leading the reservoir to be full, the excess water should be released. The early warning period should be set one month before the potential drought period. Therefore, the drought early warning period  $y$  is related to reservoir storage  $S$  at the end of the flood season, inflow  $x$  during dry season and water supply rules  $I$ . Thus,  $y = f(S, x, I)$ .

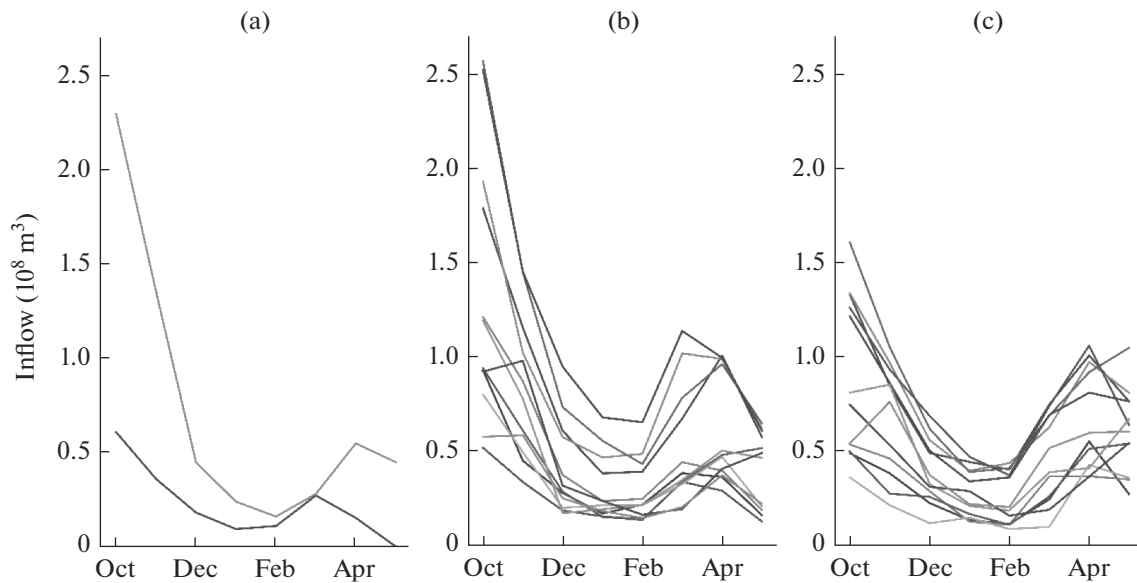
According to the identification method of hydrological drought in the water supply system, the potential drought period can be distinguished, and the drought degree of the water supply system can be assessed. The potential drought period and the relative water shortage ( $DI$ ) are determined as follows [9]:

(1) Calculation of the water transfer relationship among different time periods. In the  $k$ th month, the water transfer that the reservoir can get from the previous  $k - 1$  month is:

$$\Delta w(k) = \sum_{t=1}^{k-1} [w(t) - w_0(t)], \quad (7)$$

where  $w(t)$  is the actual inflow,  $10^8 \text{ m}^3$ ;  $w_0(t)$  is the actual water demand,  $10^8 \text{ m}^3$ ; and  $\Delta w(k)$  is the remaining water,  $10^8 \text{ m}^3$ . When  $\Delta w(k)$  is negative, it is set to zero.

(2) The calculation of effective water supply. As the water transfer is known, the actual water supply in a



**Fig. 3.** The “shape” clusters of the dry season inflow process. (a)–(c) are 3 classifications obtained through the hierarchical cluster analysis.

certain month can be calculated. The effective water supply in the  $k$ th month is:

$$Q(k) = w(k) + \Delta w(k). \quad (8)$$

(3) When  $Q(k) < w_0(k)$ , it is believed that the drought occurs, and drought degree is described by the relative water shortage ( $DI$ ).

$$DI = \sum_{t=T_0}^{T_e} \left[ \frac{Q(t) - w_0(t)}{w_0(t)} \right], \quad (9)$$

where  $T_0$  and  $T_e$  are, respectively, the start time and the end time of the drought.

#### *The Determination of the Dynamic Drought Limit Water Level*

Considering the drought early warning period as a dynamic regulation result of  $f(S, x, I)$ , to achieve the early warning effect, the inflow series  $x$  adopts the annual design inflow of the drought. However, there is a significant difference between the annual design inflow and the actual inflow. To overcome the uncertainty of the inflow process during the dry season and to maintain continuous early drought warning effectiveness of the drought limit water level, a rolling computation is conducted at the beginning of each month to determine the drought limit water level. The full procedure is as follows:

(1) Simulation of the water level changes during water supply period. The water level changes are determined according to the water storage  $S$  at the end of flood season, annual design inflow  $x$  and water supply  $I$  under the SOP.

(2) Determination of the drought early warning period. According to the water level simulation results, the relative water shortage index  $DI$  is calculated, and the months when  $DI < 0$  are taken as the potential drought period. One month prior to the potential drought period is selected as the drought early warning period  $Td$ .

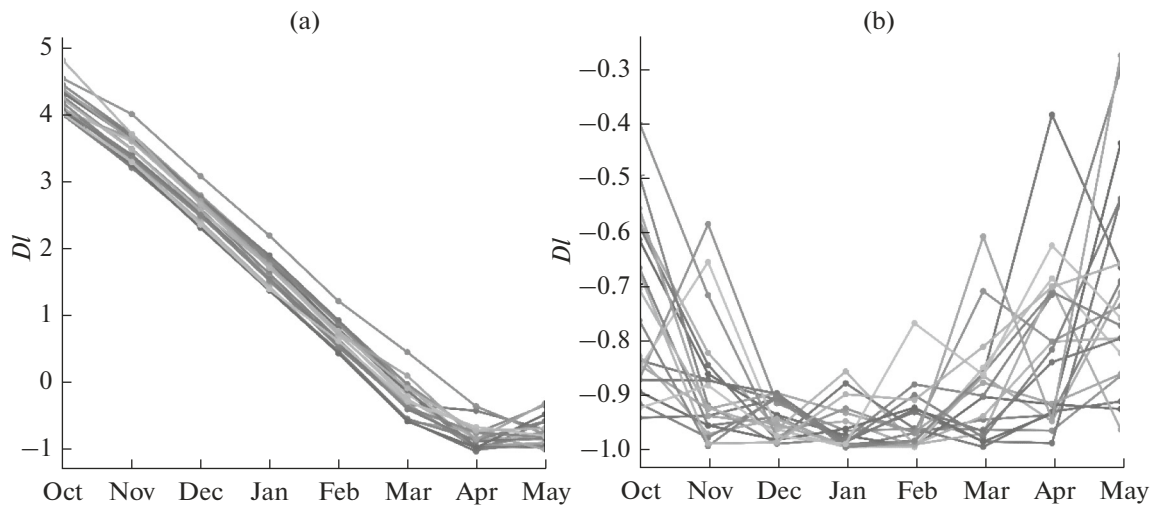
(3) Determination of the number pair “early warning period/drought limit water level” ( $Td, DL$ ). The water supply in early warning month and the first dry month thereafter is taken as the total water supply, and the total water supply plus the dead capacity is set to the reservoir storage at the beginning of the early warning month. The corresponding water level of this capacity is the drought limit water level under the early warning period.

(4) The dynamic regulation of the drought limit water level. The inflow series is modified monthly according to the actual inflow, and the potential drought period and drought early warning period are recalculated. Correspondingly, the drought limit water level is modified.

## RESULTS AND DISCUSSION

### *“Shape” Classification of the Dry Season Inflow*

By estimating each index of the intra-drought-season inflow for every year, a hierarchical cluster analysis was conducted. Based on the structure of the cluster dendrogram and breaks in slope in the agglomeration schedule, 3 classifications provided an informative subdivision of the data set. Figure 3 illustrates the clustering results.



**Fig. 4.** Relative water shortage in dry season under (a) the normal water storage condition and (b) the water storing failure condition.

As shown in Fig. 3, among the three classes, class (a) has a higher concentration degree, an earlier concentration period, a greater non-uniformity coefficient and an overall adjustment coefficient, a larger  $C_{\max}$  and a smaller  $C_{\min}$ . Class (c) has indicators contrary to (a). Class (b) has the indicators somewhere in-between. Since there are some low-flow year samples in each class, it is reasonable to choose the lowest flow year from each class (1999, 2000 and 2009) to serve as reference “shapes” to calculate drought limit water level.

#### *Impact of Water Storage on Early Warning Period*

During the Yuqiao Reservoir flood season, the inflow has certain periodic characteristics. The reservoir can store water to the normal water level in flood years, but in dry years it may not reach the normal water level at the end of flood season. Suppose the reservoir can reach the normal water level at the end of flood season, applying the dry season inflow of the Yuqiao Reservoir from 1990 to 2009 (from October to May) following the SOP regulation, the relative water shortage ( $DI$ ) of the reservoir in the water supply period was calculated as shown in Fig. 4a.

When the reservoir reaches the normal water level at the end of flood season, even if there is little inflow, the drought does not occur immediately in the water supply period. As seen in Fig. 4a, the reservoir can still guarantee the water supply from December to February when the inflow is the smallest. Ultimately, the drought occurs in March and lasts until May. Thus, according to the early warning requirements of the drought limit water level, the drought early warning period should be set prior to March.

Suppose the reservoir failed to store water at the end of flood season, applying the natural dry season inflow of the Yuqiao Reservoir from 1990 to 2009 (from October to May) following the SOP regulation, the relative water shortage of the reservoir in the water supply period was calculated. As shown in Fig. 4b, the negative value indicates drought, which will occur as soon as the dry season begins. According to the monthly relative water shortage ( $DI$ ), the most severe drought occurs in December and lasts until February, because in this period, the rainfall reaches the yearly minimum. Because the early warning period should be set before the drought period, the drought warning would be initiated before it enters the water supply period. This situation mostly occurs in the course of a prolonged drought and no water can be stored during the flood season.

#### *The Determination of the Drought Limit Water Level*

In the general year, the reservoir always stores a certain amount of water in the flood season. Assume that the reservoir water storage is  $2.0 \times 10^8 \text{ m}^3$  at the end of flood season (September 30th), and the corresponding water level is 19.10 m. Then, October 1st would be taken as the starting point to calculate the drought limit water level. The water level changes can be determined according to design inflow of  $P = 75\%$  with the shape of the dry season hydrograph obtained by the cluster result shown as Fig. 3. Water supply  $I$  followed the SOP, and the overall water balance and water storage changes were shown by a ternary phase diagram in Fig. 5.

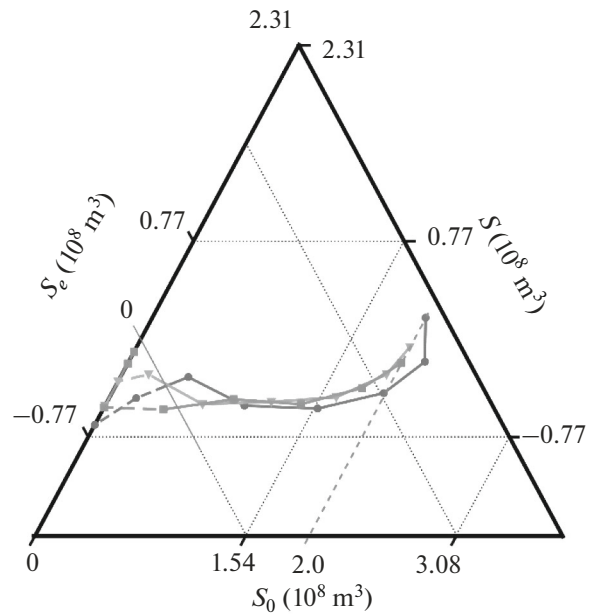
In Fig. 5, for  $P = 75\%$  inflow in dry season, the water storage tended to decline. When the water storage at the end of the month  $S_e$  was less than 0 ( $DI < 0$ ),

the reservoir simulation operation line was shown with a dashed line (left of the red solid line), indicating that reservoir could not meet the water demand for this month under the SOP water supply strategy. For the inflow process with “shape” class (a), the state  $DI < 0$  occurred in April and May; for the inflow process with “shape” class (b), the state  $DI < 0$  occurred in March, April and May. The state  $DI < 0$  occurred from February to May when the inflow process with “shape” class (c) compared with the other two classes. Figure 5 indicates that the inflow process with “shape” class (c) is more adverse to the reservoir drought relief compared to the other two conditions when the dry season total inflow is constant.

According to the operation simulation results, the first month with  $DI$  less than 0 for inflow process “shapes” (a), (b) and (c) are, respectively, April, March and February, and the corresponding water deficits are  $0.26 \times 10^8$ ,  $0.08 \times 10^8$  and  $0.11 \times 10^8$   $m^3$ . The months prior to the water shortage were set to be the early warning periods. The water demand of the early warning period plus the following water shortage month is set to the reservoir storage for drought resistance, and the corresponding water level is taken as the drought limit water level. Thus, for the three classes inflow processes, taking October 1st as the starting point of calculation, it is concluded that the drought limit water level is (March, 17.13 m) for inflow shape (a), (February, 17.18 m) for inflow shape (b), and (January, 17.60 m) for inflow shape (c).

As the reservoir water level varies between 15.00 m (dead storage level) and 25.00 m at the end of flood season each year, to facilitate reservoir management, the drought limit water level was calculated in steps of 0.01 m according to the dynamic control method. The “early warning month/drought limit water level” corresponding to different water storage, with Oct 1st as the calculation starting point is shown as Fig. 6.

As shown in Fig. 6, the drought limit water level is affected by both the water storage at the end of the flood season and the distribution of the inflow during the dry season. The early warning period is delayed as the water level at the end of the flood season increased. When the water level at the end of the flood season is lower than the starting points of the drought limit water level line, it means that the reservoir has already been in a warning state at the beginning of the water supply period. When the water level at the end of flood season exceeds 20.32 m, the reservoir can guarantee the water supply on condition that the design inflow is the 75% guarantee rate. The drought limit water level varies as the “shape” of the inflow process during the dry season changes. The early warning period would be brought forward in the order of inflow process with “shape” of class (a), (b) and (c). When the early warning period occurred early in the dry season (October and November), a lower drought limit water level would be obtained using the inflow process with



**Fig. 5.** Water storage change in drought period.  $S_0$  represents the water storage at the beginning of each month;  $\Delta S$ , the storage increment at each month, equals inflow minus supplying water; and  $S_e$  is the water storage at the end of each month. Here and on the Fig. 6: the curve with round markers was inflow process with shape (a), the orange line with triangle marker was with shape (b), while the green line with square marker was with shape (c).

“shape” class (a). When the early warning period occurred late in the dry season (April and May), a higher drought limit water level would be obtained with the “shape” class (a) inflow process. Under conditions of inflow with “shape” class (c), opposite results were achieved. Class (b) “shapes” would trigger a water level in-between the two end members.

The study of drought limit water level is at the initial stage, and it has ample development opportunity to better guide reservoir drought-resistance strategies. However, drought limit water level is not clearly associated with water supply strategy at present, making it difficult to compare the three classes by the benefit of corresponding water supply. This study took the number of samples in three clustering classes as a criterion to evaluate the possibility of the occurrence of each “shape”, such that the drought limit water level under class (c) was considered to be more accurate to warn of drought.

#### *The Rolling Computation of the Dynamic Drought Limit Water Level*

When calculating the drought limit water level, an inflow of the 75% guarantee rate was first utilized as the inflow series. However, the actual inflow process would be quite different from the adopted inflow, as the inflow process does not necessarily occur in such

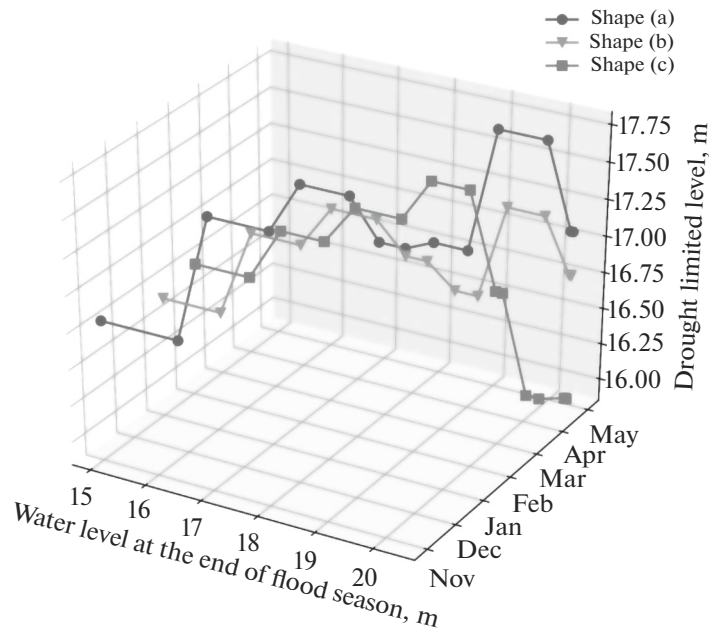


Fig. 6. Water level at the end of flood season—drought early warning period—drought limit water level.

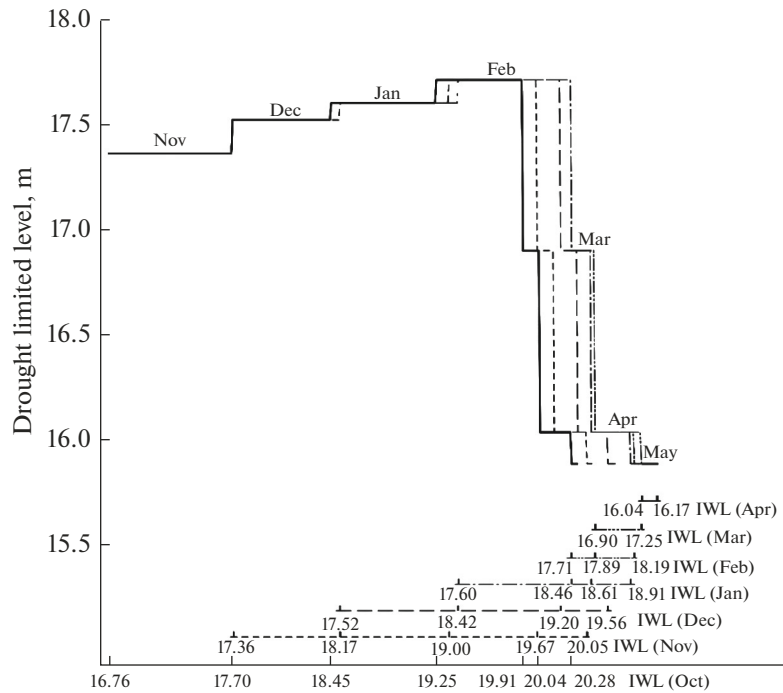


Fig. 7. Monthly rolling computation of drought limit water level. IWL is the initial water level at the beginning of each month, and the annotation above the drought limit water level is the early warning period.

a magnitude or shape in actuality. To overcome the uncertainty of the inflow process, the designed inflow series were modified monthly on the basis of the actual

inflow. Then, the potential drought period and drought early warning period are recalculated, and the drought limit water level correspondingly modified.



Figure 7 shows the rolling computation of the drought limit water level in the Yuqiao Reservoir, with each month as the calculation starting point.

#### *Contrast and Analysis of Dynamic and Static Drought Limit Water Level*

Compared with the traditional static drought limit water level, the advantages of the dynamic drought limit water level are obvious. The static drought limit water level of Yuqiao Reservoir is 16.70 m for a type (c) inflow process (using the method introduced in section 1). However, in the actual control process as shown in Fig. 7, as long as the water level is lower than 17.70 m at the beginning of the dry season, the reservoir is imminently facing a severe drought from December and later. If the reservoir warning still refers to the early warning water level 16.70 m, there will be no meaning. In addition, when the reservoir water level in May is lower than 16.70 m, but higher than 15.89 m, the reservoir can supply water normally in June under the guaranteed rate, and the drought early warning is not required. In general, the static drought limit water level is low in the early dry season but high at the end of dry season.

In addition, the traditional drought limit water level needs to set up a relationship between the drought limit water level and designed guarantee rate. If the adopted standard is too high, the drought limit water level will also be high and early warnings will occur too frequently. The dynamic drought limit water level effectively overcomes this problem. First, the dynamic drought limit water level employs a number pair (month, water level), which is more targeted in time, and will not warn frequently. Second, although the adopted guarantee rate of the initial drought limit water level is 75%, the water level can be modified monthly due to the annual rolling computation mechanism. When the inflow decreases significantly during the water supply period, the early warning can be advanced by modifying the calculation.

## CONCLUSIONS

This study concentrated on assessing the impact of the “shape” of the intra-drought-season inflow process and the inter-month water transfer relationship on the determination of reservoir drought limit water level. The dynamic drought limit water level was introduced and applied in the Yuqiao Reservoir. The following conclusions can be summarized:

(1) The Yuqiao Reservoir  $P = 75\%$  inflow process can be subdivided into three classes using a hierarchical agglomeration cluster method. By simulating the reservoir operation month by month, the state  $DI < 0$  occurred in April and May for “shape” (a) inflow; the state  $DI < 0$  occurred in March, April and May for “shape” (b) inflow; and the state  $DI < 0$  would occur from February to May for “shape” (c) inflow. Com-

prehensively considering the warning effect and proportion of the inflow samples in the clustering classes, class (c) was considered the most suitable for drought limit water level determination.

(2) The impact of inter-month water transfer relationship on drought limit water level was analysed. The paper employs the number pair “early warning period/drought limit water level” ( $T_d$ ,  $DL$ ) format to represent the drought limit water level. The drought early warning period  $y$  is related to reservoir storage  $S$  at the end of flood season, inflow  $x$  during dry season and water supply rules  $I$ . Thus,  $y = f(S, x, I)$ .

(3) To overcome the uncertainty of the inflow process during the dry season and to maintain the continuous early drought warning effectiveness of the drought limit water level, a rolling computation mechanism has been added to the determination of drought limit water level.

(4) This paper proposed a dynamic drought limit water level for reservoir operation to aid water authorities in the decision-making process while confronting drought threats. Managers can use water level alone to monitor the status of drought.

(5) At present, the monitoring system of reservoir water level has been built in different parts of the world, which laid the foundations for the implementation of the rolling computation of the drought limit water level presented in this paper. The dynamic management of reservoir can be achievable through regulation mode of reservoir presented in this paper. So, the findings of this study are also very useful to other reservoirs.

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