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Spatiotemporal variations of water levels and river-lake interaction in the Poyang Lake basin under the extreme drought

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A R T I C L E I N F O

Keywords:
Extreme drought
Poyang Lake
Three Gorges Dam
River-lake interaction
Water level

A B S T R A C T

Study region: Poyang Lake, China's largest freshwater lake
Study focus: The water level variations of Poyang Lake and the combined effects of the upstream rivers and the Yangtze River during extreme drought events are not yet fully understood. In this study, the temporal and spatial variations of Poyang Lake's water level and the river-lake interactions were investigated using mathematical statistics and regression models.
New hydrological insights for the region: Extreme drought occurrences in Poyang Lake have increased over fourfold compared to previous periods since the 21st century. The 2022 extreme drought represents the most intense, severe, and prolonged drought event in Poyang Lake since 1956. It is characterized by unprecedented low water levels during both the flood and dry seasons. The study further emphasizes the changes in river-lake interactions during the extreme drought, indicating a reduced blocking effect of the Yangtze River on Poyang Lake during the flood season and a diminished emptying effect during the retreating and dry seasons. Compared to multi-year averages, reduced upstream discharge, Yangtze River flow, and the Three Gorges Dam operations during this drought contributed 23.68 %, 38.10 %, and 38.22 % respectively to the water level decline. During the drought period, both natural precipitation-driven flow increase in upstream rivers and water released from the dam provided short-term relief, though insufficient to fully mitigate the drought conditions.

1. Introduction

Lakes, expansive water bodies formed by the accumulation of water in surface depressions, play a crucial role in the Earth's

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hydrological cycle (Pi et al., 2022). Globally, over 100 million lakes contain approximately 87 % of the planet's liquid surface freshwater (Peter, 1993; Verpoorter et al., 2014; Woolway et al., 2020). As a crucial component of water resources, lakes play a key role in regulating river flows, supporting irrigation, and supplying water for industrial and domestic use (Raymond et al., 2013; Williamson et al., 2009). Additionally, they sustain a rich biodiversity, providing essential ecosystem services (Xu et al., 2001). However, lakes are highly sensitive to external disturbances such as climate change and human activities (Grant et al., 2021; Woolway et al., 2020). Maintaining the stability of lakes is essential for the sustainable development of aquatic ecosystems (Tian et al., 2023).

Drought, defined by below-average water availability, is a prevalent natural disaster with profound adverse effects on water resources, agriculture, ecological environment, and socio-economic development (Akyuz et al., 2012; She et al., 2013; Long et al., 2013). Droughts affecting lakes can lead to significant social issues by impacting the livelihoods of local populations (Satgé et al., 2017). The resulting decline in lake water levels can increase pollutant concentrations and trigger the release of substances from sediments, threatening the ecological health of these water resources (McGowan et al., 2005). Among various drought types, extreme droughts stand out due to their scarce occurrence yet significant impact, marked destructiveness, and high unpredictability (Zhang et al., 2013). For instance, the extreme drought along the Yangtze River in 2006 saw a 54 % decrease in flow at the Datong hydrology station (Dai et al., 2008). Severe droughts in the Mekong River-Tonle Sap Lake system have led to significant reductions in river and lake water levels, substantially impacting local fisheries and agricultural production (Morovati et al., 2024a). The contraction of Poyang Lake's surface area during extreme drought events triggers a cascade of ecological impacts (Li et al., 2022), including water quality deterioration (Li et al., 2020) and habitat degradation (Mu et al., 2022). In recent years, the escalating frequency and intensity of droughts worldwide have been attributed to the combined effects of climate change and anthropogenic activities (Chen et al., 2023b). A comprehensive understanding of the impact of drought on lakes is essential for improving water resource management and mitigating the losses caused by drought.

Poyang Lake, the largest freshwater lake in China, holds a pivotal role as an internationally recognized wetland reserve (Li et al., 2019; Tan et al., 2015). It serves as the wintering ground for an estimated 95 % of the world's Siberian cranes (Wu et al., 2009). As one of the few lakes directly connected to the Yangtze River, Poyang Lake receives 17 % of its annual inflow from the river (Li et al., 2021). The water level in Poyang Lake is influenced by its interactions with upstream rivers and the Yangtze River (Wu et al., 2021), creating a distinct seasonal hydrological regime governed by runoff and rainfall (Zhang et al., 2022). This regime is characterized by an area exceeding 3000 km^2 during the flood season (Chen et al., 2023a; Feng et al., 2012) and a significant shrinkage into a narrow, winding channel during the dry season (Liu et al., 2013). Recent shifts in this hydrological regime, driven by climate change and human activities (Yao et al., 2016), have resulted in altered precipitation patterns and increased extreme drought frequency (Chai et al., 2019),

Fig. 1. The situation of the extreme drought event at Poyang Lake in 2022 (photographed on October 12, 2022). (a) Poyang Lake turned into the Poyang "River". (b) The bottom of Poyang Lake became passable for vehicles. (c) The extreme drought led to the mass mortality of clams. (d) Desiccated bivalve shell.

with projections indicating more severe droughts in the future (Yao et al., 2023). Human interventions, particularly the Three Gorges Dam (TGD) operation, have further modified the lake's hydrology through water regulation, mitigating flood risks during the wet season but leading to earlier and prolonged low water periods during the dry season (Zhang et al., 2012). These combined effects have manifested in reduced water levels during several periods of the year (Guo et al., 2012) and an increased joint probability of concurrent droughts in Poyang Lake and the Yangtze River during spring, summer, and autumn post-2003 (Zhang et al., 2017). While the increasing frequency of extreme events is widely recognized (Zhang et al., 2011), there remains a lack of models to quantify the probability of extreme drought occurrence, which is essential for understanding hydrological regime changes in Poyang Lake.

The extreme drought affecting the Yangtze River basin in the summer of 2022 led to a rapid decrease in Poyang Lake's water levels, resulting in a prolonged period of low water conditions. The basin experienced nearly 50 % less rainfall than usual due to the westward extension of the western Pacific subtropical high, and the combined effect of high temperatures and heat waves led to a rapid worsening of the drought (Xu et al., 2023). The drought significantly reduced the water surface area, leading to severe socioeconomic and ecological problems. More than 5.3 million people in Jiangxi province have suffered from its impacts (Hu, 2023). The contraction of aquatic habitats has significantly diminished the living and foraging areas for aquatic life, elevating the risk of finless porpoises becoming stranded (Xue et al., 2023). The accelerated receding of water levels in Poyang Lake led to fish, initially swept into floodplain depressions by currents, being stranded and desiccated into fish jerky before they could return to the river channels in time (Zhang et al., 2023). The extensive drying and exposure of the lakebed has made survival difficult for many benthic organisms, such as clams (Fig. 1). The abrupt onset of the dry season prompts premature sprouting and growth of floodplain vegetation, leading to widespread death of submerged plants before they can accumulate nutrients at their roots (Huang et al., 2022). The reduction in fish and aquatic plants poses a significant survival challenge for the wintering migratory birds at Poyang Lake (Guo et al., 2022).

Some studies have been conducted to analyze hydrological regime variations of Poyang Lake under extreme droughts (Zhang et al., 2017, 2015). Liu et al. (2023b) employed various satellite datasets to investigate the extreme drought event that occurred in the Poyang Lake basin in 2022, estimating the lake's minimum area to be 814 km^2. Chen et al. (2023b) found that extreme drought leads to a substantial decrease in groundwater levels within the floodplain regions surrounding Poyang Lake, increasing groundwater discharge to approximately three times the typical rate. Zhang et al. (2023) explored the impacts and causes of drought in Poyang Lake based on long-term series of meteorological and hydrological data, previous research findings and hydrological forecast simulations. While existing studies and reports have identified the 2022 extreme drought event as the most severe due to its record-low water levels, the characteristics of this drought such as its severity and duration have yet to be quantified in comparison to other historical extreme droughts in Poyang Lake. Such quantification is essential for effective drought assessment and response. Previous studies that examined the impact of extreme drought events on hydrology have typically focused on overall water level changes, often overlooking the complex processes involved. For instance, the TGD released water to the middle and lower reaches of the Yangtze River during the drought, but it remains unclear whether this intervention alleviated the extreme drought conditions in Poyang Lake. Moreover, as the direct cause of drought, precipitation may not have remained consistently low throughout the drought period and sudden precipitation events in the basin could have provided temporary relief. The extent of such relief, however, requires further investigation.

The interactions between Poyang Lake and the Yangtze River have been extensively studied (Guo et al., 2012; Lai et al., 2013; Wu et al., 2021). These interactions vary seasonally (Wu et al., 2021). In the wet season, elevated water levels in the Yangtze River exert a blocking effect on Poyang Lake, particularly during floods, where the river can even reverse its flow into the lake (Hu et al., 2007). The rising water levels in Poyang Lake, due to increased inflows from its basin, can mitigate the blocking effect from the Yangtze River (Wu et al., 2021). After the operation of TGD, the regulation of floods has reduced the effect of the Yangtze River on Poyang Lake (Guo et al., 2012). During the dry season, the lowering of the Yangtze River's water level leads to an emptying effect on Poyang Lake, which has been intensified following the operation of the TGD, resulting in increased outflows from the lake (Mei et al., 2015; Tian et al., 2023). Extreme droughts have significantly altered the hydrological regimes between the Poyang Lake basin and the Yangtze River, potentially leading to substantial changes in their interactions. Zhang et al. (2015) identified that the conjunction of extreme droughts in Poyang Lake and the upper Yangtze River, coupled with the impoundment of TGD, was the main cause of the low water levels in Poyang Lake. However, seasonal variations in these interactions during extreme droughts remain unclear, and there is currently a lack of quantitative understanding regarding the contributions of the lake basin and the Yangtze River to lake water level changes under such extreme conditions.

In this study, mathematical statistics and regression models were used to investigate the variations in water level and the interaction of rivers and the lake in Poyang Lake basin under extreme drought in 2022. More specifically, this study focuses on (a) the spatiotemporal characteristics of hydrological variations during extreme drought; (b) seasonal changes in river-lake interactions under extreme drought; and (c) an analysis of the causes behind the water level variations during this period. To quantify extreme drought probability, a logistic regression model based on drought indices was developed. To assess the contributions of basin inflows and the Yangtze River to Poyang Lake's water level changes, we proposed a time-lagged multiple linear regression model. This study aims to provide new insights into changes in the hydrological regime and the river-lake interactions of Poyang Lake under extreme drought conditions. The methods employed are expected to be applicable to the study of other lakes globally.

2. Materials and methods

2.1. Study area

Situated in the middle reaches of the Yangtze River, Poyang Lake (28°4′-29°46′N, 115°49′-116°46′E) is a prominent hydrological feature in the region and a world-famous wetland (Fig. 2a). The Poyang Lake basin covers an area of 162,200 km^2, accounting for 9 %

of the Yangtze River basin (Zhang et al., 2014). The lake is characterized by a subtropical monsoon climate, with a mean annual precipitation of 1485 mm/yr and pan evaporation of 1428 mm/yr (Li et al., 2018). Poyang Lake has obvious seasonal characteristics, and its water level goes through four water periods in a year: rising, flooding, retreating, and drying (Jia et al., 2023; Yao et al., 2018). The lake is influenced by the inflow from upstream rivers as well as the Yangtze River (Fig. 2b). This results in annual water level fluctuations ranging from 8 to 22 m, and corresponding dynamics in the water surface area, varying from less than 1000 to more than 3000 km^2 (Mei et al., 2016). The inflow of Poyang Lake is primarily supplied by five major upstream rivers, namely Ganjiang, Xinjiang, Raohe, Fuhe, and Xiushui rivers, which collectively contribute approximately 89 % of the total water input to the lake (Li et al., 2015, 2018). There were 10,798 reservoirs with a combined storage capacity of 32.8 billion cubic meters in Poyang Lake catchment by 2020, including 33 large reservoirs and 260 medium-sized reservoirs (Li et al., 2023b). Upstream water enters Poyang Lake, flowing northward through a narrow, deep channel into the Yangtze River. In recent years, the hydrological regimes of Poyang Lake have changed due to climate change and human activities such as water conservancy project construction (Huang et al., 2021), land use (Ye et al., 2013) and sand mining (Lai et al., 2014), with an increase in the frequency of extreme events (Ye et al., 2014). For instance, since the construction of TGD in 2003, Poyang Lake's water levels have decreased during the wet season, while the onset of the dry season has advanced and its duration extended (Feng et al., 2016).

2.2. Data

The station distribution of meteorological data (daily precipitation) is shown in Fig. 2a, covering the period from 1961 to April 2023, which is from the China Meteorological Data Service Center. The precipitation data is used to investigate the variations in average precipitation across the catchment under the 2022 extreme drought and to compare the differences with the long-term average precipitation. The hydrological data used for the extreme drought analysis are presented in Table 1. Daily average water level data in the lake were obtained from five monitoring stations, namely Hukou, Xingzi, Duchang, Tangyin, and Kangshan, which is used to investigate the temporal and spatial variations of the lake water level under the extreme drought. Jiujiang is the closest station to the Poyang Lake outlet along the Yangtze River mainstem (Fig. 2). The water level data at the Jiujiang station on the Yangtze River was used to study the spatial differences in water levels between the lake and the river. Due to missing discharge data from Jiujiang station, discharge at Hankou station, located 270 km upstream (Zhang et al., 2024), was used as a substitute to reflect changes in Yangtze River hydrology. To account for the potential influence of tributaries between Hankou and Jiujiang on discharge, a comparison of 2022 discharge data from both stations was made to evaluate these effects (Fig. S1). The discharge patterns and magnitudes of the two stations are closely aligned. In 2022, the average discharge at Jiujiang was 2.26 % higher than at Hankou. The discharge at the Yichang

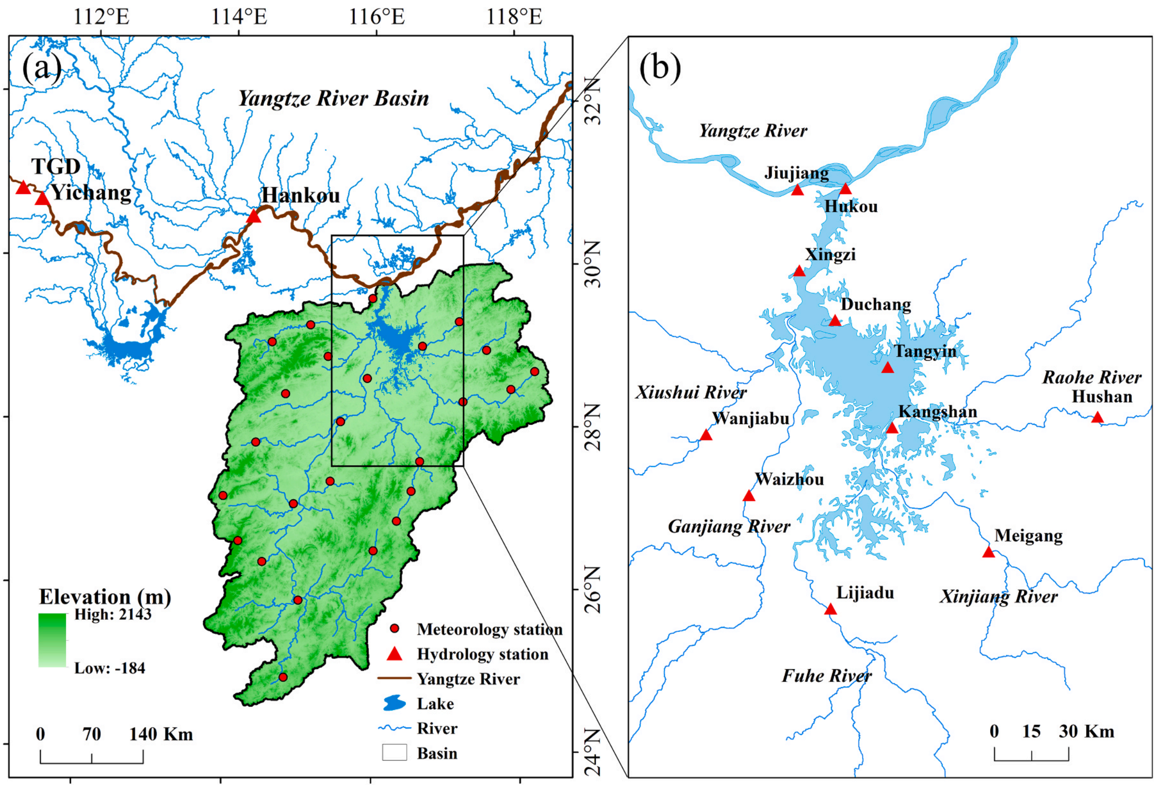

Fig. 2. The study area and hydrological stations: (a) Yangtze River and Poyang Lake basin. (b) Hydrological gauging stations of Poyang Lake and five major rivers upstream.

Table 1
Hydrological data used in this study.

Station	Location	Data type	Period	Frequency
Hankou	Yangtze River	Discharge	1960-Apr.2023	Daily
YiChang	Yangtze River	Discharge	1960-Apr.2023	Daily
Jiujiang	Yangtze River	Water level	1960-Apr.2023	Daily
Hukou	Junction of Poyang Lake and Yangtze River	Water level / Discharge	1960- Apr.2023 / 1970- Apr.2023	Daily
Three Gorges Dam	Three Gorges Dam	Water level / Inflow / outflow	2003 - Apr.2023	Daily
Xingzi	Poyang Lake	Water level	1956- Apr.2023	Daily
Duchang	Poyang Lake	Water level	1960- Apr.2023	Daily
Tangyin	Poyang Lake	Water level	1962- Apr.2023	Daily
Kangshan	Poyang Lake	Water level	1960- Apr.2023	Daily
Wanjiabu	Xiushui River	Discharge	1960- Apr.2023	Daily
Waizhou	Ganjiang River	Discharge	1960- Apr.2023	Daily
Lijiadu	Fuhe River	Discharge	1960- Apr.2023	Daily
Meigang	Xinjiang River	Discharge	1960- Apr.2023	Daily
Hushan	Raohe River	Discharge	1960- Apr.2023	Daily

station was used as the Yangtze River variable in the regression model due to its proximity to the TGD, facilitating the exclusion of the impact of TGD by accounting for inflow and outflow. Discharge for the five main rivers upstream was obtained from representative station data (Table 1). Daily average reservoir water levels and inflow/outflow data since the regulation of TGD in 2003 were collected to analyze its impact on the extreme drought in Poyang Lake. The above hydrological data are sourced from the Jiangxi Hydrological Monitoring Center.

2.3. Methods

2.3.1. Drought index and characteristics

The Standardized Runoff Index (SRI) is a valuable tool for assessing regional hydrological drought. SRI is based on the Standardized Precipitation Index (SPI) proposed by Mckee et al. (1993), which is calculated using the gamma distribution probability density function to determine the cumulative probability of precipitation over a given time scale. Assuming the precipitation over a certain period is x, the probability density function of the gamma distribution for x is expressed as follows:

$$g(x) = \frac{1}{\beta^{\alpha}\Gamma(a)} x^{\alpha-1} e^{-x/\beta}, \tag{1}$$

$$\Gamma(a) = \int_0^{\infty} x^{a-1} e^{-x} \mathrm{d}x, \tag{2}$$

where $g(x)$ is the probability density function, α represents the shape parameter, β denotes the scale parameter, x is the precipitation amount, e is the base of the natural logarithm, $\Gamma(\alpha)$ is the gamma function. The parameters α and β are estimated using the maximum likelihood estimation method, as follows:

$$\widehat{\alpha} = \frac{1 + \sqrt{1 + 4A/3}}{4A}, \tag{3}$$

$$\widehat{\beta} = \frac{\overline{x}}{\widehat{\alpha}}, \tag{4}$$

$$A = \ln \overline{x} - \frac{1}{n}\sum_{i=1}^{n} \ln x_i, \tag{5}$$

where n is the length of the calculated sequence. When calculating the cumulative probability density function $G(x)$, since the gamma function does not include $x = 0$ but actual precipitation can be zero, the following formula is used for transformation:

$$H(x) = q + (1-q)G(x), \tag{6}$$

where q is the frequency of occurrence of 0 in the precipitation series. SPI value is obtained by standardizing $H(x)$ with Gaussian function. To eliminate autocorrelation within the sample, SPI values for different months within the time series are calculated separately and then combined to obtain the overall time series SPI value. SRI replaces the precipitation amount used in the SPI calculation with runoff or water level data. SRI is available in various scales, including monthly, seasonal, and annual, denoted as SRI-1、SRI-3、SRI-6、SRI-12, respectively. SRI-1 (month time scale) was calculated in this study using water level data.

To quantify drought characteristics, this study adopts the metrics of drought duration (D), drought magnitude (M), and drought intensity (M/D), following the research by Mckee et al. (1993) and Zhang et al. (2015). Drought duration (D) represents the total number of consecutive months during which a drought event persists. A drought is considered to commence and terminate when the

SRI falls below and rises above −1.0, respectively, while an extreme drought episode is identified when the SRI drops below −2.0. The drought magnitude (M) is expressed as:

$$M = -\sum_{i=1}^{D} \mathrm{SRI}(i), \tag{7}$$

where SRI(i) is the SRI value, D is drought duration and i represents the sequential month within a drought event (Chen et al., 2009).

2.3.2. Mann-Kendall rank test

To evaluate the trends and abrupt changes in drought indices, the Mann-Kendall test (MK test), is utilized in this study (Zhang et al., 2006). For a time series x with n sample size, a rank sequence is constructed as follows:

$$s_k = \sum_{i=1}^{k} r_i \ (k = 2, 3, \dots, n), \tag{8}$$

where r_i is as follows:

$$r_i = \begin{cases} +1, & x_i > x_j \\ 0, & x_i \le x_j \end{cases} \ (j = 1, 2, \dots, i). \tag{9}$$

Assuming the time series possesses randomness and independence, a statistical measure is defined as follows:

$$UF_k = \frac{[s_k - E(s_k)]}{\sqrt{\mathrm{var}(s_k)}} \ (k = 1, 2, \dots, n), \tag{10}$$

where $UF_1 = 0$, and $E(s_k)$ and var(s_k) represent the mean and variance of the cumulative number s_k, respectively, which can be calculated using the following formulas:

$$E(s_k) = \frac{k(k+1)}{4}, \tag{11}$$

and

$$\mathrm{var}(s_k) = \frac{k(k-1)(2k+5)}{72} (2 \le k \le n). \tag{12}$$

Reversing the time series x in descending order, such that it is arranged as x_n, $x_{n\text{-}1} \dots x_1$, the aforementioned process is repeated. Concurrently, set UB_k = -UF_k for $k = n$, n-1, …, 1, with $UB_k = 0$. Given a significant level of $\alpha = 0.05$, $U_\alpha = \pm 1.96$. $UF_k > 0$ signals an ascending trend, becoming statistically significant at values over 1.96. In contrast, a descending trend is marked by $UF_k < 0$, with significance established when it falls under −1.96. If the UF_k and UB_k curves intersect and the intersection point lies between the critical lines ($U_\alpha = \pm 1.96$), this point is identified as the mutation point.

2.3.3. Regression models

Considering the potential influence of climate change and human activities on the occurrence of extreme droughts in Poyang Lake, a model is anticipated to be developed to quantify the probability of these events and to explore their evolutionary patterns. Whether a particular month experiences extreme drought can be considered a binary outcome, where the response variable Y is 1 if SRI ≤ -2.0, and 0 otherwise. Therefore, logistic regression is useful to quantify changes in Poyang Lake's extreme drought probability, as follows (Stagge et al., 2015):

$$\log \frac{p(Y)}{1 - p(Y)} = \beta_0 + \beta_1 t + \beta_2 t^2 + \beta_3 \sin\left(\frac{2\pi t}{T}\right) + \beta_3 \cos\left(\frac{2\pi t}{T}\right), \tag{13}$$

where $p(Y)$ is the probability of Y= 1, t (month) represents time, β_i (i = 0, 1, 2, 3) are fitting coefficients, T is the hydrological period of Poyang Lake, whose value is one year (Zhang et al., 2022). The sum of the two trigonometric functions represents the periodic hydrological variations of Poyang Lake.

To investigate the contribution of various factors including the upstream flow of Poyang Lake, natural inflow from the Yangtze River, and the regulation of TGD to the water level of Poyang Lake under extreme drought conditions compared to the multi-year average, a multiple linear regression model was constructed as follows:

$$\begin{aligned} W = {} & \beta_0 + \beta_1 \sin\left(\frac{2\pi t}{T}\right) + \beta_2 \cos\left(\frac{2\pi t}{T}\right) + \beta_3 Q_u + \beta_4 \mathrm{ADV}(Q_u) \\ & + \beta_5 Q_Y + \beta_6 \mathrm{ADV}(Q_Y) + \beta_7 W_{\mathrm{TGD}} + \beta_8 \mathrm{ADV}(W_{\mathrm{TGD}}) + \varepsilon \end{aligned}, \tag{14}$$

and

$$\mathrm{ADV}\left(X, d\right) = \frac{X_j + dX_{j-1} + \ldots + d^{j-1}X_1}{1 + d + \ldots + d^{j-1}} \ (X = Q_u, Q_Y, W_{\mathrm{TGD}}), \tag{15}$$

where W (m) is the water level of Poyang Lake, β_i are fitting coefficients, t (day) is the time, T is the hydrological period of Poyang Lake, Q_u (m^3/s) is the sum of the discharge of the five major rivers upstream, Q_Y is the discharge of the Yangtze River (Yichang station), W_{TGD} (m) is the water level of TGD, and ε is the error, X represents the variable from day 1 to day j, d is the discount factor from 0.1 to 1. The sum of the two trigonometric functions represents the periodic hydrological variations of Poyang Lake itself, which is inspired by the research of Xu et al. (2018). ADV (average discounted variables), defined by reference to Wang and Tian (2013) and Xu et al. (2018), represents the hysteresis of hydrological effects. The value of d for each ADV is set when the adjusted highest R^2 is achieved. The contribution of each predictor to the water level of Poyang Lake can be separated by Eq. (7). The impact of TGD encompasses both the variable W_{TGD} and changes in the variable Q_Y caused by the dam's operation. To isolate the effects of the dam, it is essential to use Yangtze River flow data unaffected by the dam. This is achieved by combining the flow measurements at Yichang with the inflow and outflow data from TGD in our analysis. After that, the water level changes in 2022 due to variations in predictors under extreme drought is determined by subtracting their multi-year average contributions to the water level from their contributions during the drought period.

2.3.4. Analysis of river-lake interaction

Following Dai et al. (2015), the Water Surface Slope (WSS) is employed to analyze changes in the interaction between Poyang Lake and the Yangtze River under extreme drought conditions. WSS represents the change in water surface elevation per unit of horizontal distance along the downstream direction. It is computed by calculating the ratio of the difference in water surface elevation between two points (i.e., monitoring stations) to the horizontal distance separating them. The formula is as follows:

$$\mathrm{WSS} = \frac{Z_u - Z_l}{l}, \tag{16}$$

where Z_u and Z_l denote the water levels at the upstream and downstream monitoring stations, respectively, and l represents the distance between the two stations. WSS of Hukou-Xingzi and Duchang-Kangshan serves as an indicator of river-lake interaction and the rate of water storage change, respectively (Dai et al., 2015).

3. Results

3.1. Historical extreme drought characteristics

The results of SRI-1 values calculated using the monthly water level at Xingzi station are shown in Fig. 3a. The SRI values demonstrated characteristics of fluctuating variation. A record low SRI value of −4.09 in September 2022 marks the driest month for Poyang Lake since records began in 1956. Fig. 3b presents the box plot of SRI values, illustrating the overall SRI value distributions before and after the construction of TGD. The data reveals a relatively balanced distribution of SRI values across both positive (wet conditions) and negative (drought conditions) spectrums, yet with a higher incidence of negative outliers. Notably, the post-construction SRI value distribution shows a significant shift towards more frequent negative outliers and an absence of positive outliers.

The MK test results for the SRI values at Xingzi station in Poyang Lake are shown in Fig. 4. From the mid-1950s to the mid-1960s, the *UF* curve fluctuates near zero, indicating no significant trend during this period. From the mid-1960s until the end of the 20th century, the *UF* line exhibits an increasing trend, suggesting a gradual alleviation of drought conditions in Poyang Lake, especially from the 1980s to the turn of the century, where the *UF* curve consistently remains above the 0.05 significance threshold, highlighting

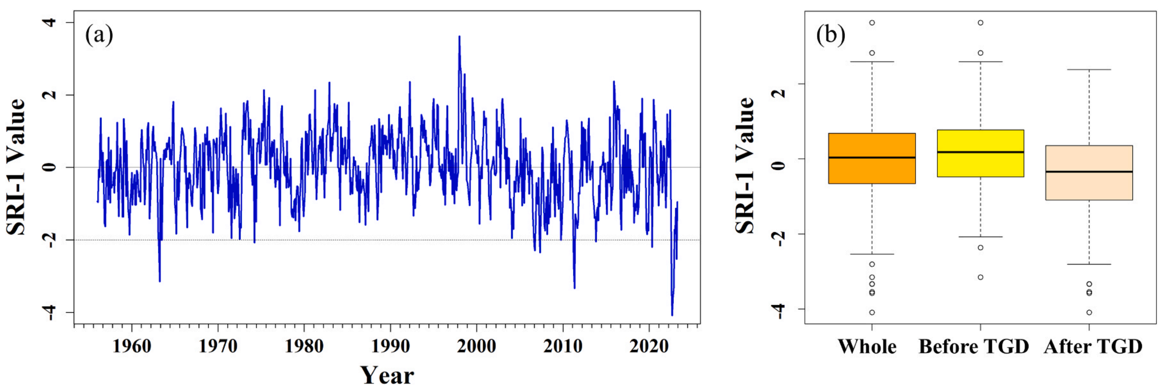

Fig. 3. (a) Temporal variation of SRI-1 values at Xingzi station from 1956 to April 2023 and (b) its box plot.

a significant reduction in drought conditions. Since the beginning of the 21st century, the *UF* curve demonstrates a clear declining trend, pointing towards a gradual intensification of drought conditions in Poyang Lake. The crossover of the *UF* and *UB* lines in 2022, positioned between two critical lines, marks the extreme drought event of 2022 as a significant turning point, leading to a notable shift in the SRI values.

The extreme dry months (SRI ≤ -2) of Poyang Lake are shown in Table 2, revealing 17 such occurrences from 1956 to April 2023, with four occurring in 2022 alone. To elucidate the temporal trends in extreme dry months, their frequency and cumulative distribution are depicted in Fig. 5a. It can be seen that the frequency of extreme dry months has significantly increased since the beginning of the 21st century. The probability of extreme drought in Poyang Lake was quantified by logistic regression quadratic model (Fig. 5b). Due to the lack of significant trends prior to 2005, the model was reconstructed with the assumption that the values were constant before 2005 and followed a temporal trend thereafter (Fig. 5c). Although the small sample size limits the statistical significance of the periodicity, the results exhibit substantial periodic variability, peaking in May and reaching its lowest in November (Fig. 5d). The regression analysis indicates a continuous increase in the probability of extreme droughts in Poyang Lake in recent years. The average likelihood was 1.06 % before the 21st century, and by 2023, this probability increased to over 12 %. The average probability of extreme droughts post-21st century is approximately four times higher than that prior to the 21st century. Table 3 details historical extreme drought events since 1956, including their characteristics. The 2022 extreme drought event is identified as occurring from August 2022 to March 2023. It exceeds previous instances in terms of duration, magnitude, and intensity, marking it as the most severe drought event recorded since 1956.

3.2. Spatiotemporal variation of water level in Poyang Lake under extreme drought

The water level variations at Xingzi station in Poyang Lake under the 2022 extreme drought event are shown in Fig. 6. The water level experienced a marked decline and remained well below the average from July 2022, with the difference reaching a maximum of −8.12 m in September 2022. September was the driest month (SRI = −4.09), with the water level at that time reaching only 48.8 % of the average (Fig. 7). From October 2022 to March 2023, it remained significantly low, with an average level of 7.43 m and experiencing four distinct fluctuations. The fluctuations may be related to the upstream inflow and the hydrological variations of the Yangtze River, as discussed in a later section. The water level rose in March 2023 and approached the average, marking the end of the extreme drought.

Fig. 8a presents the total discharge of the five major upstream rivers under the 2022 extreme drought. A significant decline was observed starting from late July, maintaining values significantly below the multi-year average from August to November at only 26.4 %-36.1 % of the average (Fig. 7). Subsequent significant fluctuations were observed in December this year and February and March of the following year with discharge approximately 7, 9.7, and 14.6 times higher than the levels observed prior to these fluctuations, which are related to large-scale precipitation in the catchment (Fig. 8b). These three fluctuations in upstream flow correspond to increases in Poyang Lake's water levels in December 2022 and February and March 2023, raising levels at Xingzi station by 1.92 m, 2.69 m, and 4.23 m, respectively (Fig. 6). Thus, it is evident that the increase in upstream flow has, to some extent, mitigated the extreme drought conditions in Poyang Lake.

The hydrological regime of the Yangtze River mainstream underwent considerable alterations as a result of the 2022 extreme drought (Figs. 7 and 9). Since July, the discharge dropped sharply, with a 44 % reduction observed within a single month (Fig. 9a). This downward trend persisted until mid-September, reaching a peak deviation from the multi-year average of -2.3×10^3 m^3/s, with discharge declining to just 32.4 % of the historical average that month. In October, a surge in flow at Hankou, increasing by approximately 60 %, was attributed to the water release from TGD (Fig. 9b), which coincided with the surge observed at Poyang Lake in October, leading to a 1.49 m increase in water level at Xingzi station (Fig. 6). Since December, the discharge was approaching the

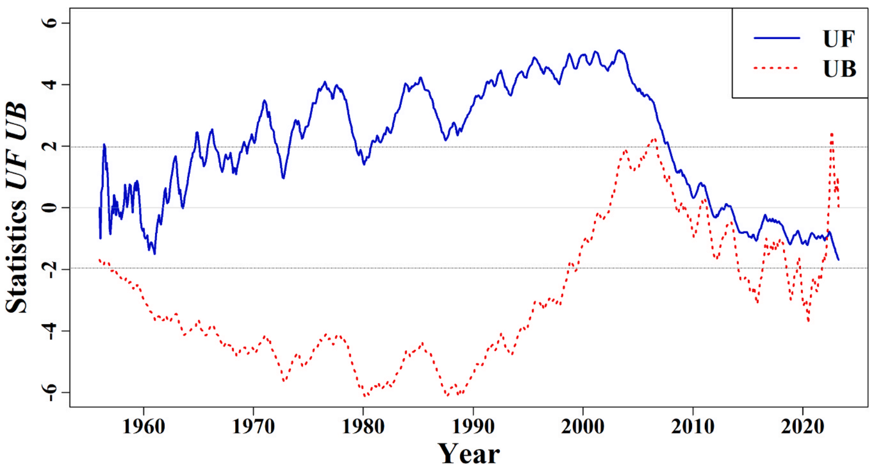

Fig. 4. MK test of SRI-1 values at Xingzi station.

Table 2
Extreme drought month in Poyang Lake from 1956 to April 2023.

Year/Month	SRI-1
1963/3	−2.36
1963/4	−3.15
1963/7	−2.01
1974/4	−2.07
2006/9	−2.19
2006/10	−2.30
2007/5	−2.35
2009/10	−2.01
2011/4	−2.80
2011/5	−3.33
2013/11	−2.05
2020/5	−2.20
2022/8	−3.54
2022/9	−4.09
2022/10	−3.57
2022/11	−3.33
2023/3	−2.53

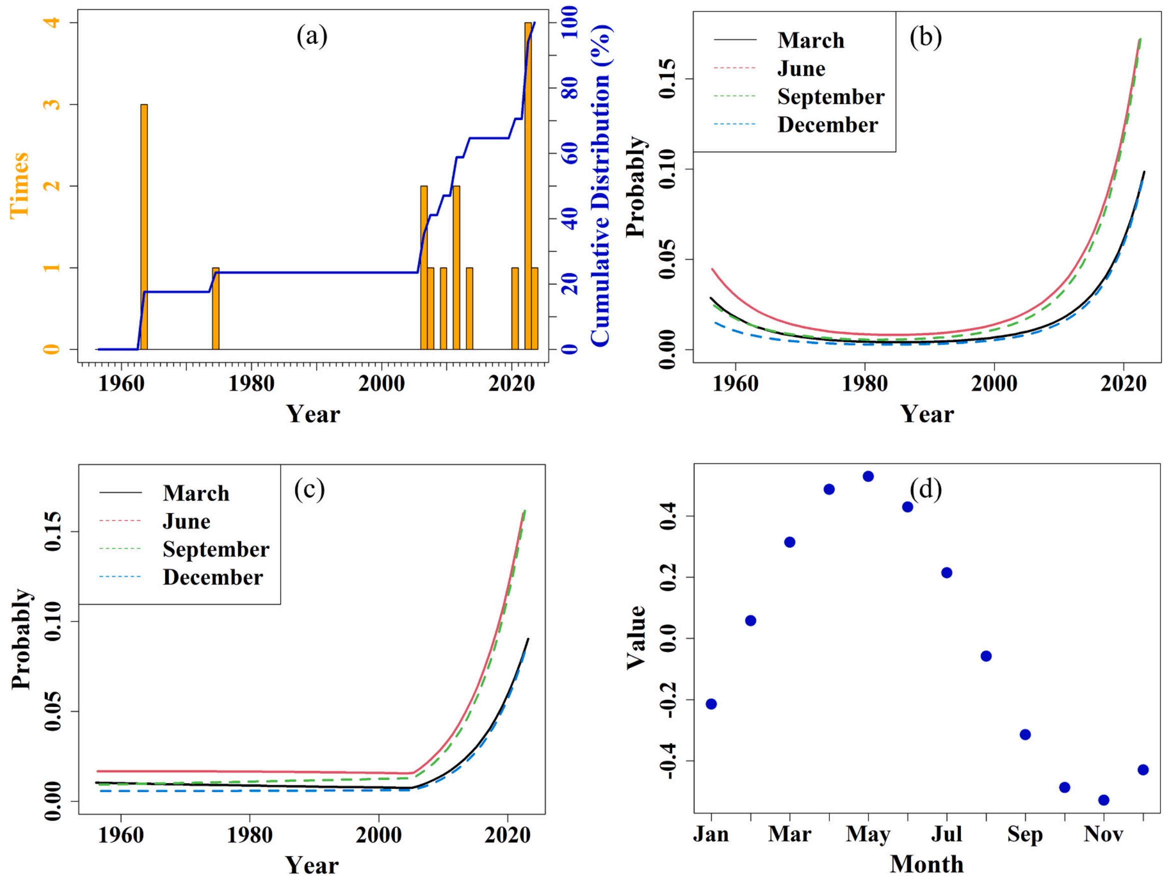

Fig. 5. (a) The times and cumulative distribution of extreme dry months in Poyang Lake from 1956 to April 2023. The probability of extreme drought occurrence in Poyang Lake based on logistic regression through (b) whole-segment simulation and (c) segmented simulation. (d) Seasonal variations in the probability of extreme droughts.

multi-year average, indicating an alleviation of drought conditions in the Yangtze River. In addition to the reduction of natural inflows, the construction and operation of TGD have also altered drought conditions, as observed from historical hydrological patterns (Fig. S2). After TGD was completed, discharge at Hankou decreased from June to November and increased from December to May. However, water levels at Xingzi consistently declined throughout the year. From August to March, the TGD contributed to an average

Table 3
Extreme drought events and their characteristics in Poyang Lake from 1956 to April 2023.

Start and end dates	Drought magnitude	Drought intensity	Drought duration (month)
1963/2–1963/4	−7.30	−2.43	3
1963/6–1963/7	−3.10	−1.55	2
1974/4–1974–4	−2.07	−2.07	1
2006/7–2006/11	−9.14	−1.83	5
2007/4–2007/6	−5.82	−1.94	3
2009/10–2009/12	−5.01	−1.67	3
2011/3–2011/10	−14.89	−1.86	8
2013/8–2014/2	−9.64	−1.38	7
2020/5–2020/5	−2.20	−2.20	1
2022/8–2023/3	−21.73	−2.72	8

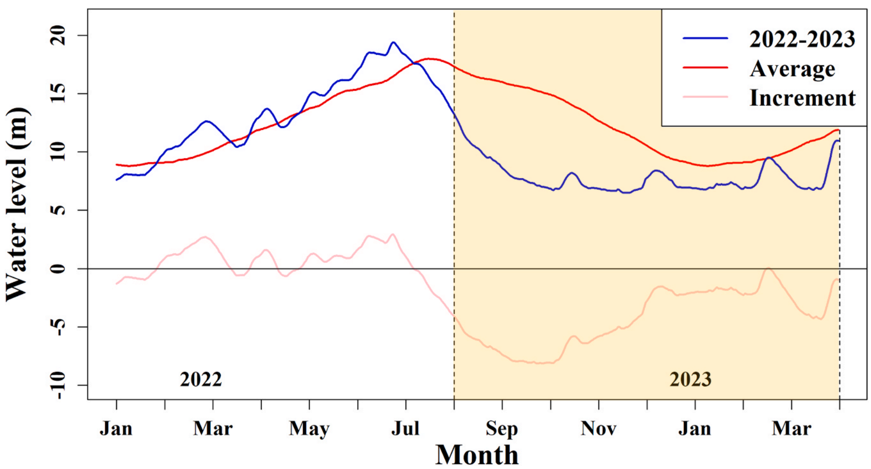

Fig. 6. Water level variations at Xingzi station under the 2022 extreme drought. The yellow background area represents the extreme drought event.

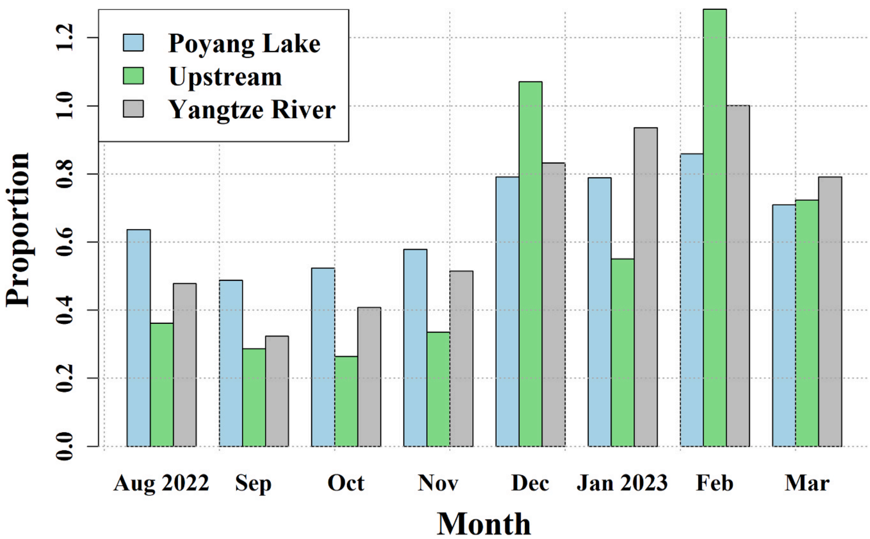

Fig. 7. Proportion of Poyang Lake water level, upstream river discharge, and Yangtze River discharge during the 2022 extreme drought relative to their respective intra-annual averages.

drop of 1.06 m in the water level at Xingzi station. Fig. 10b illustrates the operational response of TGD during the extreme drought. In the absence of drought conditions in the first half of 2022, the dam operated according to standard regulations, releasing water from May to the end of June to free up capacity for the anticipated flood season. However, from July 2022, the hydrological conditions in the Yangtze River mainstream shifted dramatically from flood-prone to arid, leaving minimal surplus water for replenishing the middle

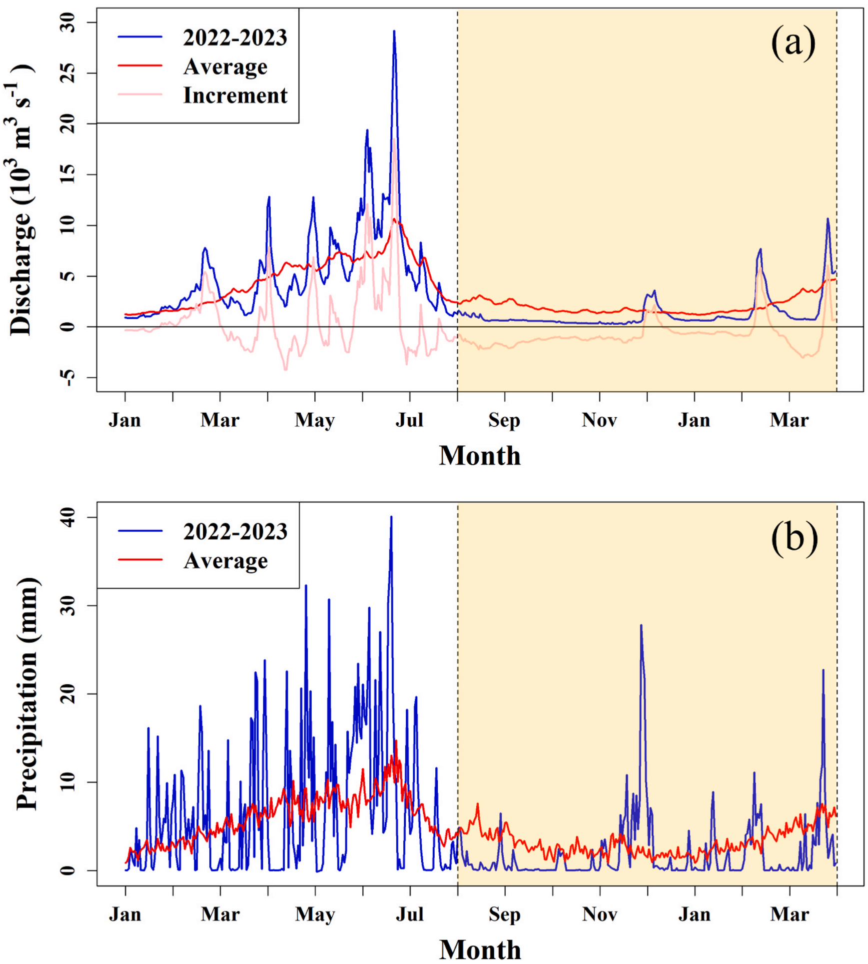

Fig. 8. (a) The total discharge of the five main rivers upstream and (b) average precipitation in Poyang Lake basin under the 2022 extreme drought. The yellow background area represents the extreme drought event. Drought conditions significantly altered the precipitation-runoff relationship. Under the same precipitation conditions, runoff increase was lower during drought periods.

and lower reaches via TGD. Consequently, by the end of the storage period in November, the water level at TGD was only about 160 m, significantly lower than the usual 175 m.

The water level variations at different stations in Poyang Lake exhibit distinct patterns under extreme drought conditions (Fig. 10a). The water levels at most stations started to decline sharply from nearly the same peak level, but the magnitude of the decline decreased at stations located further south. The water replenishment effect of TGD in October caused an increase in water levels in the northern (Hukou and Xingzi) and central (Duchang) regions of the lake, with minimal impact on the southern regions (Tangyin and Kangshan). However, the three precipitation events in the Poyang Lake basin led to an increase in water levels across all stations in the lake. The spatial variations of the water level under the 2022 extreme drought in Poyang Lake are shown (Fig. 10b). It can be seen that the relative positions of water levels among the stations under the extreme drought remain unchanged compared to the multi-year average, with the lowest water levels at Hukou station and gradually increasing towards the south, peaking at Kangshan station. However, the extreme drought induces differential changes at each station. Jiujiang and Hukou stations experienced nearly identical reductions in water levels (about −3.95 m). From Hukou station southward, the extent of water level decline increases, reaching a maximum at Duchang station (-4.32 m), suggesting that the central part of Poyang Lake experienced the most significant drop, being the most affected by the extreme drought. Southward from Duchang station, a notable increase in the water level gradient of Poyang Lake was observed, suggesting a more gradual decrease in water levels in the southern portion of the lake, which appears to be the least impacted by the extreme drought event.

3.3. WSS variations under the 2022 extreme drought

Fig. 11a illustrates the WSS of Hukou-Xingzi under the 2022 extreme drought. In the wet season (July-September), the extreme drought led to a pronounced decline in water levels in both Poyang Lake and the Yangtze River, with a WSS that remained largely

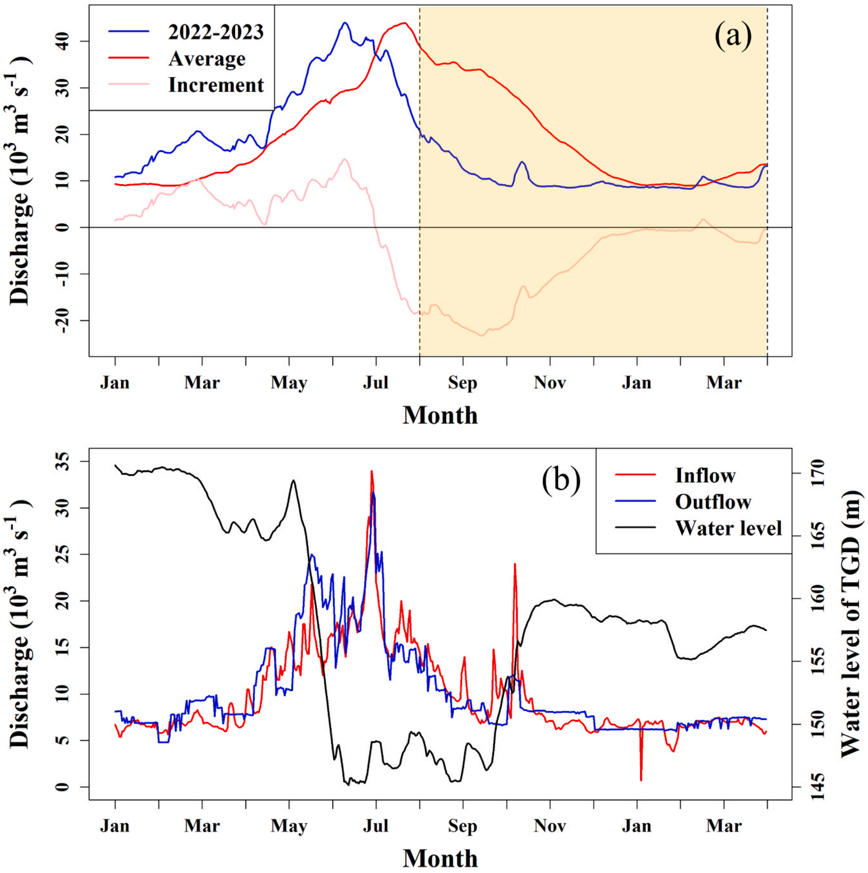

Fig. 9. (a) The discharge at Hankou station and (b) water level, inflow and outflow in TGD under the 2022 extreme drought. The yellow background area represents the extreme drought event.

consistent with the multi-year average. However, from October 2022 to March 2023, the WSS exhibited lower values than the average, indicating a significant reduction in Poyang Lake's water levels due to the drought. Notably, this decrease was more pronounced than the reduction in water levels observed in the Yangtze River. In December, February, and March of the following year, three increases in lake water levels, associated with precipitation events within the Poyang Lake basin, led to an increase in WSS.

The WSS of Duchang-Kangshan under the 2022 extreme drought is shown in Fig. 11b. From May to June, the WSS decreased more rapidly and approached zero under the effects of substantial upstream inflow and the blocking effect of the Yangtze River, suggesting substantial water storage and a generally slow flow in the lake. However, the WSS swiftly rose due to the onset of the extreme drought starting from mid-July, significantly exceeding the average, which indicates increased flow velocity and rapidly decreasing water storage in the lake. From September 2022 to March 2023, the WSS remained at a higher level with continuous water outflow from Poyang Lake. In October 2022, the supplementary water from TGD induced a downward fluctuation in the WSS, alleviating water outflow from Poyang Lake. The increase in the upper reaches in December 2022, February, and March of the following year also caused downward fluctuations in the WSS.

3.4. Cause analysis of the extreme drought

Fig. 12 illustrates the regression model's fit, indicating a robust performance (R^2=0.8509). This model successfully captures the decline in the water level of Poyang Lake during the flood season during the 2022 extreme drought. Dissecting the model to analyze individual predictors reveals their effects on water level fluctuations during the drought (Fig. 13). From July, both upstream and Yangtze River flows begin to exert a negative influence on the lake's water levels, marking a marked decline. Specifically, upstream flow's contribution to water levels dropped from a June peak to a July nadir by 3.94 m, while the Yangtze River's flow contribution fell by 2.59 m. From August to November, the reduction in upstream inflow, along with decreased natural inflow from the Yangtze River and water storage at TGD, collectively triggered the extreme drought in Poyang Lake. The most significant adverse effect came from the reduced Yangtze inflow, its impact on the lake's water levels being over twice that of upstream flows. After December, as the Yangtze River flows neared historical averages (Fig. 10a), its negative contribution to water levels gradually diminished (Fig. 13). Three upward peaks in upstream flow in December 2022, February and March 2023 shifted their contribution from negative to positive, enhancing water levels by 1.27 m, 1.48 m, and 1.88 m, respectively, corresponding to the peaks in the water level at Xingzi

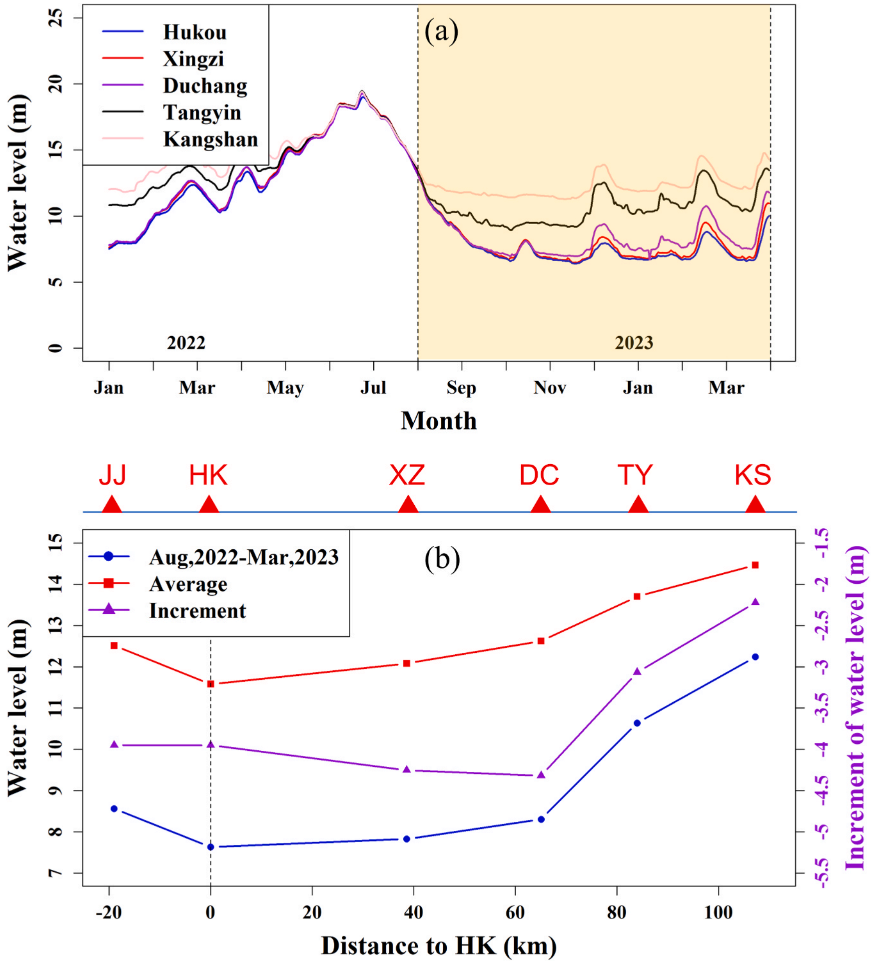

Fig. 10. (a) Temporal variations in water levels at different stations and (b) their mean changes, where JJ, HK, XZ, DC, TY, KS represent Jiujiang, Hukou, Xingzi, Duchang, Tangyin and Kangshan station, respectively.

station previously described (Fig. 6). By averaging and aggregating the effects of each contributory factor during the drought period, it can be deduced that the respective contribution rates of the decline in upstream discharge, the natural discharge reduction of the Yangtze River, and the operation of TGD to the reduction in Poyang Lake's water level are 23.68 %, 38.10 %, and 38.22 %.

The sensitivity analysis of the effect of annual variations in upstream river flow and Yangtze River flow on the water level at Xingzi station is shown in Fig. 14. Reductions in upstream river discharge to 90 %, 80 %, and 70 % result in annual average water level decreases of 0.17 m, 0.34 m, and 0.52 m, respectively; while the same reductions of Yangtze River discharge lead to the decreases of 0.27 m, 0.55 m, 0.84 m, respectively. This analysis indicates that the lake's water levels are more sensitive to changes in Yangtze River discharge. Specifically, the water level's sensitivity peaks to upstream river flow changes from May to July and to Yangtze River flow changes from June to September throughout the year. It highlights that reductions in water may be more likely to cause drought during the wet season, a critical factor in the 2022 flood season's extreme drought, which signals the importance of increased vigilance and the adoption of mitigative strategies by relevant authorities to address drought challenges during the wet season.

4. Discussion

4.1. Identification and characterization of extreme droughts

Drought identification is one of the primary challenges in studying extreme droughts (Zhang et al., 2013). During the extreme drought of 2022, studies reported it as the most severe drought on record since 1951, as key stations recorded new historical lows (Zhang et al., 2023). However, the quantitative characteristics of this drought remain unknown. In this study, the extreme drought event of 2022 was defined using SRI. Its characteristics, including drought magnitude, drought intensity, and drought duration, were quantified (Table 3). The results indeed support the conclusion that it was the most severe drought. Additionally, the increased probability of extreme events may lead to more severe droughts in the future under the effect of climate change (Yao et al., 2023).

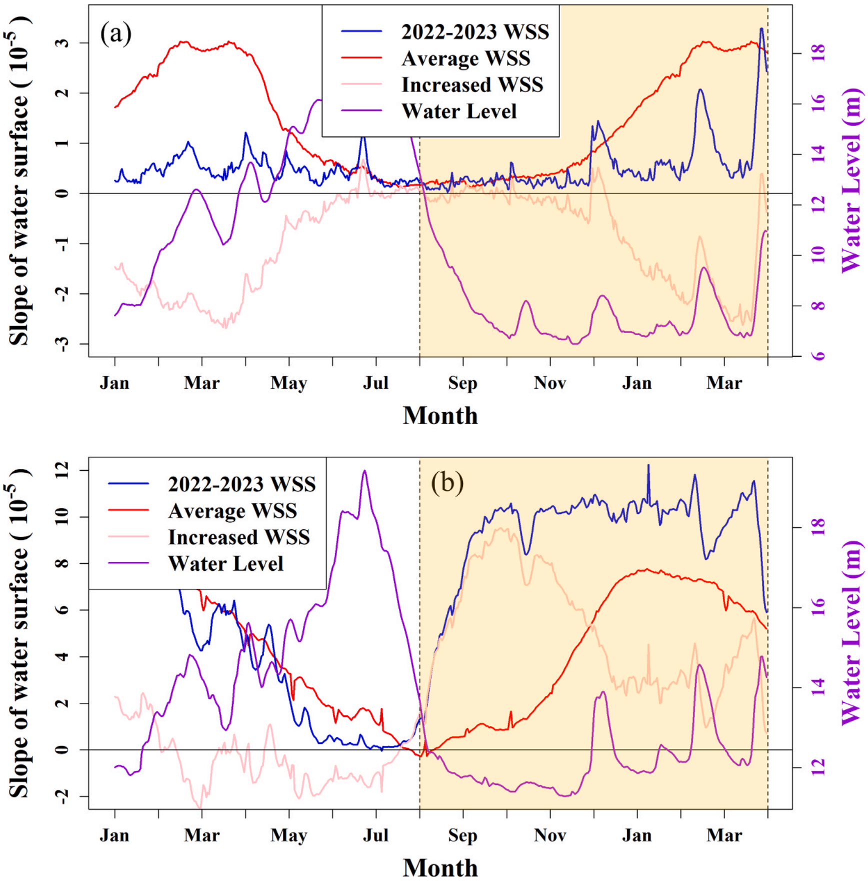

Fig. 11. The water surface slope of (a) Hukou-Xingzi and (b) Duchang-Kangshan in 2022–2023 compared to the multi-year average. The yellow background area represents the extreme drought event. The water levels in (a) and (b) represent those at Xingzi station and Kangshan station, respectively.

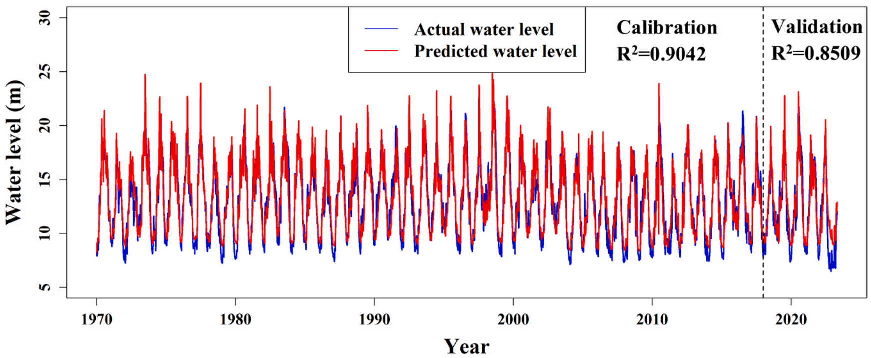

Fig. 12. Comparison of actual water level and predicted water level of Xingzi station. The calibration period of the modified model is from 1970 to 2017 and the validation period is from 2018 to Apr.2023, which are separated by the black dotted line.

Anthropogenic interventions, particularly TGD operations, have substantially exacerbated both the frequency and magnitude of downstream drought events (Liu et al., 2016). Our logistic regression model quantifies this trend, showing an increased probability of extreme droughts in Poyang Lake since the 21st century, extending beyond the qualitative patterns identified by Liu et al. (2011) through a rigorous probability assessment. The primary cause of this phenomenon is the decline in the water level of Poyang Lake (Li et al., 2023a). Since 2003, the average water level has decreased, resulting in a notably higher drought frequency, as drought is defined by lower-than-usual water levels (Akyuz et al., 2012). As a seasonal lake, Poyang Lake exhibits distinct seasonal patterns in the probability of extreme drought, with a notably higher risk during the wet season (Fig. 5b). These observations are consistent with

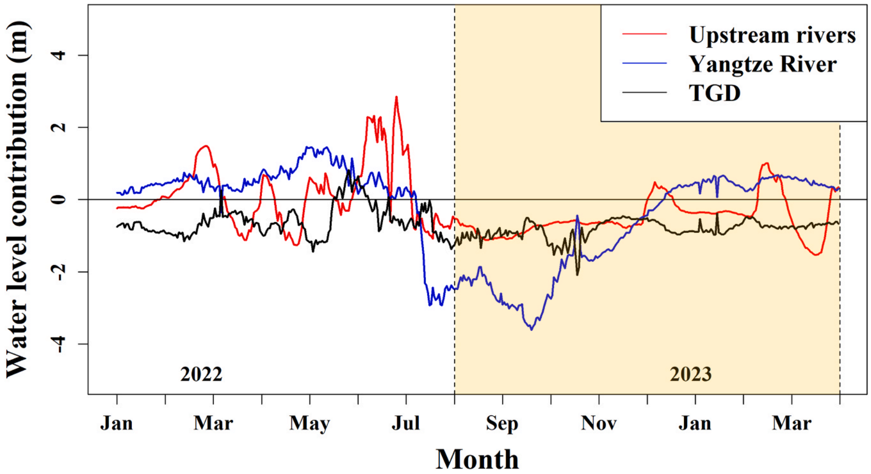

Fig. 13. Effects of contributing factors on the water level variations of Xingzi station under the 2022 extreme drought compared to the multi-year average. The discharge of the Yangtze River represents natural incoming water, which has removed the effect of TGD. The yellow background area represents the extreme drought event.

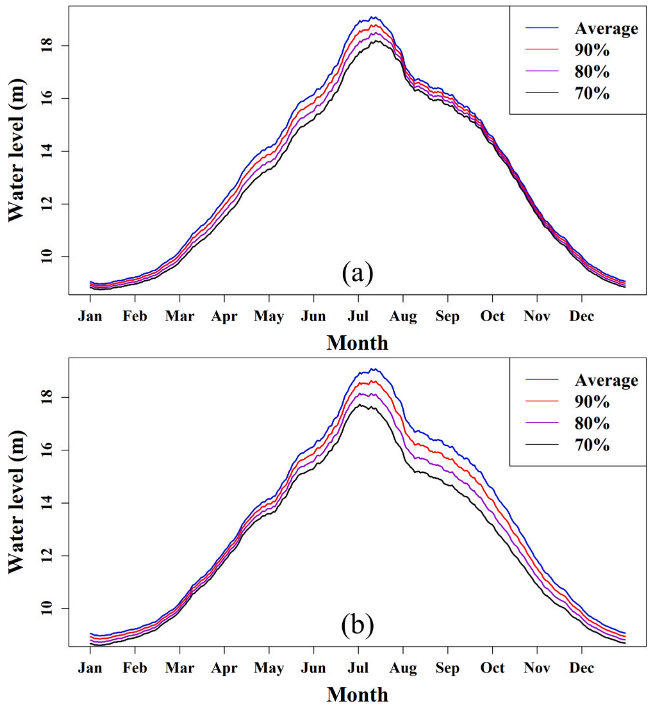

Fig. 14. Sensitivity of Xingzi station water level to (a) upstream rivers discharge and (b) Yangtze River discharge.

Zhang et al. (2017), who demonstrated that the synchronous drought events between the lake and the Yangtze River have become more pronounced during spring, summer, and autumn from 2003 to 2013, attributed to the weakened blocking effect of the Yangtze River. Our study further reveals that the lake's heightened sensitivity to water level fluctuations during the wet season likely contributes to a higher probability of extreme droughts in this period compared to other seasons (Fig. 14).

Drought characteristics analysis is crucial for understanding drought mechanisms and improving drought management. Various studies have investigated drought characteristics of Poyang Lake basin using different approaches (Hong et al., 2015; Lai et al., 2024; Liu et al., 2020; Ye et al., 2016). Zou et al. (2024) revealed that hydrological drought typically lagged behind meteorological drought by approximately 35 days during development and 10 days during recovery periods based on the run theory and Bayesian network. Peng et al. (2024) quantified terrestrial water storage variations and drought characteristics in the Poyang Lake basin utilizing a novel GNSS-based approach. Recent satellite-based studies have demonstrated the effectiveness of multi-source remote sensing data in capturing drought characteristics, especially during the 2022 extreme event (Liu et al., 2023b). Our study demonstrated the hydrological variations of Poyang Lake, upstream rivers, and the Yangtze River during the 2022 extreme drought. Temporally, the entire basin experienced dramatic changes in water levels and discharge, with the drought spanning both flood and dry seasons, consistent with the observations of Liu et al. (2023b). Spatially, the impacts of drought exhibited significant heterogeneity across the lake, which may be attributed to the variations in flow dynamics and lake topography (Huang et al., 2023; Liu et al., 2023a). While our study focused on surface water dynamics during the 2022 extreme drought, groundwater systems also exhibited significant heterogeneous responses. Chen et al. (2023b) documented spatially variable impacts on groundwater levels, with maximum declines exceeding 4 m in the eastern floodplain while western regions experienced relatively modest drops of less than 1 m. These differential groundwater responses further underscore the severity and spatial complexity of this drought event.

Extreme droughts have altered both the magnitude of precipitation and runoff and the relationship between them in the Poyang Lake basin (Fig. 8). On the one hand, drought periods experience significantly reduced precipitation, leading to a corresponding decrease in runoff. On the other hand, under the same precipitation conditions, non-drought periods exhibit a more substantial increase in river flow. For instance, substantial precipitation occurred in the Poyang Lake basin in late November 2023, but runoff increase was minimal compared to the pre-drought months (Fig. 8). This occurs because drought conditions alter the precipitation-runoff relationship, which manifests in modeling as a decline in fit coefficients (Wu et al., 2024; Tian et al., 2018). Physically, prolonged drought lowers soil moisture, causing incoming precipitation primarily absorbed by the soil and preventing a significant runoff increase (Maurer et al., 2022; Qin et al., 2015). In contrast, during non-drought periods, frequent rainfall keeps soil moisture at a saturated level, enabling new precipitation to flow directly into rivers, leading to a notable increase in runoff (Hanel et al., 2018; Grigorev et al., 2023).

4.2. River-lake interactions under the 2022 extreme drought

This study confirms that river-lake interactions indeed changed under extreme drought conditions using WSS and regression model results. Notably, prior to the extreme drought event in 2022, both the Poyang Lake Basin and the Yangtze River experienced abundant water levels. For instance, from January to June, water levels in Poyang Lake and the Yangtze River rose, resulting in consistently low WSS values between Hukou and Xingzi, indicating a strong blocking effect of the Yangtze River on Poyang Lake (Fig. 11a). In June, the water level in Poyang Lake peaked, and the WSS between Duchang and Kangshan approached zero, suggesting that water levels across various stations in the lake had nearly equalized due to the ample water supply (Fig. 10a). However, the sudden onset of an extreme drought rapidly disrupted this state. Given that the 2022 extreme drought spanned both the wet and dry seasons of Poyang Lake, it is necessary to discuss the seasonal variations in river-lake interactions separately. During the wet season, both the Yangtze River and Poyang Lake experienced significant water level declines. The WSS at Hukou-Xingzi did not show significant deviations from the multi-year average (Fig. 11), indicating that the Yangtze River still exerted a blocking effect on Poyang Lake. However, the regression model results revealed a negative contribution of the Yangtze River to Poyang Lake's water level changes during the wet season (Fig. 13), suggesting that the drought in the Yangtze River may have reduced this blocking effect. The WSS between Duchang and Kangshan increased significantly, indicating a continuous reduction in the lake water levels due to decreased inflows from the basin and a weakening of the blocking effect of Yangtze River. In the dry season, the WSS results at Hukou-Xingzi indicate a reduced ability of the Yangtze River to drain water from Poyang Lake, leading to diminished outflow from the lake into the river. The regression model also showed that, under these conditions, the Yangtze River had a positive influence on maintaining higher water levels in Poyang Lake. This suggests that the river-lake interaction may have alleviated the drought conditions in Poyang Lake. This is likely because the water level in Yangtze River had mostly recovered to non-drought conditions (Fig. 9a), while Poyang Lake continued to suffer from the drought (Fig. 6). Unlike the drought events analyzed by Zhang et al. (2015), where low water levels were attributed to simultaneous droughts in both systems coupled with TGD operations, our study revealed a distinct pattern in the 2022 extreme drought. This event was characterized by an initial phase of concurrent droughts in both the Poyang Lake basin and the Yangtze River, followed by a later phase where drought persisted only in the Poyang Lake basin. Our study provides a quantitative approach through regression modeling to assess the relative contributions of upstream rivers, the Yangtze River, and TGD operations to water level variations in Poyang Lake. It is important to note that the significant reduction in precipitation on both the Yangtze River basin and Poyang Lake basin, rather than the operation of TGD, should be primarily responsible for the 2022 extreme drought.

The new insights into river-lake interactions under extreme droughts may provide a theoretical foundation for implementing drought mitigation measures through regulation. This study analyzed the impact of basin precipitation and water supplementation from the TGD on water levels of Poyang Lake. The contribution of the TGD to alleviating drought in Poyang Lake was found to be very limited, indicating that reliance on the dam's regulation may be insufficient to address extreme droughts in the lake (Xue et al., 2023). In contrast, basin precipitation effectively mitigated the extreme drought conditions in Poyang Lake, suggesting that managing inflows from the basin could be an effective approach (Dong et al., 2019). Li et al. (2023b) demonstrated that the regulation of a group of reservoirs in the basin significantly increased Poyang Lake water levels during the dry season. For example, the Hongmen Reservoir on the Fuhe River has diverted water for residential consumption during extreme drought periods, despite its primary function of hydropower generation (Xu et al., 2020). However, whether the regulation can effectively address extreme droughts remains to be further investigated. Additionally, the proposed hydraulic project is soon to be constructed on the waterway to the north of the lake, with a management strategy focused on regulating only during the dry season without intervention during the flood season, which is believed to have potential in alleviating droughts in Poyang Lake (Yao et al., 2022). Xue et al. (2023) found that the proposed hydraulic project could effectively cope with extreme droughts, such as the one experienced in 2022, restoring the water level to a reasonable state. Future research should focus on the hydrological regime changes in Poyang Lake following the construction of this project.

4.3. Limitations and uncertainties

An uncertainty in this study is related to the time scale of the data, as daily data were used rather than sub-daily data. For studying river-lake interactions, sub-daily data may provide greater accuracy. For example, in the Tonle Sap Lake and Mekong River system, sub-daily and daily water level profiles exhibit distinct patterns (Morovati et al., 2024b). From a long-term perspective, we found consistency between daily and hourly water level data in the Yangtze-Poyang Lake system (Fig. S4 and Table S1); however, certain differences were observed in discharge records (Fig. S5 and Table S1). The extreme drought did not alter the temporal patterns of daily and sub-daily water levels (Fig. S6a), with their maximum deviation reaching 3.6 % during the 2022 drought (Fig. S6b). Future research could benefit from using sub-daily data for a more detailed analysis, with results compared and discussed alongside other river-lake systems, such as the Tonle Sap Lake and Mekong River. Beyond data resolution, dataset length is also critical. Although hydrological records in this study begin in 1956, records for Poyang Lake date back to 1951 (Zhang et al., 2018). Existing reports suggest that even with data from 1951 onward, the 2022 extreme drought ranks as the most severe recorded, though this study does not directly validate it. Additionally, the logistic model detected seasonal variations in the frequency of extreme droughts, but the results were not statistically significant due to the relatively short time series. Climate change and human activities are likely to intensify the magnitude and seasonal patterns of extreme water levels in Poyang Lake in the future (Yao et al., 2023). Future research should consider using more larger datasets to explore the seasonal variability under extreme droughts.

In this study, a multiple linear regression model was employed to analyze water level variations in Poyang Lake, incorporating average discounted variables to improve the accuracy of model fitting. The limitation of the model lies in its tendency to overestimate low water levels, which affects drought analysis by underestimating drought severity. However, this limitation does not significantly impact the assessment of drought duration of the event, as it captures the decline in water levels during the wet season (Fig. 12). Prediction intervals were introduced to assess this uncertainty (Fig. S3). The 90 % prediction interval generally encompasses low flows under normal conditions, but even the 99 % prediction interval failed to capture the observed decline in water levels during the extreme drought period, highlighting the severity of this event. The drought, likely exacerbated by multiple interacting factors, proved challenging to predict accurately within the current model framework. This discrepancy may stem from alterations in hydrological conditions during dry or extreme drought periods, potentially manifesting as changes in the coefficients of predictive variables, thereby altering their impact on water levels. Segmented modeling or using more complex nonlinear relationships for fitting may help improve the accuracy of low flows simulations. Moreover, the model overlooks several variables, such as groundwater, land use, sand mining, and local precipitation and evaporation, which may significantly impact the drought processes of the lake (Liu et al., 2022; Yao et al., 2019). Minor streams, groundwater discharge, and rainfall collectively account for approximately 8 % of the lake water volume (Li et al., 2015, 2018). Extreme drought conditions can triple the rate of groundwater discharge, with floodplain wetlands experiencing a discharge rate approximately 14.5 times higher than in average years during 2022 (Chen et al., 2023b). Excessive evaporation was a direct catalyst for the 2022 extreme drought (Liu et al., 2023b). Sand mining reduced the annual water level of Poyang Lake by 0.26–0.75 m from 2000 to 2014 (Ye et al., 2018). Human activities, such as project construction and land use, diminished the lake surface area from 5160 km^2 to 3860 km^2 between 1954 and 1998 (Shankman et al., 2006). Future research could aim for further model optimization, potentially by integrating more data, segmenting the analysis based on water levels, introducing additional variables and considering nonlinear relationships for a more accurate simulation.

5. Conclusions

Based on mathematical statistics and regression models, the temporal and spatial variations of Poyang Lake water level and the river-lake interaction under the 2022 extreme drought were analyzed. The probability of extreme droughts in Poyang Lake remained stable before the 21st century but has since increased significantly, reaching a level four times higher than before. By identifying historical extreme drought events in Poyang Lake and quantifying their characteristics, this study demonstrates that the 2022 drought was the most severe since 1956, with water levels significantly lower than any previously observed. Extreme droughts have altered the precipitation-runoff relationship in the Poyang Lake basin, limiting runoff response to precipitation during drought conditions. The blocking effect of the Yangtze River during the wet season decreased, leading to a rapid reduction in Poyang Lake's water storage. The decline in water levels during the receding and dry seasons weakened the lake's capacity to recharge the Yangtze River. The relative contributions of upstream and downstream river flows to Poyang Lake water level were quantified during the drought. In the second half of 2022, the reduction in Yangtze River flow had the most significant impact, more than doubling the contribution from upstream river flows. In the first half of 2023, reductions in upstream flow were the primary cause of the lake's decreased water levels. Throughout the drought period, the contribution rates of the upstream discharge, the natural discharge of the Yangtze River and the operation of the Three Gorges Dam to the reduction in Poyang Lake's water level are 23.68 %, 38.10 %, and 38.22 %, respectively.

A limitation of this study is its failure to account for the impacts of groundwater, land use, and sand mining, which may have a significant influence on the drought conditions of the lake. Additionally, the scope of this study was limited to the immediate hydrological impacts, without considering the potential environmental and ecological consequences. Future studies could benefit from integrating more comprehensive environmental and ecological data to understand the impacts of extreme droughts. Investigating the potential for adaptive management strategies involving the dams could provide solutions for mitigating the impacts of extreme droughts.

This study provides new insights into the variations in the hydrological regime of Poyang Lake under extreme drought conditions, contributing to improved water resource management in the Poyang Lake basin. It is imperative to consider the flow conditions from the upstream areas and the Yangtze River in the research and management of Poyang Lake, indicating the necessity of viewing the lake and rivers as an integrated system. Human activities, such as the operation of water conservancy projects, have a mixed impact on lakes. They could potentially increase the frequency of extreme drought conditions, yet possess the capability to mitigate drought situations through water supplementation. The regression model proposed in this study is expected to be applicable to other lakes, and provides a valuable tool for quantifying the influence of surrounding rivers.

CRediT authorship contribution statement

Guangqiu Jin: Writing – review & editing, Resources, Funding acquisition, Conceptualization. **Jinran Wu:** Writing – review & editing, Methodology. **Hongwu Tang:** Resources, Funding acquisition. **Zhongtian Zhang:** Writing – review & editing, Visualization. **You-Gan Wang:** Writing – review & editing, Methodology. **Siyi Zhang:** Writing – review & editing. **Yanqing Deng:** Data curation. **Hexiang Chen:** Writing – original draft, Visualization, Methodology, Investigation, Conceptualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.ejrh.2024.102165.

Data availability

The data that has been used is confidential.

References

Akyuz, D.E., Bayazit, M., Onoz, B., 2012. Markov chain models for hydrological drought characteristics. J. Hydrometeorol. 13 (1), 298–309. https://doi.org/10.1175/Jhm-D-11-019.1.

Chai, Y.F., Li, Y.T., Yang, Y.P., Li, S.X., Zhang, W., Ren, J.Q., Xiong, H.B., 2019. Water level variation characteristics under the impacts of extreme drought and the operation of the Three Gorges Dam. Front. Earth Sci. 13 (3), 510–522. https://doi.org/10.1007/s11707-018-0739-3.

Chen, H.X., Zhang, Z.T., Jin, G.Q., Tang, H.W., Zhang, S.Y., Zhang, Q., 2023a. Effects of periodic fluctuation of water level on solute transport in seasonal lakes in Poyang floodplain system. Water Resour. Res. 59 (12). https://doi.org/10.1029/2023WR034739.

Chen, J., Li, Y.L., Shu, L.C., Fang, S.W., Yao, J., Cao, S.J., Zeng, B.R., Yang, M., 2023b. The influence of the 2022 extreme drought on groundwater hydrodynamics in the floodplain wetland of Poyang Lake using a modeling assessment. J. Hydrol. 626. https://doi.org/10.1016/j.jhydrol.2023.130194.

Chen, S.T., Kuo, C.C., Yu, P.S., 2009. Historical trends and variability of meteorological droughts in Taiwan. Hydrol. Sci. J. -J. Des. Sci. Hydrol. 54 (3), 430–441. https://doi.org/10.1623/hysj.54.3.430.

Dai, X., Wan, R.R., Yang, G.S., 2015. Non-stationary water-level fluctuation in China's Poyang Lake and its interactions with Yangtze River. J. Geogr. Sci. 25 (3), 274–288. https://doi.org/10.1007/s11442-015-1167-x.

Dai, Z.J., Du, J.Z., Li, J.F., Li, W.H., Chen, J.Y., 2008. Runoff characteristics of the Changjiang River during 2006: effect of extreme drought and the impounding of the Three Gorges Dam. Geophys. Res. Lett. 35 (7). https://doi.org/10.1029/2008gl033456.

Dong, N.P., Yu, Z.B., Gu, H.H., Yang, C.G., Yang, M.X., Wei, J.H., Wang, H., Arnault, J., Laux, P., Kunstmann, H., 2019. Climate-induced hydrological impact mitigated by a high-density reservoir network in the Poyang Lake Basin. J. Hydrol. 579. https://doi.org/10.1016/j.jhydrol.2019.124148.

Feng, L., Hu, C.M., Chen, X.L., Cai, X.B., Tian, L.Q., Gan, W.X., 2012. Assessment of inundation changes of Poyang Lake using MODIS observations between 2000 and 2010. Remote Sens. Environ. 121, 80–92. https://doi.org/10.1016/j.rse.2012.01.014.

Feng, L., Han, X.X., Hu, C.M., Chen, X.L., 2016. Four decades of wetland changes of the largest freshwater lake in China: Possible linkage to the Three Gorges Dam? Remote Sens. Environ. 176, 43–55. https://doi.org/10.1016/j.rse.2016.01.011.

Grant, L., Vanderkelen, I., Gudmundsson, L., Tan, Z.L., Perroud, M., Stepanenko, V.M., Debolskiy, A.V., Droppers, B., Janssen, A.B.G., Woolway, R.I., Choulga, M., Balsamo, G., Kirillin, G., Schewe, J., Zhao, F., del Valle, I.V., Golub, M., Pierson, D., Marcé, R., Seneviratne, S.I., Thiery, W., 2021. Attribution of global lake systems change to anthropogenic forcing. Nat. Geosci. 14 (11), 849–854. https://doi.org/10.1038/s41561-021-00833-x.

Grigorev, V.Y., Kharlamov, M.A., Semenova, N.K., Sazonov, A.A., Chalov, S.R., 2023. Impact of precipitation and evaporation change on flood runoff over Lake Baikal catchment. Environ. Earth Sci. 82 (1). https://doi.org/10.1007/s12665-022-10679-0.

Guo, H., Hu, Q., Zhang, Q., Feng, S., 2012. Effects of the Three Gorges Dam on Yangtze River flow and river interaction with Poyang Lake, China: 2003-2008. J. Hydrol. 416 (1), 19–27. https://doi.org/10.1016/j.jhydrol.2011.11.027.

Guo, X., Zhu, A., Li, Q., Xia, Z., Chen, R., 2022. Long-term solutions for China's heat and drought. Science 378 (6624). https://doi.org/10.1126/science.adf6012.

Hanel, M., Rakovec, O., Markonis, Y., Máca, P., Samaniego, L., Kysely, J., Kumar, R., 2018. Revisiting the recent European droughts from a long-term perspective. Sci. Rep. 8. https://doi.org/10.1038/s41598-018-27464-4.

Hong, X.J., Guo, S.L., Xiong, L.H., Liu, Z.J., 2015. Spatial and temporal analysis of drought using entropy-based standardized precipitation index: a case study in Poyang Lake basin, China. Theor. Appl. Climatol. 122 (3-4), 543–556. https://doi.org/10.1007/s00704-014-1312-y.

Hu, Q., Feng, S., Guo, H., Chen, G., Jiang, T., 2007. Interactions of the Yangtze river flow and hydrologic processes of the Poyang Lake, China. J. Hydrol. 347 (1-2), 90–100. https://doi.org/10.1016/j.jhydrol.2007.09.005.
Hu, Z.P., 2023. Serious drought in Poyang Lake in 2022 and countermeasures for drought prevention and disaster reduction. China Flood Drought Manag. 33 (2), 1–6. https://doi.org/10.16867/j.issn.1673-9264.2022491.
Huang, A.P., Liu, X.B., Peng, W.Q., Dong, F., Han, Z., Du, F., Ma, B., Wang, W.J., 2023. Spatiotemporal heterogeneity of inundation pattern of floodplain lake wetlands and impact on wetland vegetation. Sci. Total Environ. 905. https://doi.org/10.1016/j.scitotenv.2023.167831.
Huang, S., Xia, J., Zeng, S.D., Wang, Y.L., She, D.X., 2021. Effect of Three Gorges Dam on Poyang Lake water level at daily scale based on machine learning. J. Geogr. Sci. 31 (11), 1598–1614. https://doi.org/10.1007/s11442-021-1913-1.
Huang, W.Q., Hu, T.F., Mao, J.Q., Montzka, C., Bol, R., Wan, S.X., Li, J.X., Yue, J., Dai, H.C., 2022. Hydrological drivers for the spatial distribution of wetland herbaceous communities in Poyang Lake. Remote Sens. 14 (19). https://doi.org/10.3390/rs14194870.
Jia, Y.X., Zhang, Q., Xue, C.Y., Tang, H.W., 2023. Nonstationary frequency analysis and uncertainty quantification for extreme low lake levels in a large river-lake-catchment system. Sci. Total Environ. 903. https://doi.org/10.1016/j.scitotenv.2023.166329.
Lai, X.H., Zeng, H., Zhao, X.M., Shao, Y.W., Guo, X., 2024. Impact of Extreme Drought on Vegetation Greenness in Poyang Lake Wetland. Forests 15 (10). https://doi.org/10.3390/f15101756.
Lai, X.J., Jiang, J.H., Liang, Q.H., Huang, Q., 2013. Large-scale hydrodynamic modeling of the middle Yangtze River Basin with complex river-lake interactions. J. Hydrol. 492, 228–243. https://doi.org/10.1016/j.jhydrol.2013.03.049.
Lai, X.J., Shankman, D., Huber, C., Yesou, H., Huang, Q., Jiang, J.H., 2014. Sand mining and increasing Poyang Lake's discharge ability: a reassessment of causes for lake decline in China. J. Hydrol. 519, 1698–1706. https://doi.org/10.1016/j.jhydrol.2014.09.058.
Li, B., Yang, G.S., Wan, R.R., 2020. Multidecadal water quality deterioration in the largest freshwater lake in China (Poyang Lake): Implications on eutrophication management. Environ. Pollut. 260. https://doi.org/10.1016/j.envpol.2020.114033.
Li, B., Yang, G.S., Wan, R.R., Lai, X.J., Wagner, P.D., 2022. Impacts of hydrological alteration on ecosystem services changes of a large river-connected lake (Poyang Lake), China. J. Environ. Manag. 310. https://doi.org/10.1016/j.jenvman.2022.114750.
Li, B., Yang, G.S., Wan, R.R., 2023a. Reassessment of the declines in the largest freshwater lake in China (Poyang Lake): uneven trends, risks and underlying causes. J. Environ. Manag. 342. https://doi.org/10.1016/j.jenvman.2023.118157.
Li, Q.Y., Lai, G.Y., Devlin, A.T., 2021. A review on the driving forces of water decline and its impacts on the environment in Poyang Lake, China. J. Water Clim. Change 12 (5), 1370–1391. https://doi.org/10.2166/wcc.2020.216.
Li, X.H., Ye, X.C., Yuan, C.Y., Xu, C.Y., 2023b. Can water release from local reservoirs cope with the droughts of downstream lake in a large river-lake system? J. Hydrol. 625. https://doi.org/10.1016/j.jhydrol.2023.130172.
Li, Y.L., Zhang, Q., Werner, A.D., Yao, J., 2015. Investigating a complex lake-catchment-river system using artificial neural networks: Poyang Lake (China). Hydrol. Res. 46 (6), 912–928. https://doi.org/10.2166/nh.2015.150.
Li, Y.L., Zhang, Q., Ye, R., Yao, J., Tan, Z.Q., 2018. 3D hydrodynamic investigation of thermal regime in a large river-lake-floodplain system (Poyang Lake, China). J. Hydrol. 567, 86–101. https://doi.org/10.1016/j.jhydrol.2018.10.007.
Li, Y.L., Zhang, Q., Lu, J.R., Yao, J., Tan, Z.Q., 2019. Assessing surface water-groundwater interactions in a complex river-floodplain wetland-isolated lake system. River Res. Appl. 35 (1), 25–36. https://doi.org/10.1002/rra.3389.
Liu, B., Li, Y.L., Jiang, W.Y., Chen, J., Shu, L.C., Liu, J.X., 2022. Understanding groundwater behaviors and exchange dynamics in a linked catchment-floodplain-lake system. Sci. Total Environ. 853. https://doi.org/10.1016/j.scitotenv.2022.158558.
Liu, M.Y., Zhang, P.P., Cai, Y.P., Chu, J.W., Li, Y.L., Wang, X., Li, C.H., Liu, Q., 2023a. Spatial-temporal heterogeneity analysis of blue and green water resources for Poyang Lake basin, China. J. Hydrol. 617. https://doi.org/10.1016/j.jhydrol.2022.128983.
Liu, S.L., Wu, Y.L., Xu, G.D., Cheng, S.Y., Zhong, Y.L., Zhang, Y., 2023b. Characterizing the 2022 extreme drought event over the Poyang Lake basin using multiple satellite remote sensing observations and in situ data. Remote Sens. 15 (21). https://doi.org/10.3390/rs15215125.
Liu, W.L., Zhu, S.N., Huang, Y.P., Wan, Y.F., Wu, B., Liu, L., 2020. Spatiotemporal Variations of Drought and Their Teleconnections with Large-Scale Climate Indices over the Poyang Lake Basin, China. Sustainability 12 (9). https://doi.org/10.3390/su12093526.
Liu, Y.B., Song, P., Peng, J., Fu, Q.N., Dou, C.C., 2011. Recent increased frequency of drought events in Poyang Lake Basin, China: climate change or anthropogenic effects? Hydro-Climatol.: Var. Change 344, 99–104.
Liu, Y.B., Wu, G.P., Zhao, X.S., 2013. Recent declines in China's largest freshwater lake: trend or regime shift? Environ. Res. Lett. 8 (1). https://doi.org/10.1088/1748-9326/8/1/014010.
Liu, Y.B., Wu, G.P., Guo, R.F., Wan, R.R., 2016. Changing landscapes by damming: the Three Gorges Dam causes downstream lake shrinkage and severe droughts. Landsc. Ecol. 31 (8), 1883–1890. https://doi.org/10.1007/s10980-016-0391-9.
Long, D., Scanlon, B.R., Longuevergne, L., Sun, A.Y., Fernando, D.N., Save, H., 2013. GRACE satellite monitoring of large depletion in water storage in response to the 2011 drought in Texas. Geophys. Res. Lett. 40 (13), 3395–3401. https://doi.org/10.1002/grl.50655.
Maurer, T., Avanzi, F., Glaser, S.D., Bales, R.C., 2022. Drivers of drought-induced shifts in the water balance through a Budyko approach. Hydrol. Earth Syst. Sci. 26 (3), 589–607. https://doi.org/10.5194/hess-26-589-2022.
McGowan, S., Leavitt, P.R., Hall, R.I., 2005. A whole-lake experiment to determine the effects of winter droughts on shallow lakes. Ecosystems 8 (6), 694–708. https://doi.org/10.1007/s10021-003-0152-x.
Mckee, T.B., Doesken, N.J., Kleist, J.R. (1993) The relationship of drought frequency and duration to time scales. Preprints, 8th Conference on Applied Climatology. 179-184, Anaheim, California.
Mei, X.F., Dai, Z.J., Du, J.Z., Chen, J.Y., 2015. Linkage between Three Gorges Dam impacts and the dramatic recessions in China's largest freshwater lake, Poyang Lake. Sci. Rep. 5 (9), 1–8. https://doi.org/10.1038/srep18197.
Mei, X.F., Dai, Z.J., Fagherazzi, S., Chen, J.Y., 2016. Dramatic variations in emergent wetland area in China's largest freshwater lake, Poyang Lake. Adv. Water Resour. 96, 1–10. https://doi.org/10.1016/j.advwatres.2016.06.003.
Morovati, K., Tian, F.Q., Pokhrel, Y., Someth, P., Shi, L.D., Zhang, K.R., Nakhaei, P., Ly, S., 2024a. Fishery and agriculture amidst human activities and climate change in the Mekong River: A review of gaps in data and effective approaches towards sustainable development. J. Hydrol. 644. https://doi.org/10.1016/j.jhydrol.2024.132043.
Morovati, K., Zhang, K., Shi, L.D., Pokhrel, Y., Wu, M.Z., Someth, P., Ly, S., Tian, F.Q., 2024b. On the cause of large daily river flow fluctuations in the Mekong River. Hydrol. Earth Syst. Sci. 28 (22), 5133–5147. https://doi.org/10.5194/hess-28-5133-2024.
Mu, S.J., Yang, G.S., Xu, X.B., Wan, R.R., Li, B., 2022. Assessing the inundation dynamics and its impacts on habitat suitability in Poyang Lake based on integrating Landsat and MODIS observations. Sci. Total Environ. 834. https://doi.org/10.1016/j.scitotenv.2022.154936.
Peng, Y.J., Chen, G., Chao, N.F., Wang, Z.T., Wu, T.T., Luo, X.Y., 2024. Detection of extreme hydrological droughts in the poyang lake basin during 2021-2022 using GNSS-derived daily terrestrial water storage anomalies. Sci. Total Environ. 919. https://doi.org/10.1016/j.scitotenv.2024.170875.
Peter, H.G., 1993. Water and conflict: fresh water resources and international security. Int. Secur. 18 (1), 79–112.
Pi, X.H., Luo, Q.Q., Feng, L., Xu, Y., Tang, J., Liang, X.Y., Ma, E.Z., Cheng, R., Fensholt, R., Brandt, M., Cai, X.B., Gibson, L., Liu, J.G., Zheng, C.M., Li, W.F., Bryan, B. A., 2022. Mapping global lake dynamics reveals the emerging roles of small lakes. Nat. Commun. 13 (1). https://doi.org/10.1038/s41467-022-33239-3.
Qin, Y., Yang, D.W., Lei, H.M., Xu, K., Xu, X.Y., 2015. Comparative analysis of drought based on precipitation and soil moisture indices in Haihe basin of North China during the period of 1960-2010. J. Hydrol. 526, 55–67. https://doi.org/10.1016/j.jhydrol.2014.09.068.
Raymond, P.A., Hartmann, J., Lauerwald, R., Sobek, S., McDonald, C., Hoover, M., Butman, D., Striegl, R., Mayorga, E., Humborg, C., Kortelainen, P., Dürr, H., Meybeck, M., Ciais, P., Guth, P., 2013. Global carbon dioxide emissions from inland waters. Nature 503 (7476), 355–359. https://doi.org/10.1038/nature12760.
Satgé, F., Espinoza, R., Zolá, R.P., Roig, H., Timouk, F., Molina, J., Garnier, J., Calmant, S., Seyler, F., Bonnet, M.P., 2017. Role of Climate Variability and Human Activity on Poopo Lake Droughts between 1990 and 2015 Assessed Using Remote Sensing Data. Remote Sens. 9 (3). https://doi.org/10.3390/rs9030218.

Shankman, D., Keim, B.D., Song, J., 2006. Flood frequency in China's Poyang Lake region: Trends and teleconnections. Int. J. Climatol. 26 (9), 1255–1266. https://doi.org/10.1002/joc.1307.

She, D.X., Xia, J., Song, J.Y., Du, H., Chen, J.X., Wan, L., 2013. Spatio-temporal variation and statistical characteristic of extreme dry spell in Yellow River Basin, China. Theor. Appl. Climatol. 112 (1-2), 201–213. https://doi.org/10.1007/s00704-012-0731-x.

Stagge, J.H., Kohn, I., Tallaksen, L.M., Stahl, K., 2015. Modeling drought impact occurrence based on meteorological drought indices in Europe. J. Hydrol. 530, 37–50. https://doi.org/10.1016/j.jhydrol.2015.09.039.

Tan, Z.Q., Tao, H., Jiang, J.H., Zhang, Q., 2015. Influences of climate extremes on NDVI (normalized difference vegetation dndex) in the Poyang Lake Basin, China. Wetlands 35 (6), 1033–1042. https://doi.org/10.1007/s13157-015-0692-9.

Tian, B.Q., Gao, P., Mu, X.M., Zhao, G.J., 2023. Water Area Variation and River-Lake Interactions in the Poyang Lake from 1977-2021. Remote Sens. 15 (3). https://doi.org/10.3390/rs15030600.

Tian, W., Liu, X.M., Liu, C.M., Bai, P., 2018. Investigation and simulations of changes in the relationship of precipitation-runoff in drought years. J. Hydrol. 565, 95–105. https://doi.org/10.1016/j.jhydrol.2018.08.015.

Verpoorter, C., Kutser, T., Seekell, D.A., Tranvik, L.J., 2014. A global inventory of lakes based on high-resolution satellite imagery. Geophys. Res. Lett. 41 (18), 6396–6402. https://doi.org/10.1002/2014gl060641.

Wang, Y.G., Tian, T., 2013. Sediment concentration prediction and statistical evaluation for annual load estimation. J. Hydrol. 482, 69–78. https://doi.org/10.1016/j.jhydrol.2012.12.043.

Williamson, C.E., Saros, J.E., Vincent, W.F., Smol, J.P., 2009. Lakes and reservoirs as sentinels, integrators, and regulators of climate change. Limnol. Oceanogr. 54 (6), 2273–2282. https://doi.org/10.4319/lo.2009.54.6_part_2.2273.

Woolway, R.I., Kraemer, B.M., Lenters, J.D., Merchant, C.J., O'Reilly, C.M., Sharma, S., 2020. Global lake responses to climate change. Nat. Rev. Earth Environ. 1 (8), 388–403. https://doi.org/10.1038/s43017-020-0067-5.

Wu, G.F., de Leeuw, J., Skidmore, A.K., Prins, H.H.T., Best, E.P.H., Liu, Y.L., 2009. Will the Three Gorges Dam affect the underwater light climate of Vallisneria spiralis L. and food habitat of Siberian crane in Poyang Lake? Hydrobiologia 623 (1), 213–222. https://doi.org/10.1007/s10750-008-9659-7.

Wu, H.W., Huang, Q., Fu, C.S., Song, F., Liu, J.Z., Li, J., 2021. Stable isotope signatures of river and lake water from Poyang Lake, China: Implications for river-lake interactions. J. Hydrol. 592. https://doi.org/10.1016/j.jhydrol.2020.125619.

Wu, J.F., An, P.Y., Zhao, C.X., Wei, Z.Q., Lan, T., Li, X.M., Wang, G.Q., 2024. Effects of multi-year droughts on the precipitation-runoff relationship: An integrated analysis of meteorological, hydrological, and compound droughts. J. Hydrol. 634. https://doi.org/10.1016/j.jhydrol.2024.131064.

Xu, D.D., Lyon, S.W., Mao, J.Q., Dai, H.C., Jarsjo, J., 2020. Impacts of multi-purpose reservoir construction, land-use change and climate change on runoff characteristics in the Poyang Lake basin, China. J. Hydrol. -Reg. Stud. 29. https://doi.org/10.1016/j.ejrh.2020.100694.

Xu, F.L., Tao, S., Dawson, R.W., Li, P.G., Cao, J., 2001. Lake ecosystem health assessment: Indicators and methods. Water Res. 35 (13), 3157–3167. https://doi.org/10.1016/S0043-1354(01)00040-9.

Xu, G.D., Wu, Y.L., Liu, S.L., Cheng, S.Y., Zhang, Y., Pan, Y.J., Wang, L.C., Dokuchits, E.Y., Nkwazema, O.C., 2023. How 2022 extreme drought influences the spatiotemporal variations of terrestrial water storage in the Yangtze River Catchment: Insights from GRACE-based drought severity index and in-situ measurements. J. Hydrol. 626. https://doi.org/10.1016/j.jhydrol.2023.130245.

Xu, J., Jin, G.Q., Tang, H.W., Zhang, P., Wang, S., Wang, Y.G., Li, L., 2018. Assessing temporal variations of Ammonia Nitrogen concentrations and loads in the Huaihe River Basin in relation to policies on pollution source control. Sci. Total Environ. 642, 1386–1395. https://doi.org/10.1016/j.scitotenv.2018.05.395.

Xue, C.Y., Zhang, Q., Jia, Y.X., Yuan, S.Y., 2023. Intensifying drought of Poyang Lake and potential recovery approaches in the dammed middle Yangtze River catchment. J. Hydrol. -Reg. Stud. 50. https://doi.org/10.1016/j.ejrh.2023.101548.

Yao, J., Zhang, Q., Li, Y.L., Li, M.F., 2016. Hydrological evidence and causes of seasonal low water levels in a large river-lake system: Poyang Lake, China. Hydrol. Res. 47, 24–39. https://doi.org/10.2166/nh.2016.044.

Yao, J., Zhang, Q., Ye, X.C., Zhang, D., Bai, P., 2018. Quantifying the impact of bathymetric changes on the hydrological regimes in a large floodplain lake: Poyang Lake. J. Hydrol. 561, 711–723. https://doi.org/10.1016/j.jhydrol.2018.04.035.

Yao, J., Zhang, D., Li, Y.L., Zhang, Q., Gao, J.F., 2019. Quantifying the hydrodynamic impacts of cumulative sand mining on a large river-connected floodplain lake: Poyang Lake. J. Hydrol. 579. https://doi.org/10.1016/j.jhydrol.2019.124156.

Yao, J., Gao, J.F., Yu, X.B., Zhang, Q., 2022. Impacts of a proposed water control project on the inundation regime in China's largest freshwater lake (Poyang Lake): Quantification and ecological implications. J. Hydrol. -Reg. Stud. 40. https://doi.org/10.1016/j.ejrh.2022.101024.

Yao, S.Y., Chen, C., Chen, Q.W., Zhang, J.Y., He, M.N., 2023. Combining process-based model and machine learning to predict hydrological regimes in floodplain wetlands under climate change. J. Hydrol. 626. https://doi.org/10.1016/j.jhydrol.2023.130193.

Ye, X.C., Zhang, Q., Liu, J., Li, X.H., Xu, C.Y., 2013. Distinguishing the relative impacts of climate change and human activities on variation of streamflow in the Poyang Lake catchment, China. J. Hydrol. 494, 83–95. https://doi.org/10.1016/j.jhydrol.2013.04.036.

Ye, X.C., Li, Y.L., Li, X.H., Zhang, Q., 2014. Factors influencing water level changes in China's largest freshwater lake, Poyang Lake, in the past 50 years. Water Int. 39 (7), 983–999. https://doi.org/10.1080/02508060.2015.986617.

Ye, X.C., Li, X.H., Xu, C.Y., Zhang, Q., 2016. Similarity, difference and correlation of meteorological and hydrological drought indices in a humid climate region - the Poyang Lake catchment in China. Hydrol. Res. 47 (6), 1211–1223. https://doi.org/10.2166/nh.2016.214.

Ye, X.C., Xu, C.Y., Zhang, Q., Yao, J., Li, X.H., 2018. Quantifying the human induced water level decline of China's largest freshwater lake from the changing underlying surface in the lake region. Water Resour. Manag. 32 (4), 1467–1482. https://doi.org/10.1007/s11269-017-1881-5.

Zhang, D., Chen, P., Zhang, Q., Li, X.H., 2017. Copula-based probability of concurrent hydrological drought in the Poyang lake-catchment-river system (China) from 1960 to 2013. J. Hydrol. 553, 773–784. https://doi.org/10.1016/j.jhydrol.2017.08.046.

Zhang, G.Y., Tan, G.M., Zhang, W., Chai, Y.F., Wang, J.W., Yin, Z., Hu, Y., 2024. Characteristics and causes of water level variations in the Chenglingji-Jiujiang reach of the Yangtze River following the operation of the Three Gorges Dam. Hydrol. Res. 55 (6), 628–645. https://doi.org/10.2166/nh.2024.010.

Zhang, M.J., He, J.Y., Wang, B.L., Wang, S.J., Li, S.S., Liu, W.L., Ma, X.N., 2013. Extreme drought changes in Southwest China from 1960 to 2009. J. Geogr. Sci. 23 (1), 3–16. https://doi.org/10.1007/s11442-013-0989-7.

Zhang, Q., Xu, C.Y., Becker, S., Jiang, T., 2006. Sediment and runoff changes in the Yangtze River basin during past 50 years. J. Hydrol. 331 (3-4), 511–523. https://doi.org/10.1016/j.jhydrol.2006.05.036.

Zhang, Q., Sun, P., Chen, X.H., Jiang, T., 2011. Hydrological extremes in the Poyang Lake basin, China: changing properties, causes and impacts. Hydrol. Process. 25 (20), 3121–3130. https://doi.org/10.1002/hyp.8031.

Zhang, Q., Li, L., Wang, Y.G., Werner, A.D., Xin, P., Jiang, T., Barry, D.A., 2012. Has the Three-Gorges Dam made the Poyang Lake wetlands wetter and drier? Geophys. Res. Lett. 39 (20), L20402. https://doi.org/10.1029/2012GL053431.

Zhang, Q., Ye, X.C., Werner, A.D., Li, Y.L., Yao, J., Li, X.H., Xu, C.Y., 2014. An investigation of enhanced recessions in Poyang Lake: comparison of Yangtze River and local catchment impacts. J. Hydrol. 517, 425–434. https://doi.org/10.1016/j.jhydrol.2014.05.051.

Zhang, Q., Xue, C.Y., Xia, J., 2023. Impacts, contributing factors and countermeasures of extreme droughts in Poyang Lake. Bull. Chin. Acad. Sci. 38 (12), 1894–1902. https://doi.org/10.16418/j.issn.1000-3045.20230813005.

Zhang, Q.H., Dong, X.H., Chen, Y.W., Yang, X.D., Xu, M., Davidson, T.A., Jeppesen, E., 2018. Hydrological alterations as the major driver on environmental change in a floodplain Lake Poyang (China): evidence from monitoring and sediment records. J. Gt. Lakes Res. 44 (3), 377–387. https://doi.org/10.1016/j.jglr.2018.02.003.

Zhang, Z.T., Jin, G.Q., Tang, H.W., Zhang, S.Y., Zhu, D., Xu, J., 2022. How does the three gorges dam affect the spatial and temporal variation of water levels in the Poyang Lake? J. Hydrol. 605. https://doi.org/10.1016/j.jhydrol.2021.127356.
Zhang, Z.X., Chen, X., Xu, C.Y., Hong, Y., Hardy, J., Sun, Z.H., 2015. Examining the influence of river-lake interaction on the drought and water resources in the Poyang Lake basin. J. Hydrol. 522 (7), 510–521. https://doi.org/10.1016/j.jhydrol.2015.01.008.
Zou, R., Wang, X.J., Yin, Y.X., Ma, X.Y., Yang, X.Q., Huang, P.N., Ullah, I., 2024. Comparing spatio-temporal propagation patterns of hydrological and meteorological droughts: Insights from SWAT modelling in the poyang lake basin. Catena 243. https://doi.org/10.1016/j.catena.2024.108183.