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Hydrological drought in the lower reaches of the Yangtze River (China): a 70-year data analysis

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The combined impact of climate change and human activity has brought uncertainty regarding hydrological drought in the lower reaches of the Yangtze River (LYR), thereby threatening the security of regional water resources. To address this uncertainty, based on data from over 70 years, the trends, mutations, and causes of hydrological drought in the LYR were analyzed using the Mann–Kendall test method. The results of this study show that the most extreme annual hydrological drought situation defined by the daily minimum value improved, but the scenario defined by the monthly average intensified in September and October after the flood season, with a mutation in the 2000s after the Three Gorges Reservoir. The continuous decline in water availability during the flood season and the water storage of reservoirs after flooding made 2022 the most severe drought period in nearly 70 years. The rapid storage of reservoirs after flooding has promoted hydrological droughts in the LYR. In future scenarios, the impact of riverbed cutting on hydrological drought should be comprehensively evaluated, and the effects of future tide level changes under global climate change conditions should be measured.

KEYWORDS

hydrological drought, trend and mutation, Lower Yangtze River, extreme drought, downstream reservoir

1 Introduction

Hydrological drought refers to the phenomenon wherein river runoff is lower than its normal value or the water level decreases significantly (Linsley et al., 1975) and has been reported to be closely related to vegetation growth (Xiao et al., 2021; Mo et al., 2022). Under the influence of multiple factors such as climate change and human activity, hydrological droughts have occurred at a global scale over the past few decades (Kumar et al., 2014; Wang et al., 2015) and may continue well into the future (Rahiz and New, 2013). These changes have manifested as a gradual increase in the drought period (Seager et al., 2022)

and an increase in drought severity in dry areas (Seager et al., 2022), which can cause a series of adverse effects on river management. For example, droughts can drive changes in the availability of water resources during the dry season, leading to crises in water supply management (Zhao et al., 2021), affecting water intake along riverbanks (Ke et al., 2023), and deteriorating navigation conditions (Xia et al., 2021). Ecologically, a drought state in rivers can also affect phytoplankton (Townsend and Douglas, 2017; da Costa et al., 2022) and the transport of organic and inorganic substances in the water (Ran et al., 2017; Shang et al., 2023). Hydrological drought has an even stronger impact on tidal river sections, as it may lead to an increase in tidal dynamics, thereby enhancing sediment resuspension and considerably affecting channel evolution (Hua et al., 2020; Wang et al., 2020). In tidal river sections, drought conditions can also invite the invasion of saltwater from the ocean, thus adversely affecting the utilization of freshwater resources along the river (Xie et al., 2017; Zhu et al., 2021). In addition, tides have a substantial impact on the transport of phytoplankton (Sebastiá et al., 2013), mercury (Chakraborty et al., 2019), and sulfur (Xu et al., 2019) from rivers to the ocean under drought conditions, thereby affecting coastal ecosystems. Therefore, studying the changing characteristics and causes of drought in tidal river sections is important for maintaining water resources and ecological security.

The Yangtze River, the largest river in China, has experienced increasingly intense human activity in recent decades. Coupled with the impacts of climate change, regional droughts have occurred over time (Feng et al., 2018). In some water systems, regional droughts have intensified, posing substantial risks to water security in regions such as Dongting Lake (DTL) (Ge et al., 2022) and Poyang Lake (PYL) (Wu et al., 2021; Xiong et al., 2024). In 2022, the Yangtze River Basin (YRB) experienced its largest drought in nearly a century (Guan and Zeng, 2022). The main stream of the Yangtze River and the DTL and PYL areas connected to it (Lei et al., 2023) experienced severe drought, which has attracted significant research attention. The drought situation of the Yangtze River in recent decades is related to both the decrease in precipitation caused by climate change (Ye et al., 2017) and human activities and is the result of a combination of various factors (Chai et al., 2019). Although the operation of cascade reservoirs, led by the Three Gorges Reservoir (TGR) in the upper reaches of the Yangtze River (UYR), has increased the annual average flow discharge in dry seasons in the reaches downstream of the TGR, it has also advanced the start of the dry season due to water storage after the flood season (Tian et al., 2019) and significantly exacerbated severe hydrological droughts from late September to November (Lai et al., 2014). In addition, since the reservoir impoundment in 2003, the riverbed downstream of the TGR has been downward cut, resulting in a significant decrease in the water level, especially during dry seasons (Yang et al., 2021; Mei et al., 2023). This has further affected the hydrodynamic characteristics of tidal river sections in the lower reaches of the Yangtze River (LYR) (Yuan et al., 2019). The data analysis from 1982 to 2015 indicates that extreme drought events in the YRB have a widespread negative impact on vegetation activity (Jin et al., 2021). As droughts become increasingly severe, the

inhibitory effect of drought on vegetation growth becomes more significant (Xu et al., 2024). One study using the catastrophic meteorological drought event in the YRB in 2022 as an example shows that vegetation in the middle and lower reaches of the Yangtze River has higher sensitivity response to drought (Zhao et al., 2024). The proportion of severe and extreme droughts in autumn in the YRB is expected to increase in future years (Zhang et al., 2023). Therefore, it is necessary to further clarify the historical trends and influencing factors of hydrological drought in the LYR to respond more effectively to future changes. Because hydrological characteristics remain consistent in the downstream segments of rivers with reservoirs built upstream (Liu et al., 2024), findings in the LYR can provide a reference for other rivers.

Several studies have focused on typical hydrological drought years in the YRB, including 2006 (Chai et al., 2019), 2011 (Shen et al., 2012; Yang et al., 2013), 2019 (Xu et al., 2020; Liu and Zhou, 2021; Ran et al., 2021), and 2022 (Liang et al., 2023; Lyu et al., 2023). Other studies have also analyzed droughts in the middle reaches of the Yangtze River (MYR) and LYR based on long data series. For example, Shan et al. (2018) analyzed the long-term spatiotemporal characteristics of abrupt dry-wet change events in the MYR and LYR based on daily precipitation observations from 75 rainfall stations during the summers of 1960–2015. Wu et al. (2006) defined long-term drought and flood mutation indices in the MYR and LYR using daily precipitation data from the summers of 1957–2003. Zhang and Wang (2012) analyzed the monthly precipitation during the rainy season and winter in the MYR and LYR from 1961 to 2010. However, owing to its geographical location, the trends and causes of drought in the tidal section of the Yangtze River differ from those in other areas of the basin. The drought dynamics in this region will inevitably create additional requirements for scheduling in upstream cascade reservoir water resource management (Cao et al., 2023; Ding et al., 2023; Ouyang et al., 2023). With the construction of lake water conservancy hubs, the drought dynamics in the LYR may become increasingly complex (Lai et al., 2017). Therefore, it is necessary to conduct a detailed analysis of the characteristics and causes of the recent hydrological drought in the LYR, especially in 2022, to guide the operation of cascade reservoirs in the UYR and address extreme drought in the LYR. To this end, based on data obtained over more than 70 years from the mainstream and major tributaries of the MYR, this study analyzed the trend and mutation characteristics of hydrological drought and its causes in the tidal section of the LYR. These results can support water resource management activities in the LYR.

2 Materials and methods

2.1 Study area and data

The LYR starts in Hukou County at the mouth of the PYL and ends at the Yangtze River Estuary (YRE), with no large tributaries whose total length is over 1,000 km merging along the way. The Datong hydrological station is located approximately 219 km below

the Hukou hydrological station and 624 km above the YRE. Hydrological drought is affected by upstream runoff and downstream tides in different periods of the year. Datong is the last hydrological station on the Yangtze River with daily average flow discharge (\bar{Q}_d) and water level (\bar{Z}_d) data before flowing into the ocean. Therefore, this study used representative data from the Datong station to study the hydrological drought situation in the LYR.

Runoff at the Datong station mainly originates from the UYR, large tributaries, and water systems in the MYR, such as the Han River (HR), DTL, and PYL water systems. In this study, runoff sources in Datong were divided into five categories. The first originated from the UYR, which was represented by the Yichang hydrological station. The second originated from the DTL water system, which is the sum inflow of the Xiang, Zi, Yuan, and Li Rivers and is represented by the Xiangtan, Taojiang, Taoyuan, and Shimen hydrological stations. At the outlet of DTL, \bar{Q}_d measurement data are collected by the Qilishan station, which can be used to characterize the amount of water flowing out of DTL. These data also include the amount of water that flows into DTL from the main stream of the Yangtze River through the Songzi, Taiping, and Ouchi entry points. These data are also collected by the Yichang station. Therefore, to avoid duplicate statistics, this study takes the sum of the inflow of the above four rivers in the second category originating from the DTL water system. The third was from the HR, which was represented by the Xiantao hydrological station. The fourth originated from the PYL water system, which was determined as the sum of inflows of the Gan, Fu, Xin, Rao, and Xiu Rivers. The total runoff of these rivers was represented by data from the Hukou hydrological station, which is located at the exit of the PYL. The fifth comprised runoff from other small tributaries. The study area and the diversion and confluence relationships between the rivers and lakes are shown in [Figure 1](#).

The data used in this study were the measured \bar{Q}_d and \bar{Z}_d values from hydrological stations in each river ([Figure 1](#)). To analyze the impact of tides on hydrological drought in the study area, hourly tide level (Z_h) data from the Nanjing, Zhenjiang, Tianshenggang, Yingchuangang, Xuliujing, and Baimao tide stations in the LYR were also collected. The data for each station are listed in [Table 1](#).

Reliable data are crucial for trend and mutation tests. All data were sourced from the Bureau of Hydrology, Changjiang Water Resources Commission. These data underwent hydrological data compilation ([China, 2020](#)) before being released. [Table 2](#) presents the reliability analysis results of the annual minimum \bar{Q}_d and \bar{Z}_d at Datong station. Data from all 73 years were deemed valid, with a standardized Cronbach's alpha ([Johnson, 2021](#)) of 0.949, indicating very high reliability.

2.2 Mann–Kendall method

The Mann–Kendall method is typically used to analyze river hydrology ([Du et al., 2022](#)). This method was applied to conduct trend and mutation evaluations of hydrological droughts. We used a data series (x_1, x_2, \dots, x_n) with assumed independent and random distributions. First, statistic D is calculated as follows:

$$D = \sum_{i=1}^{n-1} \sum_{j=i+1}^n \text{sgn}(x_j - x_i)$$

where x_i and x_j are the observed data corresponding to the i and j time series, respectively, and $i < j$. sgn is a symbolic function:

$$\text{sgn}(x_j - x_i) = \begin{cases} 1 & (x_j - x_i) > 0 \\ 0 & (x_j - x_i) = 0 \\ -1 & (x_j - x_i) < 0 \end{cases}$$

After standardizing the D value, the test statistic Z is calculated as follows:

$$Z = \begin{cases} \frac{D-1}{\sqrt{V_{ar}(D)}} & D > 0 \\ 0 & D = 0 \\ \frac{D+1}{\sqrt{V_{ar}(D)}} & D < 0 \end{cases}$$

where $V_{ar}(D)$ denotes variance. For a given significance level α , if $|Z| \geq Z_{1-\alpha/2}$, the original assumption is unacceptable; more specifically, there is an obvious change trend at significance level α for the time series data. In this method, the p -value was inversely calculated through the $Z_{1-\alpha/2}$. If $p > \alpha$, there is no changing trend in the sequence and vice versa. $Z > 0$ indicates an upward trend, whereas $Z < 0$ indicates a downward trend.

For mutation detection, S_k is used to represent the cumulative number of the j th sample data $x_j - x_i$ when $(1 \leq i \leq j)$:

$$S_k = \sum_{j=1}^k r_j, \quad r_j = \begin{cases} 1 & x_j > x_i \\ 0 & x_j \leq x_i \end{cases} \quad i = 1, 2, \dots, j; \quad k = 1, 2, \dots, n$$

The S_k is standardized as follows:

$$UF_k = \frac{[S_k - E(S_k)]}{\sqrt{V_{ar}(S_k)}}$$

where $E(S_k)$ is the mean of S_k and $V_{ar}(S_k)$ is the variance. For a given significance level α , $|UF_k| > U_\alpha$ indicates an obvious change trend in all datasets. UF_k can form a curve. UB_k can be calculated using this method to produce an inverse sequence. At a given significance level, for example $\alpha = 0.05$, the critical value is ± 1.96 . The UF_k and UB_k curves and ± 1.96 straight lines can be drawn in one chart. If $UF_k > 0$, the dataset exhibits an upward trend, with a downward trend for $UF_k < 0$. If these variables plot beyond the critical straight line, the change in the trend is significant. A zone exceeding the critical boundary was defined as the moment at which a mutation appeared. If UF_k and UB_k cross and the crossover point is within the critical line, the time corresponding to the intersection is the start time of the mutation.

3 Results

3.1 Trend and mutation of annual minimum values

[Figure 2](#) shows the trend and mutation analysis results of the annual minimum \bar{Q}_d and \bar{Z}_d at Datong station over the past 70

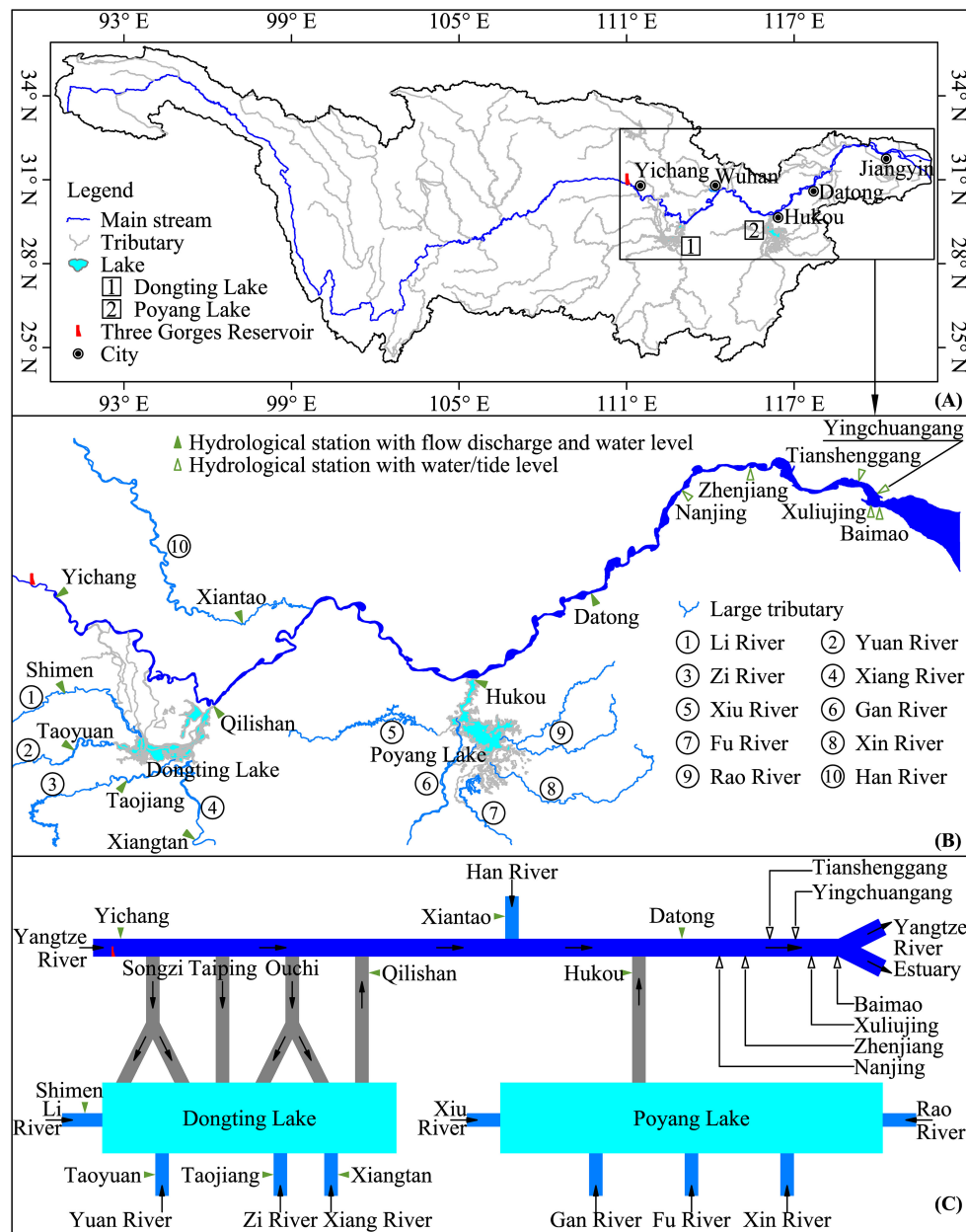


FIGURE 1 Study area showing (A) the Yangtze River Basin, (B) middle and lower Yangtze River, and (C) the diversion and confluence relationship between rivers and lakes.

years. The trend analysis results (Figures 2A, B) show that the p values of the annual minimum \bar{Q}_d and \bar{Z}_d were all close to 0, below the confidence level of 0.05, and the Z values were all >0 , indicating that the annual minimum \bar{Q}_d and \bar{Z}_d exhibited an upward trend. The mutation analysis results (Figures 2C, D) reveal that there were no cross-phenomena between UB and UF within the confidence interval for the annual minimum \bar{Q}_d , indicating a non-significant mutation. However, for the minimum \bar{Z}_d , the UB and UF curves crossed within the confidence interval around 1989, indicating a mutation during this period.

Notably, the date of occurrence of the minimum \bar{Q}_d within a year did not always correspond to that of \bar{Z}_d at Datong. Figure 3

shows the statistical results of this mismatch. Since the 1950s, the number of years in which the two events occurred on different dates has increased each year (Figure 3A). In particular, since 1996, the dates on which the two occurrences appeared each year have been almost inconsistent, and their cumulative frequency has annually increased, reaching 53.4% by 2023 (Figure 3B). Figure 3C gives the number of days in which the minimum \bar{Z}_d appeared behind the \bar{Q}_d within the year. In rare years such as 1956, 1998, and 2011, the minimum \bar{Q}_d and \bar{Z}_d values appeared at the beginning and end of the year, respectively, with an interval of more than 320 days. In the past 20 years, there has been an upward trend in delayed days, with 5 years in which the delayed days exceeded 26 days and another 4

TABLE 1 Data of the hydrological stations utilized in this study.

Name	Data type	Time Series	River (Lake)	Distance to the YRE (km)	Source
Yichang	\bar{Q}_d	1951~2023	Yangtze Rive	1837	Bureau of Hydrology, Changjiang Water Resources Commission
Hukou			Poyang Lake	/	
Datong	\bar{Q}_d, \bar{Z}_d	1951~2023	Yangtze River	624	
Nanjing	Z_h	1980~2020		398	
Zhenjiang				328	
Tianshenggang				148	
Yingchuangang				133	
Xuliujing				101	
Baimao				91	
Xiangtan	\bar{Q}_d	1951~2023		Xiang River	
Taojiang			Zi River		
Taoyuan			Yuan River		
Shimen			Li River		
Xiantao		1961~2023	Han River		

years ranging from 3 to 5 days. This result indicates that the minimum \bar{Z}_d at Datong within the year was not entirely determined by the minimum \bar{Q}_d but was also related to other factors.

3.2 Trend and mutation of monthly average values

Figure 4 shows the trend and mutation analysis results for the monthly average flow discharge (\bar{Q}_m) and water level (\bar{Z}_m). Regardless of \bar{Q}_m or the \bar{Z}_m , the p -values from January to March

before the flood season and from September to November after the flood season were all <0.05 , indicating a significant trend in the \bar{Q}_m and the \bar{Z}_m . The D -value from January to March was >0 , indicating an upward trend in these 3 months, whereas the D -value from September to November was <0 , indicating a downward trend in these 3 months.

The mutation analysis results (Figure 5) indicated that the UB and UF of the \bar{Q}_m from January to March and from September to November both crossed within the confidence interval, indicating a mutation for \bar{Q}_m . Mutations in January, February, and December occurred in the 1990s, whereas mutations in March, September, and October occurred in the 2000s. The mutation characteristics of the \bar{Z}_m were similar to those of \bar{Q}_m .

TABLE 2 Reliability analysis results of the annual minimum \bar{Q}_d and \bar{Z}_d at Datong station.

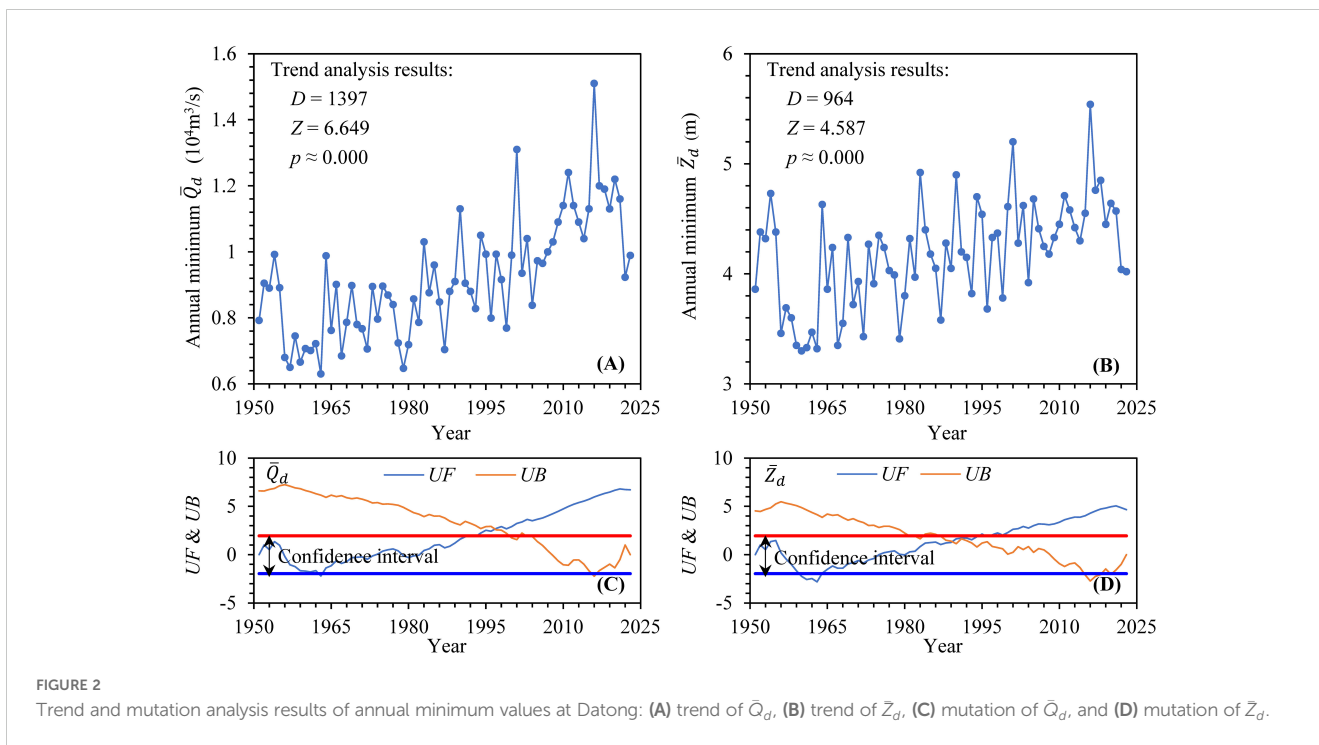
	Item	N	%
Summary	Valid	73	100.0
	Excluded	0	.0
	Total	73	100.0
Reliability statistics	Cronbach's alpha	Cronbach's alpha based on standardized items	N of items
	.001	.949	2
Item statistics			
Item	Mean	Std. deviation	N
Annual minimum \bar{Z}_d	4.1755	0.47781	73
Annual minimum \bar{Q}_d	9180.4110	1771.85985	73

3.3 Extreme drought in 2022

In 2022, the YRB experienced an extreme hydrological drought from the beginning of the flood season onward. This drought can be divided into four stages (Figure 6): a pre-flood season with abundant water, an initial flood season with a rapid decline, a main flood season with a continuous decline, and a post-flood season with the driest season.

In stage 1 in June 2022, owing to the influence of abundant rainfall in the YRB, \bar{Q}_d and \bar{Z}_d at Datong began to increase in volatility at a rate significantly higher than that of the multiyear average of the same period. The average elevated amplitude of \bar{Z}_d was 1.6 m, and the maximum was 2.41 m, which occurred on June 9. The annual maximum \bar{Q}_d (61800 m³/s) and \bar{Z}_d (13.38 m) appeared on June 24, after which the values began to decline rapidly.

In stage 2 in July, the \bar{Q}_d and \bar{Z}_d at Datong continued to rapidly decline, with an average daily decline of 0.11 m for \bar{Z}_d , and the

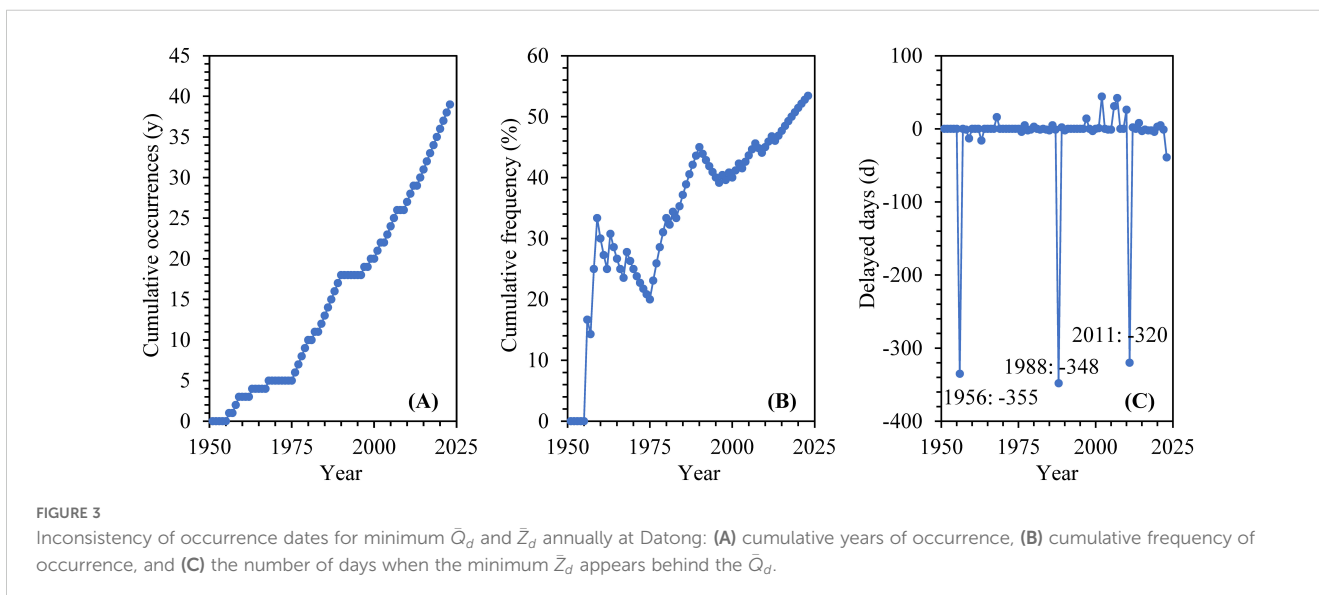


maximum of 0.19 m occurred on July 26. \bar{Q}_d and \bar{Z}_d on July 4 changed from higher to lower than the multiyear average value during the same period. Afterwards, the depressed magnitude gradually increased, from 0.12 m on July 4 to approximately 3.6 m at the end of July for \bar{Z}_d , with an average depressed magnitude of approximately 1.9 m. On July 27, \bar{Q}_d and \bar{Z}_d at Datong dropped to 35,400 m³/s and 9.83 m, respectively, ranking the 10th lowest values in the same period. The lowest monthly values of \bar{Q}_d (31,300 m³/s) and \bar{Z}_d (9.06 m) that appeared on July 31 ranked the fourth lowest in recorded history.

In stage 3 in June, the average daily decline of \bar{Z}_d was 0.11 m, with the largest of 0.28 m on August 5. The \bar{Q}_d and \bar{Z}_d in June were lower overall than the historical average, and the depressed

magnitude continued to increase, from 3.6 m at the beginning of the month to 5.6 m at the end of the month for \bar{Z}_d , with an average of approximately 5.0 m. On August 18, \bar{Q}_d (19,600 m³/s) and \bar{Z}_d (6.56 m) reached the penultimate lowest values during the study period. The monthly lowest \bar{Q}_d and \bar{Z}_d were 15,400 m³/s and 5.65 m, respectively, which occurred on August 31. The \bar{Z}_d was 0.92 m lower than the lowest value recorded in history.

In stage 4, beginning in early September, the cascade reservoirs in the UYR entered a concentrated storage period, and the \bar{Q}_d and \bar{Z}_d at Datong continued to decline. The lowest annual \bar{Q}_d was 6,400 m³/s, which occurred on September 15. By November 16, the lowest annual \bar{Z}_d was 3.91 m, which was below the drought warning level (4.3 m) for 22 days, indicating a severe hydrological drought.



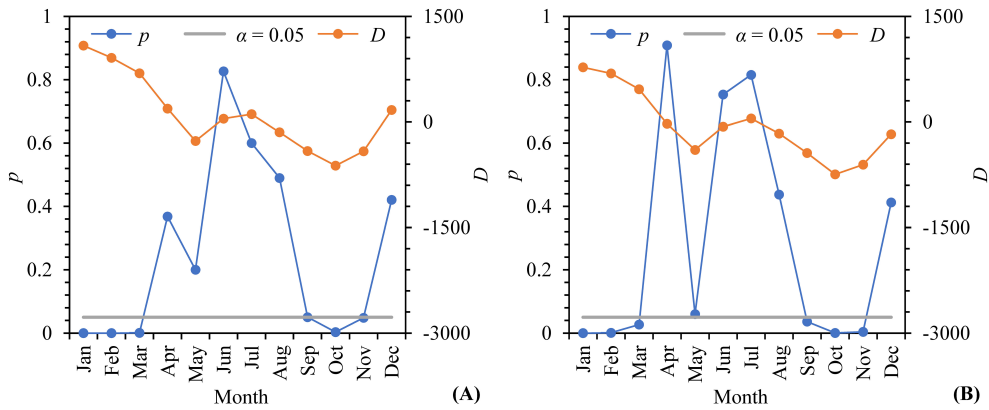


FIGURE 4 Trend analysis results of (A) \bar{Q}_m and (B) \bar{Z}_m .

Since the 1950s, the YRB has experienced multiple extreme droughts based on annual runoff, as shown in Figure 7A in 1978, 2006, 2011, 2022, and 2023. Although the annual runoff in 2022 was not the smallest, after mid-August, \bar{Q}_d and \bar{Z}_d in Datong were lower

than those of the former typical drought years (Figures 7B, C). There were 41 days with a \bar{Q}_d less than the drought warning flow discharge ($10,000 \text{ m}^3/\text{s}$); these days were mainly concentrated from October to December, with November receiving the most.

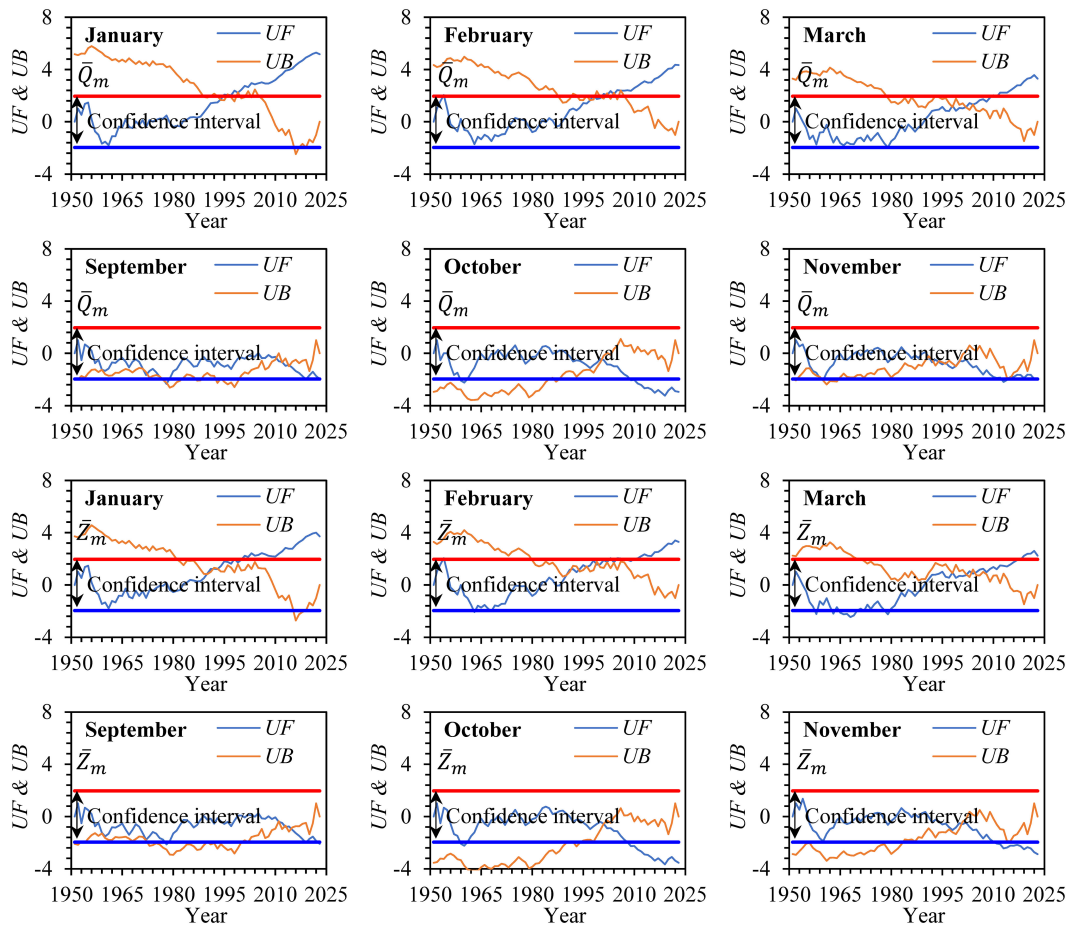


FIGURE 5 Mutation analysis results of \bar{Q}_m and \bar{Z}_m from January to March and September to November.

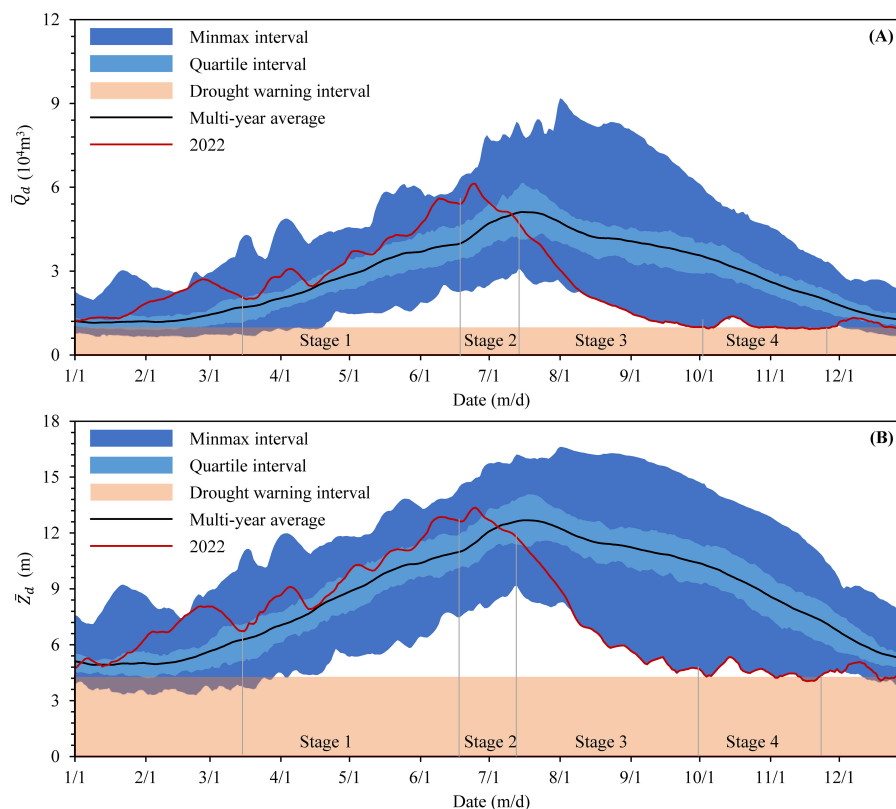


FIGURE 6

Comparison of (A) \bar{Q}_d and (B) \bar{Z}_d processes at Datong in 2022 with values recorded on the same day in history.

Compared with previous drought years, 2022 constituted a typical post-flood drought.

4 Discussion

4.1 Impact of runoff

Although precipitation is a fundamental cause of drought, it is ultimately converted into runoff for specific river reaches. Figure 8 shows variations in the annual runoff composition of Datong during different historical periods. Overall, the annual runoff source was relatively stable, and the UYR and the two lake water systems consistently remained the main sources. The proportion of annual runoff from the UYR, determined at Yichang station, fluctuated between 39.6% and 59.7%, with an average of approximately 48.4%. The proportion of the total annual runoff in the two lake water systems fluctuated between 22.2% and 46.4%, with average proportions of 18.6% and 16.7% in the DTL and PYL water systems, respectively. Compared with the two periods of 2003–2010 (before the normal storage of the TGR) and 2011–2023 (after the normal storage of the TGR), the proportion of annual runoff sources at Yichang increased slightly by 0.7%, whereas that of the DTL and PYL water systems increased by 1.9%, indicating relatively small changes.

Judging by the composition of different months (Figure 9), the runoff from Yichang increased significantly from January to May

from 2011 to 2023, with an average increase of 27%–72% (approximately 7–8.5 billion m^3) compared to runoff before 2011. This increase was even greater in February (72%). However, in September and October after the flood, runoff decreased by 24% (15.7 billion m^3) and 20% (9 billion m^3), respectively.

Overall, although the sources of annual runoff at Datong did not change, the changes in monthly runoff within the year were more obvious, mainly because of the influence of reservoir water storage in the UYR. When the water level of the reservoir decreased before the flood season, the runoff from Yichang increased, whereas it substantially decreased after the flood season (Feng et al., 2020). Because of the longer duration of the reservoir subsidence period compared with the storage period, the trend of turning from flood to drought after the flood season was more obvious at Datong station. The storage of cascade reservoirs played an important role in the hydrological drought situation in Datong after the flood season.

Widespread drought has continued to occur in various tributaries of the basin in 2022. Figure 10 shows a comparison of the runoff composition at Datong from July to October between 2022 and the typical drought years. During this period, the runoff levels from the UYR, DTL, PYL, and HR were all significantly lower. The water volume from the UYR was close to that in 2006, whereas those in the PYL, HR, and other areas in the MYR were the lowest during these drought years. As a result, the relatively small inflow in

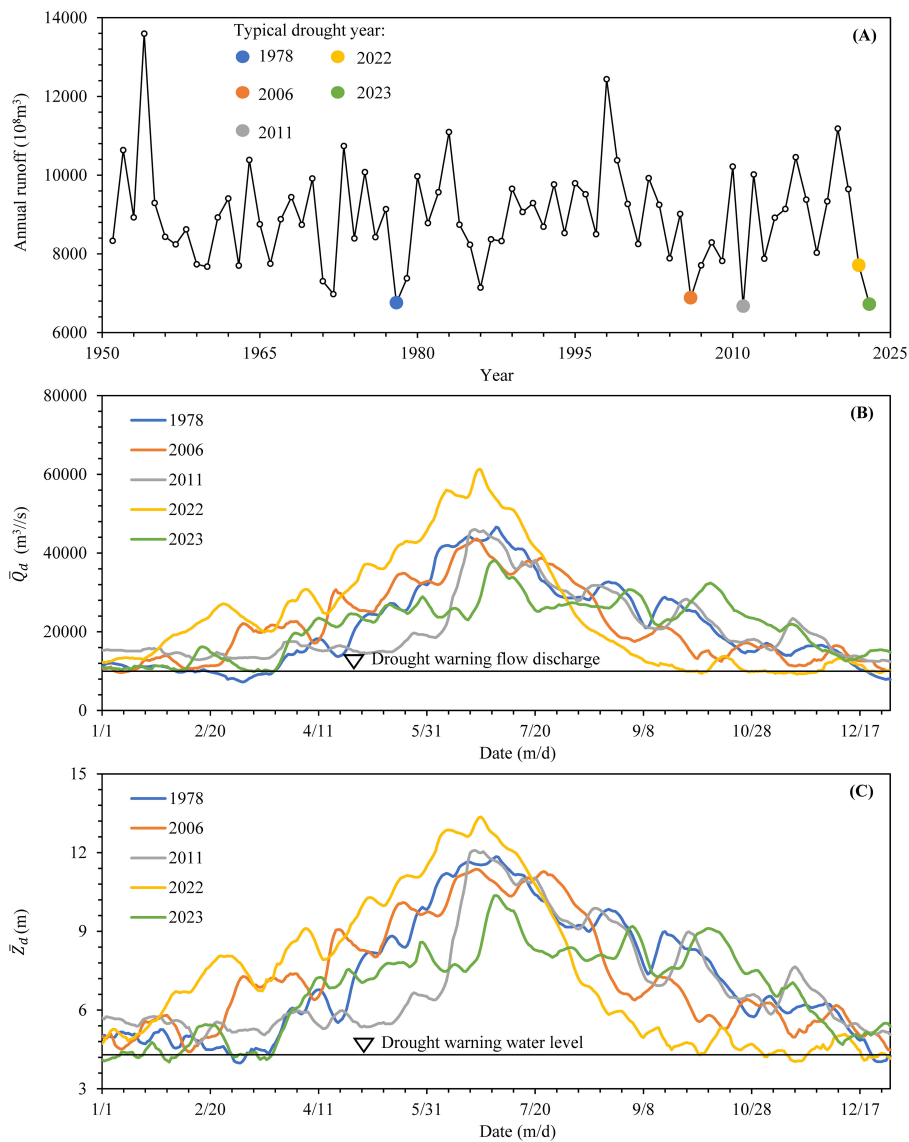


FIGURE 7 Comparison of the drought process at Datong between 2022 and typical historical drought years: (A) typical drought years defined by annual runoff since the 1950s, (B) comparison of \bar{Q}_d , (C) comparison of \bar{Z}_d .

the MYR in 2022 also substantially affected the drought conditions observed at Datong.

4.2 Influence of riverbed evolution

Since the application of the TGR from 2003 to 2021, the riverbeds in the MYR and LYR have mainly eroded (Xu et al., 2023). For the tidal reach from Datong to YRE, the erosion amount for the bankfull channel (corresponding water levels for Datong and Jiangyin are 10.06 m and 2.66 m, respectively) is 18.82×10^8 m³, of which 62.9% occurred between Datong and Jiangyin, mainly concentrated in low-water river channels, and the erosion intensity increased year by year. After a riverbed is eroded and cut down, it inevitably causes a decrease in the water level under the same inflow and tidal

conditions, thereby exacerbating the hydrological drought defined by the water level. Figure 11 shows the correlation between the lowest annual \bar{Z}_d at the Datong station and Z_h at the downstream Nanjing station. There is a close correlation between them, but this correlation varies in different periods. In recent decades, under the same lowest Z_h conditions at Nanjing, the lowest \bar{Z}_d at Datong has slightly increased, with an amplitude of generally within 0.2 m, which has a certain buffering effect on drought conditions. Although the erosion amplitude of the riverbed in the LYR is not yet severe, in future years, with the continuous operation of cascade reservoirs in the UYR, the riverbed in the LYR will inevitably suffer more severe erosion (Hu et al., 2023), and a further increase in the erosion amplitude will exacerbate the water level decrease at the Datong station. Therefore, future drought trends in the LYR will inevitably be affected by riverbed cutting and should receive sufficient attention.

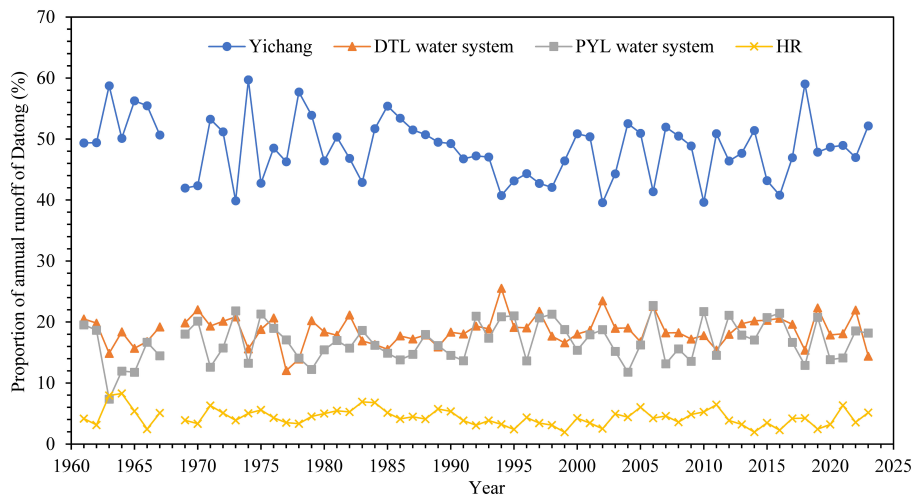


FIGURE 8 Sources of annual runoff at Datong since the 1960s.

The downcutting of the riverbed can also cause a decrease in \bar{Z}_d at the same \bar{Q}_d . Figure 12 shows the changes in the relationship between \bar{Z}_d and \bar{Q}_d at Datong station over the past 20 years. It can be seen that the relationship has been relatively stable, but the \bar{Z}_d still slightly decreases when the \bar{Q}_d is $<40,000 \text{ m}^3/\text{s}$, and the bigger the \bar{Q}_d , the smaller drop of the \bar{Z}_d . When the \bar{Q}_d are $15,000 \text{ m}^3/\text{s}$, $25,000 \text{ m}^3/\text{s}$, and $35,000 \text{ m}^3/\text{s}$, compared to 2001, the \bar{Z}_d drops in 2021 are 0.36 m, 0.28 m, and 0.16 m, respectively. When the \bar{Q}_d further increases, the \bar{Z}_d remains basically unchanged. This is

consistent with the above-mentioned riverbed erosion law, that is, erosion is mainly concentrated in low-water river channels. As a result, \bar{Z}_d decline is also mainly concentrated in smaller \bar{Q}_d .

4.3 Effect of tide currents

Tidal reach is affected by both the input runoff from the upstream river and downstream tidal currents. The tidal level at

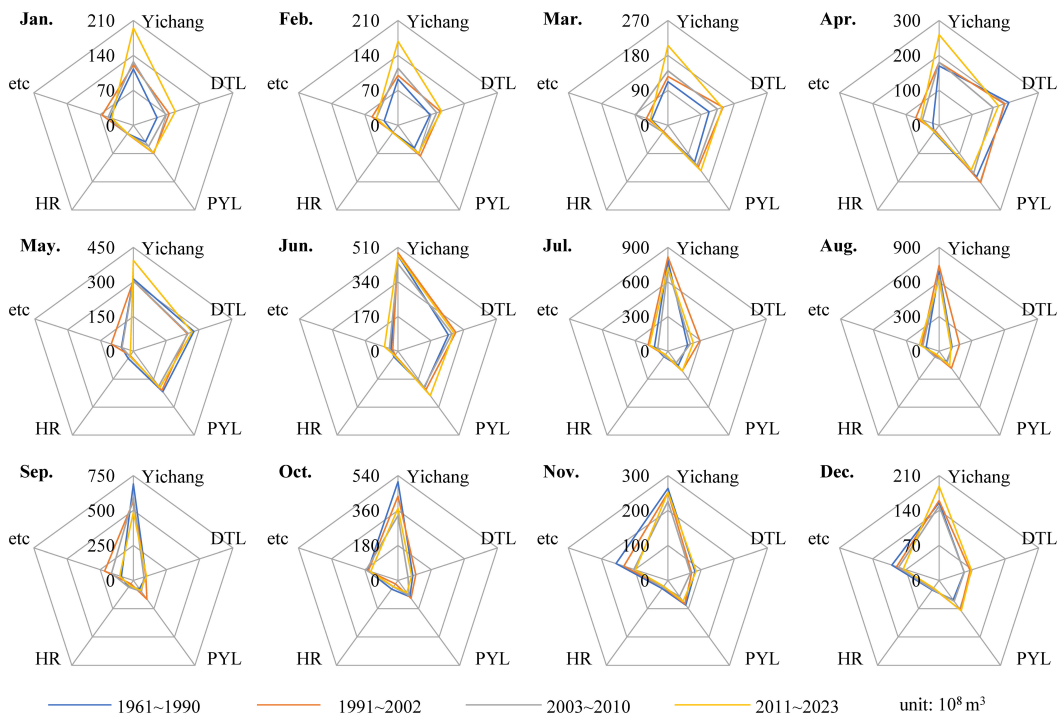


FIGURE 9 Composition of monthly runoff of Datong station.

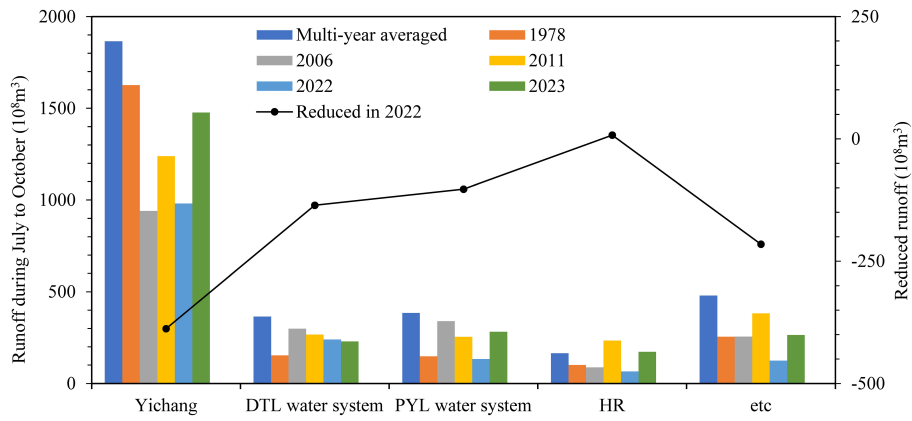


FIGURE 10 Comparison of the runoff sources composition at Datong from July to October between 2022 and other typical drought years.

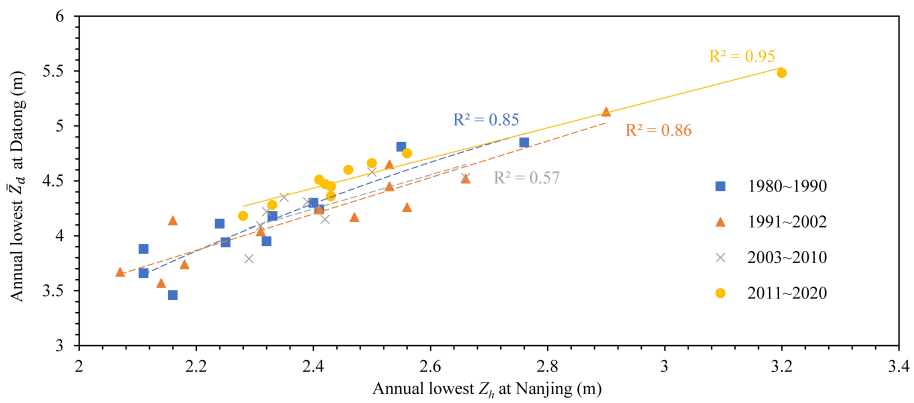


FIGURE 11 Correlation of the lowest water level between Datong and Nanjing stations.

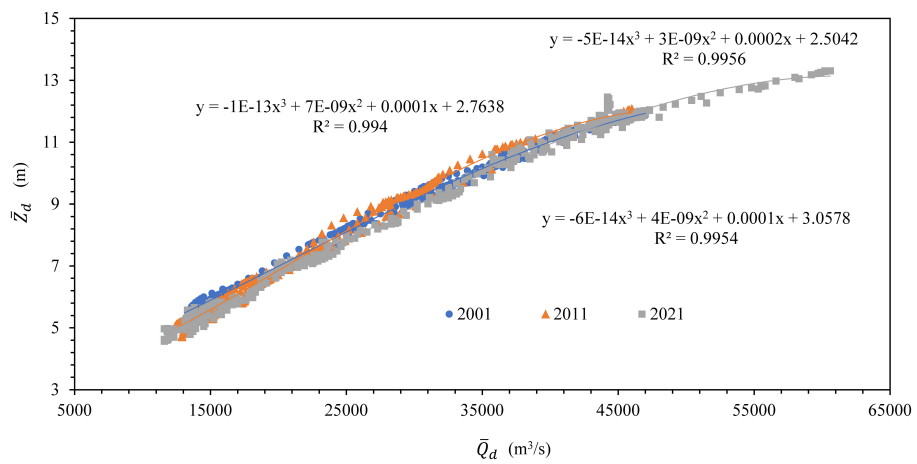


FIGURE 12 The relationship between \bar{Q}_d and \bar{Z}_d at Datong station in recent 20 years.

the Baimao hydrological station, located at the entrance of the YRE, was selected to analyze the effects of tidal currents. Figure 13 shows the correlation between the characteristic Z_h at the Baimao station and those distributed along the LYR from 2010 to 2020. A close linear correlation exists between Baimao and other stations in the LYR for the annual average low Z_h (Figure 13A). Except for the correlation coefficient with Tianshenggang, which was 0.61, the linear correlation coefficients with the other stations were above 0.9. This result indicates that, on average, low Z_h in the YRE will have a significant impact on hydrological drought in the LYR. However, for the lowest annual Z_h , the correlation between Baimao and the stations in the LYR above Xuliujing was extremely low, with a linear correlation coefficient generally within 0.2 as shown in Figure 13B. In summary, the extremely low Z_h in the YRE had a relatively small impact on the overall extreme drought in the LYR. Therefore, although the average low Z_h had an impact on drought in the LYR, because the downstream low Z_h is not controllable by human activities, future research on the impact of downstream tidal currents on droughts in the LYR should be conducted from a global climate perspective.

4.4 Impact of drought on water intake and shipping

The water intake in tidal river sections is not only affected by the lowest \bar{Z}_d but also the \bar{Q}_d . This is because the main purpose of water

intake is to utilize freshwater resources, and when the \bar{Q}_d is low, saltwater intrusion is extremely detrimental to the acquisition of freshwater resources. In recent years, under the comprehensive influence of continuous erosion of the riverbed and the replenishment scheduling of the TGR during the dry season, the frequency of extremely low \bar{Q}_d at Datong station has decreased, and the extremely low \bar{Z}_d has been raised. Therefore, for general dry water conditions, the impact of riverbed cutting is greater than the replenishment effect of reservoirs, especially since 2020, in the flow range of 11,000–25,000 m³/s, under the same inflow \bar{Q}_d , the measured average and minimum \bar{Z}_d have both decreased by approximately 0.35 m.

Considering the relationship shown in Figures 11, 12, the \bar{Z}_d was found to decrease by 0.22 m for every 1,000 m³/s decrease in \bar{Q}_d at Datong station, and the low Z_h at Nanjing station decreased by 0.53 m for every 1 m decrease in \bar{Z}_d , approaching a ratio of 2:1. To maintain the low Z_h of Nanjing station with a 95%–99% guarantee rate without decreasing, the \bar{Q}_d of Datong station needs to gradually increase from 10,000 m³/s to 12,500 m³/s. To ensure the safe operation of the existing water intake project and maintain the Z_h at Nanjing station above 2.3 m, the minimum \bar{Q}_d of Datong should be increased to 11,300 m³/s.

The continuous decline in \bar{Z}_d caused by hydrological drought will deteriorate the navigation environment, which will significantly impact shipping. The narrowing of the waterway after \bar{Z}_d decreases will make it difficult for ships to rendezvous and overtake. Due to \bar{Z}_d limitations, cargo ship loads will need to decrease to meet these

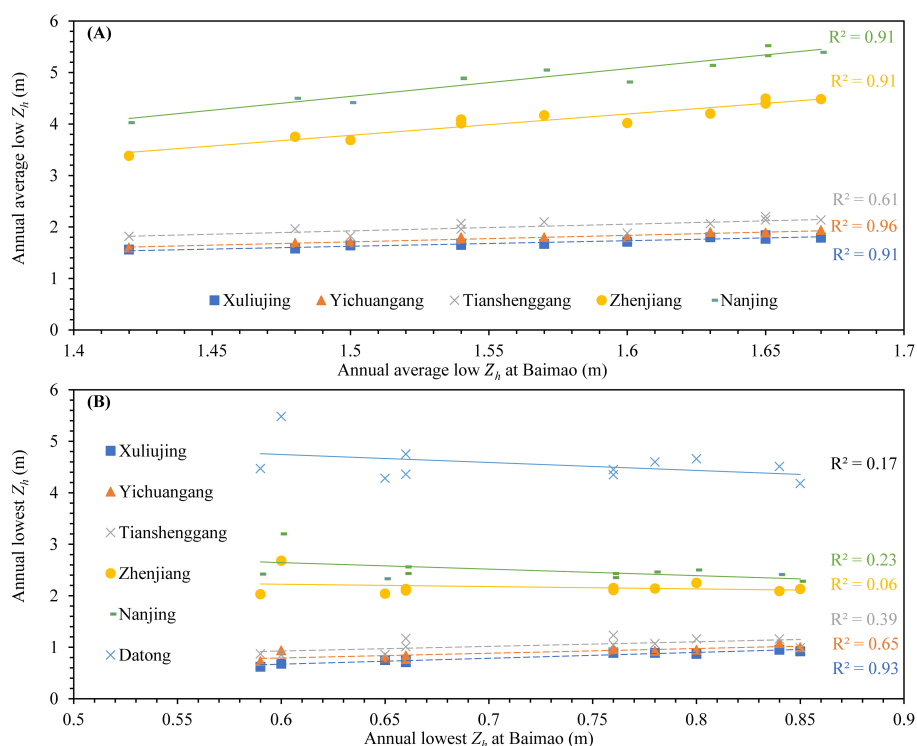


FIGURE 13 Correlation of the characteristic Z_h between the stations along the LYR: (A) annual average low Z_h , and (B) annual lowest Z_h .

navigation conditions. In addition, the rapid drop in \bar{Z}_d after the flood season can also make it difficult to maintain the corresponding depth of the sea vessel channel, leading to closures and reduced shipping efficiency.

5 Conclusions

Based on an over 70-year dataset, we analyzed the hydrological drought situation and its causes in the lower reaches of the Yangtze River using the Mann–Kendall method. The conclusions are as follows.

1. Both the annual minimum flow discharge and water level at Datong station showed an upward trend over the past 73 years. There was no mutation in the annual minimum flow discharge, but the mutation for annual minimum water level occurred around 1989. The dates on which these two events occurred each year have almost remained inconsistent since 1996, exhibiting as a delayed water level behind flow discharge and even appearing at the beginning and end of the year, respectively.
2. For both monthly average flow discharge and water level, there was a clear upward trend from January to March before the flood season and a downward trend from September to November after the flood season. For both variables, changes observed in January, February, and December occurred in the 1990s, whereas those in March, September, and October occurred in the 2000s.
3. The extreme drought in 2022 showed four distinct stages, with a rapid decline in the water situation during the initial flood season, which started the prelude to drought. The continuous decline during the flood season and the storage of reservoirs after the flood season caused 2022 to be the most severe drought period in nearly 70 years. In the future, the joint operation of cascade reservoirs can alleviate the hydrological drought more effectively in the lower reaches of the Yangtze River under extreme weather conditions. Further research to determine optimal strategies for achieving this goal is required.
4. Although the source of annual runoff in the lower reaches of the Yangtze River has not changed, the rapid storage of reservoirs after floods intensified the trend of the lower reaches of the Yangtze River from flooding to drought and promoted hydrological drought. Lower runoff from the DTL, Poyang Lake, and HR also promoted extreme drought in the lower reaches of the Yangtze River in 2022.
5. Presently, the impact of slight riverbed erosion on drought in the lower reaches of the Yangtze River is not significant. With the continuous operation of reservoirs in the upper reaches of the Yangtze River in future years, continued riverbed erosion is expected to exacerbate hydrological drought in this region. Further research should focus on the impact of riverbed cutting, and research considering

global climate change is required to determine the impacts of future tide level changes on drought conditions in lower reaches of the Yangtze River.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material. Further inquiries can be directed to the corresponding author.

Author contributions

HG: Conceptualization, Data curation, Formal analysis, Funding acquisition, Writing – original draft, Writing – review & editing. LZ: Formal analysis, Investigation, Methodology, Supervision, Validation, Writing – original draft, Writing – review & editing. BM: Formal analysis, Resources, Visualization, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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