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Hydrological Regime Shifts in River-Connected Lakes under Upstream Dam Regulation: Insights from the Three Gorges Project and Poyang Lake

Biqing Tian[1], Hao Jia[1], Peng Gao[12], Xingmin Mu[12]

[1]State Key Laboratory of Soil Erosion and Dryland Farming on the Loess Plateau, Institute of Soil and Water Conservation, Northwest A&F University, Yangling 712100, China

[2]State Key Laboratory of Soil Erosion and Dryland Farming on the Loess Plateau, Institute of Soil and Water Conservation, Chinese Academy of Sciences and Ministry of Water Resources, Yangling 712100, China

Correspondence to: Peng Gao (gaopeng@ms.iswc.ac.cn)

Abstract. Revealing the impacts of mainstream dams on the hydrological regime of connected river–lake systems is crucial for elucidating river–lake interaction mechanisms and providing a scientific basis for basin-scale water resources regulation and ecological protection. Taking the Three Gorges Project–Poyang Lake system as a representative case, this study integrates the Light Gradient Boosting Machine (LightGBM) model with the SWAT model to analyze the lake's hydrological responses to dam regulation. Based on long-term runoff, water level, and meteorological series, simulated and observed hydrological events were compared to quantify the influence of the Three Gorges Project on Poyang Lake. Results indicate that backflow events declined significantly in frequency (−11.58%), duration (−22.6 days), water level (−7.79%), and discharge (−35.60%), with the dam contributing 72.19% of the variation in backflow events discharge. The backwater effect at Hukou weakened markedly (fitted backflow -150.58×10^3 m^3/s), triggering cascading effects across the lake. Normalflow events were notably prolonged (+25.9 days), whereas flood events decreased in both frequency (−5.18%) and discharge (−11.03%), demonstrating a significant flood peak attenuation effect (fitted backflow -10512.89×10^3 m^3/s). In contrast, a decline in water levels (−7.47%) and discharge (−12.90%) during normalflow events, and a 15.18% increase in drought event frequency, to which the dam contributed 30.03% of the runoff variation. During drought events, discharge deviated substantially from model predictions ($+391.34\times10^3$ m^3/s), indicating enhanced hydraulic resistance at Hukou. Moreover, under drought events, the hydrological relationship at Hukou shifted from mainstream water-level dominance to lake-outflow dominance. Overall, the construction of the Three Gorges Dam has made hydrological variations in the Poyang Lake region more stable and secure, but has also increased drought risks, marking a gradual transition from a naturally regulated lake system to a semi-natural, dam-regulated system. Future management should aim to optimize dam operation schedules and enhance river–lake connectivity to promote the coordinated and sustainable development of water resources and ecosystems.

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1.Introduction

Connected river–lake systems are globally important hydromorphological units that link large rivers with their associated lakes through inflow and outflow channels. These systems play a crucial role in runoff regulation, water resource supply, ecosystem maintenance, and regional climate regulation. Their hydrological connectivity ensures the continuous exchange of materials, energy, and organisms, providing irreplaceable ecological functions and socioeconomic value (Leira and Cantonati, 2008; Yao et al., 2019). Typical examples include the Lake Erie–St. Lawrence River system in North America, the Lake Victoria–Nile River system in Africa, and the Poyang Lake–Yangtze River system in China. A common characteristic of these connected systems is that the stability of mainstream water levels and hydrodynamic conditions profoundly shapes the state of the lake. Periodic fluctuations of mainstream water levels drive the exchange of runoff, sediment, and nutrients through the lake outlet, regulating both inflow and outflow processes and maintaining the lake's morphological and ecological stability (Obolewski, 2011). However, when substantial changes occur in the mainstream, the ecosystem stability of these river–lake systems can be severely disrupted. Globally, the intensification of hydraulic engineering activities in the upstream reaches of major rivers—particularly the construction of large mainstream dams—has significantly altered the hydrological regimes of connected lakes. Dam construction modifies the seasonal distribution of runoff and changes mainstream water levels and flow dynamics. These hydrological alterations are transmitted and often amplified downstream, leading to systematic shifts in flood–dry cycles and river–lake interaction patterns(Li et al., 2023b; Yin et al., 2023; Zhang et al., 2015a). Maintaining a stable and sustainable river–lake relationship has therefore become a shared global challenge for all connected river–lake systems.

In recent years, the interaction between rivers and connected lakes has attracted increasing global attention. In fact, the river–lake interaction mechanisms in connected lakes represent complex and nonlinear hydrodynamic behaviors that are inherently difficult to interpret systematically. On one hand, the hydrodynamic processes are highly nonlinear and jointly influenced by rainfall, runoff, evapotranspiration, mainstream regulation, and lake storage–release conditions. These processes are difficult to accurately capture using traditional one-dimensional or quasi-two-dimensional models(Wu et al., 2022). On the other hand, limited data availability and insufficient process understanding also pose major challenges, as connected lake regions often lack high-frequency, high-precision observations, making it difficult to accurately characterize dynamic phenomena such as backflow and retention. Consequently, most existing studies have focused on water quality, ecology, or the hydrological responses of typical events, relying mainly on machine learning–based empirical models to simulate outflow or water level during representative hydrological events(Chen et al., 2025; Dong et al., 2021; Wu et al., 2022; Xia and Chen, 2021; Yang et al., 2021). Although such models can capture certain nonlinear relationships, purely data-driven approaches fail to fully reflect the intrinsic mechanisms governing river–lake interactions. To address this issue, this study integrates a watershed hydrological model (SWAT) with a long-term data-driven Light Gradient Boosting Machine (LightGBM) model to analyze river–lake interactions from both hydrological and empirical perspectives. The SWAT model is used to simulate runoff responses under the “no-dam natural scenario,” while the LightGBM model fits outflow or water level variations during the actual regulation period. By comparing the two, the impacts of mainstream regulation and other anthropogenic activities on river–lake interactions are quantitatively identified, providing scientific insights into the response mechanisms of connected lakes under upstream dam regulation.

As the largest hydraulic project in the world, the Three Gorges Project (TGP) plays critical roles in flood control, power generation, and navigation, exerting profound influences on the hydrological regime of the middle and lower Yangtze River. Since the TGP impoundment in 2003, the “peak-shaving and valley-filling” regulation has effectively mitigated downstream flooding but also altered the outflow dynamics at Hukou. Previous studies have revealed that since the impoundment, Poyang Lake has experienced persistently lower water levels, earlier dry seasons, and a reduction in lake area, reflecting substantial changes in hydrological rhythm and water availability, which further challenge the ecological stability of the lake(Hu et al., 2007; Xue et al., 2023a; Zhang et al., 2015b, 2022). Systematically characterizing such hydrological transitions provides a valuable opportunity to elucidate how large-scale dam regulation reshapes river–lake connectivity, storage–release balance, and seasonal hydrological cycles, offering an analytical framework applicable to connected lakes worldwide and contributing to integrated basin management, ecohydrological regulation, and lake restoration.

In this study, the Three Gorges Dam–Poyang Lake system is selected as a representative case to explore the hydrological effects of mainstream dams on connected lakes. Using 50 years of daily observations at Hukou, we classified and quantified flood events, normalflow events, drought events, and backflow events to characterize the temporal evolution of river–lake interactions. By integrating the SWAT model with the long-term data-driven LightGBM model, the study quantitatively disentangles the influence of mainstream dam regulation on downstream connected lakes and assesses its effects on river–lake interaction dynamics. The findings provide theoretical and practical guidance for water resource management and ecological conservation of connected lakes under large-scale dam regulation worldwide.

2. Data and Methods

2.1 Study Area

The Yangtze River is one of the world's largest rivers in terms of runoff. The Three Gorges Project (TGP), located in the middle reach of the upper Yangtze mainstream, lies approximately 1,000 km upstream from Poyang Lake. Since its operation in 2003, the TGP reservoir, with a maximum storage capacity of 39.3 billion m³, has played a significant role in peak-shaving and valley-filling, effectively mitigating flood risks in the middle and lower reaches. However, reservoir regulation and the associated channel incision have also altered the water level–discharge relationship along the middle and lower Yangtze River, thereby exerting profound impacts on the hydrological rhythm of downstream connected lakes(Guo et al., 2012).

Poyang Lake, located on the southern bank of the middle–lower Yangtze River, is the largest freshwater lake in China. It is hydraulically connected to the Yangtze mainstream through its only outlet at Hukou, and jointly influenced by the inflows of the five major tributaries—Ganjiang, Fuhe, Xinjiang, Raohe, and Xiushui. This configuration forms a typical river–lake interaction pattern characterized by pronounced seasonal fluctuations. The lake's average surface area is about 3,000 km², expanding to over 4,000 km² during the wet season and shrinking to less than 1,000 km² during the dry season. Poyang Lake not only serves as an important natural reservoir of the Yangtze River but also sustains regional wetland ecosystems, migratory bird habitats, and local livelihoods (Fig. 1) (Lai et al., 2024; Li et al., 2021; Xie et al., 2021).

As the hydrological junction of the Yangtze–Poyang Lake system, the Hukou Hydrological Station has long provided reliable observations of water level and discharge, offering valuable data for analyzing the evolution of river–lake relationships. In this study, daily discharge and water level data from the Hukou Station—covering both the pre-TGP period (1970–2002) and the post-TGP period (2003–2020)—along

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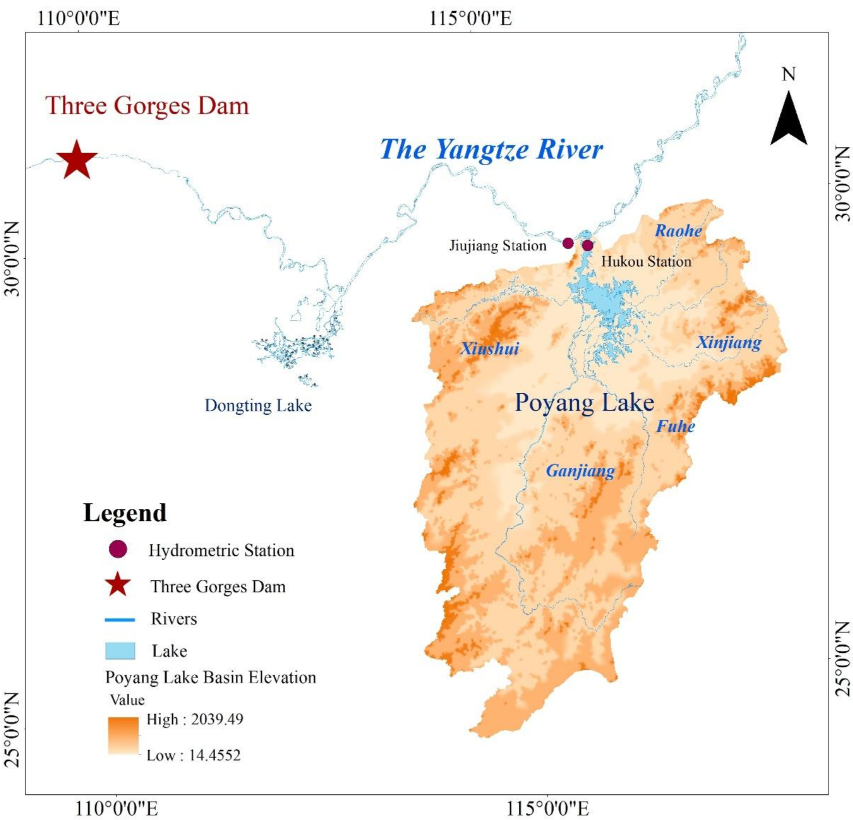
with water level data from the Jiujiang Station on the Yangtze mainstream, were used to compare and analyze the temporal evolution of flood events, normalflow events, drought events, and backflow events in Poyang Lake.



125 **Figure 1 Study area**

2.2 Methods

2.2.1 Data sources and processing

This study utilized daily hydrological records from the Hukou Station covering the period 1970–2020. Based on the flood and drought warning levels issued by the Jiangxi Provincial Department of Water Resources, threshold values were defined to classify different hydrological events: flood events were identified when the Hukou water level was ≥19.50 m, drought events when the water level was ≤7.99 m, and backflow events when the discharge values abnormally decreased or dropped below zero under relatively stable water level conditions(Jiangxi Provincial Department of Water Resources，River and

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Hydrological Conditions, 2025). All remaining conditions were classified as normalflow events. For each event type, the average water level, average discharge, event frequency, and event duration were calculated to construct a long-term hydrological event series of the lake. To assess the hydrological regime changes before and after the operation of the Three Gorges Project (TGP), the year 2003 was selected as the key dividing point, splitting the dataset into the pre-TGP period (1970–2002) and the post-TGP period (2003–2020).

2.2.2 Trend and Abrupt Change Detection

To investigate the long-term evolution of water level and discharge, the cumulative difference method was applied to derive interannual variation trends. Using 1970 as the reference year, the annual mean water level (H) and discharge (Q) were transformed into interannual variation values (ΔH and ΔQ), which were then cumulatively summed to obtain long-term variation curves.The Mann–Kendall (MK) trend test was employed to statistically evaluate long-term trends in the hydrological series. This non-parametric method does not require data to follow a specific distribution and is suitable for natural hydrometeorological time series. The test statistic Z indicates the trend significance: $|Z| > 1.96$ denotes a significant trend at the 95% confidence level, while $|Z| > 2.58$ indicates significance at the 99% confidence level. The Mann–Kendall mutation test was further applied to identify structural mutation points, determining whether significant regime shifts occurred in specific years. Mutation years were identified at the intersection of the UF and UB statistic curves within the confidence interval, thereby revealing the structural changes in hydrological processes before and after the TGP operation(Hamed and Rao, 1998). An independent samples t-test was conducted to verify the significance of differences in hydrological variables between the pre- and post-TGP periods. When $p < 0.05$, the difference in mean values was considered significant at the 95% confidence level; otherwise ($p \geq 0.05$), the difference was regarded as not significant.

2.2.3 Modeling of Normalflow Events

The Light Gradient Boosting Machine (LightGBM) is a framework based on the Gradient Boosting Decision Tree (GBDT) algorithm, belonging to the family of ensemble learning methods. It iteratively trains multiple weak learners and combines them into a strong predictive model through weighted aggregation. Compared with traditional GBDT frameworks such as XGBoost, LightGBM is optimized

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for large-scale and high-dimensional data applications, featuring fast training speed, low memory usage, and high accuracy(Mienye and Sun, 2022). Hydrological simulations of the water level–discharge relationship are inherently highly nonlinear. Traditional physically based models (e.g., SWAT, VIC, HEC-HMS, and MIKE series) can simulate these processes but often require complex parameter calibration and high computational cost. In contrast, the tree-based structure of LightGBM can flexibly capture nonlinear dependencies between variables, effectively learning the complex relationships between water level and discharge—particularly suitable for lake–river confluences exhibiting backflow phenomena. However, as a purely data-driven approach, LightGBM does not explicitly account for physical constraints such as water balance or energy conservation. Under extreme conditions—such as severe floods or strong backflow—it may produce hydrologically inconsistent or overfitted predictions(Bian et al., 2023; Kumar et al., 2023).

To mitigate these issues and avoid the influence of extreme events, the model was trained separately for the pre- and post-TGP periods using data from normalflow events. 1.Input variables included the discharges of the five major tributaries flowing into Poyang Lake (the Ganjiang, Fuhe, Xinjiang, Raohe, and Xiushui Rivers), the Hukou discharge, and monthly indicators representing seasonal effects. 2.During training, the model automatically learned the nonlinear relationships between the tributary inflows and the lake outlet discharge, including (a) the relative contributions of each river, (b) the lag effects of upstream inflow on downstream discharge, and (c) the intra-annual periodicity of hydrological processes represented by sinusoidal transformations of month variables. 3.Data were split chronologically into a training set (80%) and a testing set (20%) to prevent data leakage and maintain temporal consistency. A large number of boosting iterations and a small learning rate were used, combined with subsampling and feature sampling strategies to enhance generalization. An early stopping mechanism was employed to monitor the root mean square error (RMSE) on the validation set, effectively avoiding overfitting. 4.The model performance was evaluated using the coefficient of determination (R^2) and RMSE, computed separately for both the training and testing datasets. 5.Using the historical data, separate LightGBM models were constructed for the pre- and post-TGP periods. Then, by inputting tributary inflows under various hydrological conditions into the trained models, the Hukou outlet discharge was simulated for each period, providing a quantitative basis for analyzing the hydrological regime shifts of the lake before and after TGP operation (Figure 2).

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During model fitting, it was found that flood events had limited sample size and duration compared with drought and backflow events, which constrained the generation of lag features and hindered the model's ability to capture discharge variation trends. Although LightGBM could technically run on these data, the resulting outputs were of limited hydrological significance. Therefore, flood event modeling was excluded from the analysis. For normalflow events, the LightGBM model achieved high predictive accuracy (Figure 3). During the pre-TGP period, the model yielded $R^2 = 0.95$ and RMSE = 828.56, effectively capturing the observed hydrodynamic variability. In the post-TGP period, the model achieved $R^2 = 0.94$ and RMSE = 861.14, demonstrating comparable accuracy. These results indicate that the LightGBM model maintains stable predictive performance across both periods and can be confidently applied to quantify the hydrological impacts of the Three Gorges Project on the lake–river interaction system.

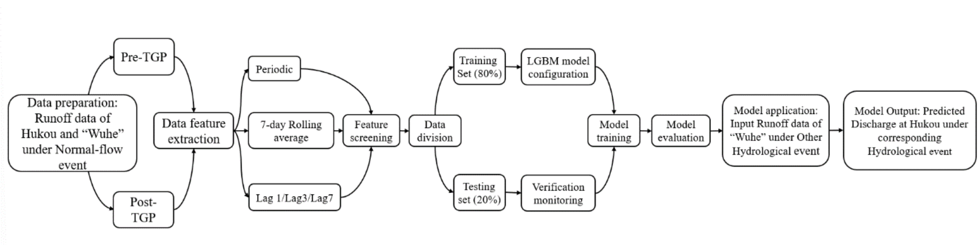

Figure 2 Workflow of the modeling framework

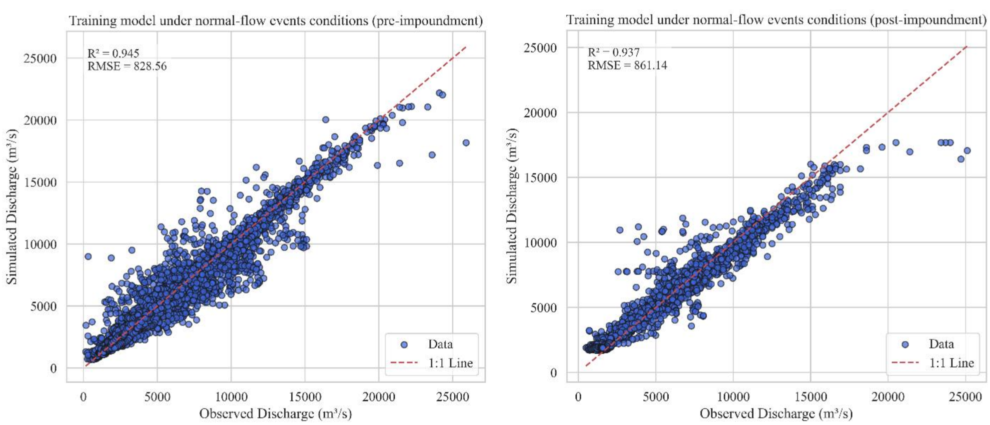

Figure 3 Validation of Simulated vs. Observed Values for the Normal-Flow Training Model

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2.2.4 Quantitative Analysis

To quantitatively assess the impact of the Three Gorges Project, the SWAT model was employed. Using meteorological data (1970–2017) and land-use data (2010) for the Poyang Lake Basin, monthly runoff data of the five tributaries (2005–2010) were used as the training dataset to reproduce the 2005–2017 monthly runoff series of the five rivers, thereby excluding the influence of human activities in the lake region. The simulation exhibited satisfactory performance (Ganjiang: $R^2 = 0.79$; Raohe: $R^2 = 0.64$; Xiushui: $R^2 = 0.67$; Fuhe: $R^2 = 0.66$; Xinjiang: $R^2 = 0.60$), indicating that the model is reliable for quantifying hydrological processes.

To further evaluate the effect of the Three Gorges Project on the Hukou discharge, the established five-river–Hukou baseline runoff model was applied to convert the SWAT-simulated monthly runoff into corresponding simulated Hukou discharge, which was then compared with the observed values to quantify the project's influence.

3. Results

3.1 Variation Characteristics of Hydrometeorological Factors in the Lake Region

The cumulative monthly variations of runoff (ΔQ) and water level (ΔH) both showed a consistent declining trend. After the initial impoundment of the Three Gorges Reservoir in 2003, the rate of water level decline accelerated from $-0.91\ m \cdot y^{-1}$ to $-1.22\ m \cdot y^{-1}$, whereas the rate of runoff reduction slightly weakened from $-0.61 \times 10^3\ m^3 \cdot s^{-1} \cdot y^{-1}$ to $-0.49 \times 10^3\ m^3 \cdot s^{-1} \cdot y^{-1}$. The cumulative decrease in water level (–2.34%) exceeded that of runoff (–2.18%) (Fig. 4), indicating that reservoir regulation exerted a stronger influence on downstream water levels at Hukou. The Mann–Kendall (MK) test further identified significant change points for both variables around 2002 (Fig. 5). The intersection of the UF and UB curves beyond the 0.05 significance level marked a structural shift in the hydrological regime. Following this breakpoint, both UF curves exhibited a sustained downward trend, confirming a continuous decline in runoff and water level. In contrast, the monthly means of evaporation and precipitation showed insignificant upward trends ($Z = 0.93$ and $Z = 0.03$, respectively), and no abrupt changes were detected around 2003. This temporal and directional inconsistency suggests that the post-2003 decline in water level and discharge at Hukou was not driven by concurrent climatic variations.

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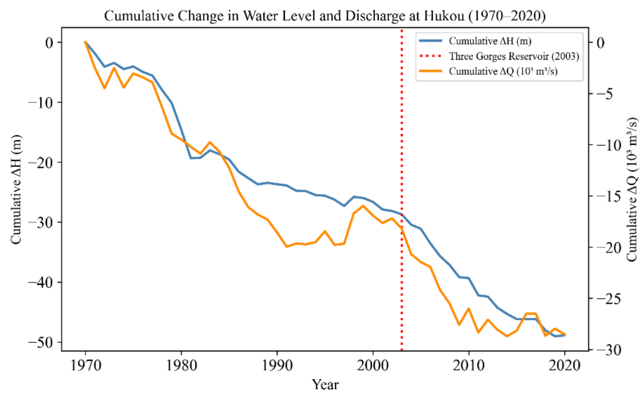

Figure 4 Trends in cumulative monthly variations of runoff and water level

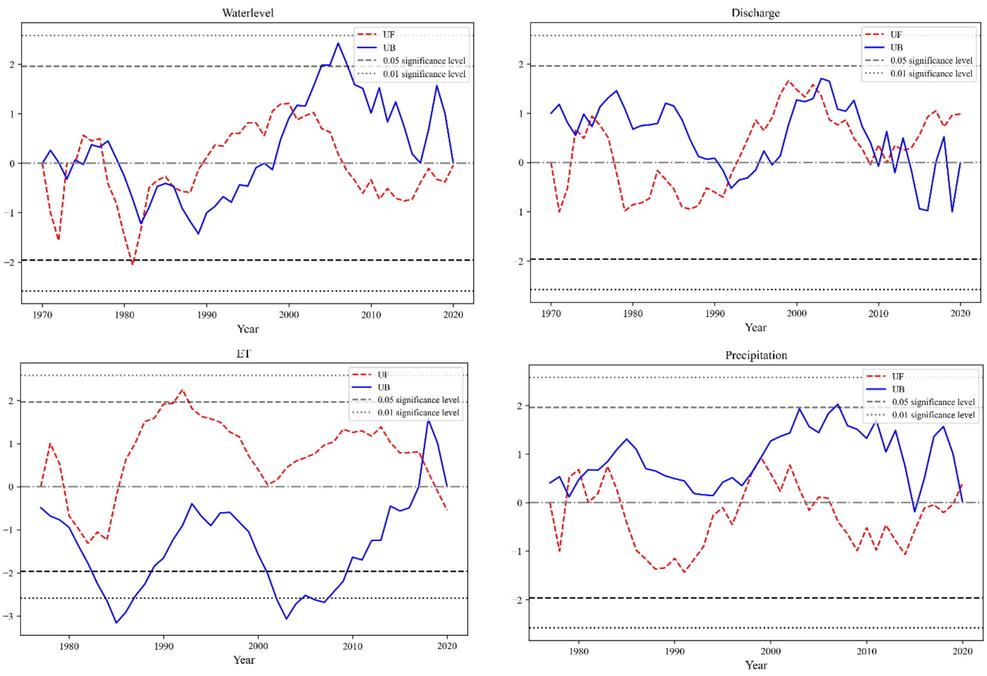

Figure 5 Mann–Kendall Test for Abrupt Changes in Hydrometeorological Variables in the Lake Region

235 **3.2. Variations in Hydrological Events in the Lake Region**

Event statistics indicated a clear decline in the frequency of both flood and backflow events. The occurrence of flood events decreased by 15.18%, with no floods recorded in September after 2003, showing a temporal shift from frequent occurrences during June–September to a more concentrated June–August period. The frequency of backflow events dropped by 11.58%, nearly ceasing in April and

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May and substantially decreasing in September–November, now occurring mainly between June and August. Normal-flow events exhibited the smallest change, decreasing by only 0.82%, with minimal variation in their intra-annual distribution. In contrast, drought events increased by 15.18%, with markedly higher frequencies in November and December after 2003 (Fig. 6).

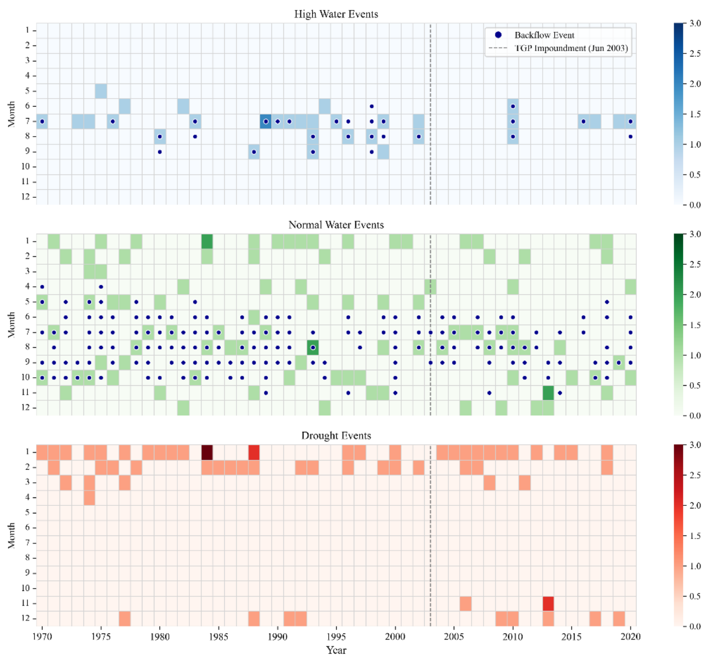

Figure 6 Spatiotemporal heatmap of hydrological events in Poyang Lake

Table 1 summarizes the variations in water level, discharge, and duration across different hydrological event types. After 2003, backflow events exhibited a significant reduction in duration ($p = 0.003 < 0.05$), accompanied by notable decreases in average water level (–7.79%) and discharge (–35.60%)—the largest changes among all event types. Moreover, the pre-dam increasing trend in water level shifted to a declining one after dam operation. In contrast, other event types showed no statistically significant trends in either water level or discharge. Normal-flow events showed a significant increase in duration ($p = 0.018 < 0.05$), indicating a non-random shift, while their average water level and discharge decreased by 7.47% and 12.90%, respectively—second only to the magnitude of change observed in backflow events. Both flood and drought events exhibited shorter durations, though these changes were not statistically significant. Flood events experienced an 11.03% decline in average discharge and only a 0.95% decrease in water level. Conversely, drought events transitioned from a decreasing to an increasing trend, with

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both discharge and water level rising—average discharge increased by 10.94% and water level by 2.39%. Collectively, when compared with the pre–Three Gorges period, the post-dam hydrological regime of Poyang Lake is characterized by a pronounced weakening of backflow events, longer but less voluminous normal-flow events, weakened flood events, and more frequent yet wetter drought events. These changes suggest that the lake's hydrological conditions have become more stable but exhibit a clear shift toward drier tendencies.

Table 1 Changes in Characteristic Indices of Hydrological Events

Events		Drought	Normal-flow	Flood	Backflow
	Pre-TGP	39.5 ± 30.9	268.5 ± 40.3	4.4 ± 7.4	53.3 ± 27.6
	Post-TGP	36.5 ± 26.8	294.4 ± 32.8	3.6 ± 6.4	30.7 ± 22.5
Duration Change (day)		-3	+25.9*	-0.8	-22.6*
Duration Change P-value		0.72	0.02	0.69	0.01
	Pre-TGP	1.12	3.68	0.71	2.59
	Post-TGP	1.29	3.65	0.47	2.29
	Pre-TGP	7.53	13.79	20.09	17.07
	Post-TGP	7.71	12.76	20.28	15.74
	Pre-TGP	1408.13	5599.09	15885.23	3565.79
	Post-TGP	1562.13	4876.80	14132.41	2296.41
	Pre-TGP	0.21	0.36	0.14	2.24*
	Post-TGP	0.07	0.00	0.73	-0.69
	Pre-TGP	-1.19	0.03	0.23	0.41
	Post-TGP	0.21	0.12	0.73	-0.40

3.3 Quantitative Evaluation of the Three Gorges Project's Effects on Lake Hydrological Events

Quantitative analysis of the five rivers' contribution rates indicates that, although their contributions vary across different hydrological events, the overall contribution structure remained largely unchanged before and after the implementation of the Three Gorges Project. The variations in contribution rates during normal-flow, backflow, and drought events were not statistically significant ($P \geq 0.05$), suggesting

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that the project had a negligible effect on the runoff–water level relationship of rivers within the Poyang Lake Basin (Fig. 7). Using SWAT-simulated monthly data for the five rivers under a no-human-activity scenario (2005–2017), the anthropogenic contribution to Hukou discharge after project implementation was estimated at 72.19% during backflow events, 42.52% during normal-flow events, and 30.03% during drought events.

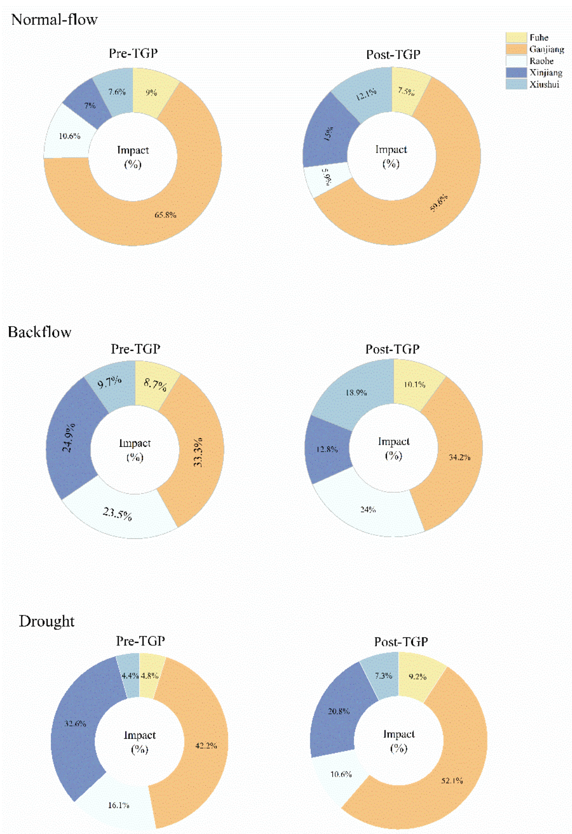

Figure 7 Variations in the relative contributions of the five tributaries

Further analysis of backflow events, based on the normal-flow model, was conducted to derive the theoretical Hukou discharge under backflow conditions. Comparison with observations shows that before 2003, the Yangtze River's backwater effect on Poyang Lake outflow intensified continuously. As shown in Fig. 8, the difference between theoretical and observed discharge (i.e., theoretical backflow, representing the Yangtze backwater constraint) had a positive median in most years, with an MK trend Z = 1.96 (significant at the 95% confidence level), indicating a strengthening backwater effect (mean =

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3641.48 m³/s). After 2003, this increasing trend disappeared and turned into a slight, nonsignificant decline (Z = –0.11), with the mean theoretical backflow reduced to 3490.90 m³/s and remaining relatively stable. Notably, theoretical backflow during major flood years differed greatly before and after reservoir impoundment: for comparable floods, pre-impoundment years had much larger theoretical backflow. For instance, in 1998 it reached 16 584.11 m³/s, whereas in 2020 it was only 6071.22 m³/s, despite higher water levels, indicating a much weaker backwater effect after impoundment.

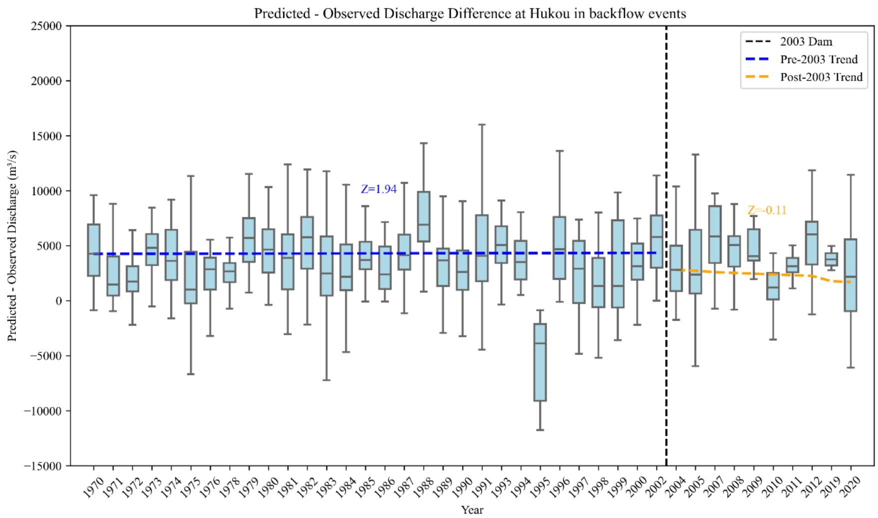

Figure 8 Variation of Differences Between Simulated and Observed Values Under Backflow Events

Further analysis of drought events (Fig. 9) shows that the theoretical backflow at Hukou remained positive in most years (mean: 354.63 m³/s), indicating that the combined outflow from the five rivers exceeded the observed Hukou discharge. However, no backflow was recorded during drought events. This discrepancy reflects hydrodynamic conditions: the model was established under normal water levels when the Yangtze River stood higher and the hydraulic gradient was stronger. During drought events, the Yangtze and Poyang Lake levels become nearly equal, flattening the gradient and increasing flow resistance at Hukou, leading to reduced or even interrupted discharge. Thus, positive differences during droughts indicate increased hydraulic resistance rather than backflow—the larger the difference, the greater the resistance and the higher the risk of flow interruption. Before 2003, the difference between theoretical and observed discharge decreased significantly (mean: 256.63 m³/s, Z = –7.14), implying reduced resistance at Hukou. After 2003, the difference widened again (mean: 647.97 m³/s, Z = –2.81), suggesting increased hydraulic resistance and a higher risk of flow blockage.

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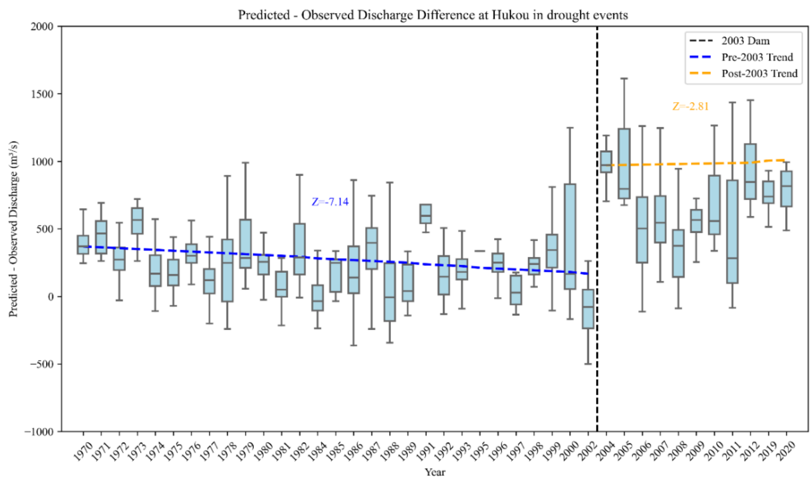

Figure 9 Variation of Differences Between Simulated and Observed Values Under Drought Events

4. Discussion

4.1. Positive Hydrological Effects of the Three Gorges Project on Poyang Lake

Unlike previous studies that primarily focused on the Three Gorges Project's regulation of individual hydrological events (Perret et al., 2021; Xia and Chen, 2021), our results reveal that hydrological responses in Poyang Lake are event-dependent. The most pronounced effects occur during backflow events, predominantly in the Hukou reach, exhibiting distinct pre- and post-2003 contrasts and cascading impacts on other hydrological regimes. Since 2003, the Three Gorges Project has impounded water during the late flood season (late August–early September), intercepting upstream Yangtze runoff and lowering downstream water levels (Guo et al., 2012). Correspondingly, the frequency of backflow events in April, May, and September–November declined, their duration shortened significantly, and water level trends shifted from rising to falling. Theoretical backflow also transitioned from an increasing to a decreasing trend. The high contribution rate (72.19%) underscores the dominant role of the Three Gorges regulation in controlling backflow dynamics.

These findings indicate that the Yangtze's backwater influence at Hukou weakened and stabilized after 2003, substantially reducing hydraulic backpressure. This facilitated floodwater discharge from the lake, mitigated flood hazards, and accelerated water level recession, leading to prolonged normal-flow periods and fewer flood events. Previous work has similarly shown that the Three Gorges Project effectively

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attenuates flood peaks and relieves downstream flood pressure (Dong et al., 2021; Jia et al., 2022; Li et al., 2021). Our analysis corroborates these results from a backflow perspective: despite higher flood levels in 2020, the theoretical backflow volume was 63.39% lower than in 1998.

Rather than merely functioning as a "flood retention and low-water compensation" mechanism, the Three Gorges Project has fundamentally reshaped the hydrodynamics of Poyang Lake through modification of the backwater regime at Hukou. This transformation has shifted the lake from a state of intensified backwater and frequent flooding toward a more regulated equilibrium, characterized by extended normal-water conditions and enhanced flexibility in water allocation.

4.2. Negative Hydrological Effects of the Three Gorges Project on Poyang Lake

Although the Three Gorges Project enhanced hydrological stability in Poyang Lake, interannual variations in runoff and water level exhibit a pronounced drying trend. Consistent with previous findings, our results show that after 2003, the frequency of drought events increased by 15.18%, particularly in November and December (Xue et al., 2023a; Zhang et al., 2022; Zhou et al., 2019). The widening gap between theoretical and observed discharge at Hukou indicates increased hydraulic resistance and a higher risk of flow interruption. Notably, despite the rising frequency of droughts, mean water level and discharge during drought events both increased, suggesting that while the Project amplified drought occurrence, it alleviated drought intensity.

To further examine this mechanism, we incorporated water level data from the Yangtze River's Jiujiang Station. Before 2003, the Hukou water-level difference (Jiujiang – Hukou) was significantly negatively correlated with discharge ($r = -0.24$, $p \approx 0.001$), with a ~5-day lag, indicating that changes in the Yangtze River level controlled lake outflow. After 2003, this relationship reversed to a significant positive correlation ($r = 0.34$, $p \approx 0.001$), with discharge leading by ~5 days, implying that during droughts, Hukou outflow began to dominate variations in the Yangtze water-level gradient. This reversal of causal direction, coupled with the widening gap between theoretical and observed discharge, highlights an intensified "lacustrine regime" under dry conditions: tributary inflows increasingly fail to discharge through Hukou, and the Yangtze's backwater influence has weakened or even vanished. Remote-sensing observations further confirm that post-2003, the lake–channel area at Hukou shrinks earlier at the end of the flood season(Tian et al., 2023; Zhou et al., 2019). Hydrodynamic simulations likewise suggest that

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coordinated operation of the Three Gorges and local reservoirs raises lake levels during droughts and mitigates drought severity(Li et al., 2023a; Xue et al., 2023a).

Overall, while the Three Gorges Project has improved regional hydrological regulation and stability, it has also increased the frequency of drought events, with Hukou discharge gradually replacing the Yangtze water-level gradient as the dominant control on river–lake interactions. Nevertheless, its reservoir regulation has moderated individual drought intensity, promoting smoother water-level and outflow variations.

4.3 Implications for Future River–Lake Management

This study demonstrates a pronounced reconfiguration of the hydrological regime within the Poyang Lake–Yangtze River system following the operation of the Three Gorges Project, manifested in heightened drought frequency, abrupt shifts in discharge–stage dynamics at Hukou, and a reversal in the direction of river–lake interactions. These findings underscore the necessity of transitioning from isolated reservoir operations to integrated river–lake management. A coordinated regulation framework between the Yangtze River and Poyang Lake should be prioritized to attenuate the amplification of drought events induced by upstream operations and to mitigate the risk of channel disconnection at Hukou. Incorporating ecological flow requirements and wetland water-level thresholds into reservoir scheduling objectives is essential to sustain hydrological stability during dry periods. Moreover, restoring floodplain connectivity and natural retention capacity would enhance the lake's buffering function and reduce hydrological vulnerability under engineered control.

From a management perspective, strengthening river–lake data integration and joint monitoring is critical. Coupling hydrological modeling with remote sensing observations can facilitate near-real-time assessment and early warning of river–lake dynamics. Future regulation strategies should further explore ecological flow trials and multi-objective optimization frameworks to reconcile hydropower generation, flood control, and ecosystem maintenance (Liu and Wu, 2016; Xue et al., 2023b). Ultimately, developing a "river–lake coordinated and nature–engineering co-regulated" dynamic management system—accounting for hydrological, climatic, and ecological constraints—will be pivotal for enhancing the resilience and sustainability of the middle and lower Yangtze River basin.

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5. Conclusions

This study examined the hydrological restructuring of the Three Gorges Project–Poyang Lake system using long-term records of discharge, water level, and meteorological data. Under stable climatic conditions, dam operation has fundamentally reorganized Poyang Lake's hydrological regime, characterized by prolonged normal-flow periods, attenuated floods, more frequent droughts, and weakened river–lake connectivity. Event-based analyses elucidate the underlying mechanisms.

The primary impact of the Three Gorges Project is concentrated in the Hukou reach, the hydraulic interface between the lake and the Yangtze River. As a key indicator of river–lake coupling, backflow events decreased markedly (frequency −11.58%, duration −22.6 days, discharge −35.60%, stage −7.79%), with a 72.19% contribution rate attributable to dam regulation. Hydrodynamic modeling further revealed a 4.14% reduction in theoretical backflow, reflecting a substantial weakening of the Yangtze River's backwater influence. The backwater effect, previously strengthening before 2003, transitioned to a phase of attenuation and stabilization thereafter.

The diminished backwater effect induced a cascade of hydrological responses across the lake system. Reduced hydraulic backpressure facilitated faster drainage and lower flood persistence, resulting in longer normal-flow periods (+25.9 days) and fewer flood events (frequency −15.18%, discharge −11.03%, stage −0.95%). For extreme floods, theoretical backflow volume declined by 63.39%, underscoring the project's substantial flood-mitigation role.

Conversely, the attenuation of backwater support intensified low-water conditions. The extended normal-flow regime (Three Gorges contribution 42.52%) was accompanied by reduced event-scale runoff (stage −7.47%, discharge −12.90%). Drought event frequency increased by 15.18%, with a 30.03% contribution rate from dam operations. The hydraulic resistance at Hukou rose sharply, widening the gap between observed and theoretical discharge by 152.49%, signifying growing flow obstruction. Post-2003, Hukou discharge replaced the Yangtze stage difference as the dominant control on river–lake interactions. Although droughts became more frequent, their hydrological intensity was moderated (discharge +10.94%, stage +2.39%), indicating the transformation of Poyang Lake from a naturally buffered system to a semi-regulated hydrological regime.

Overall, the Three Gorges Project has redefined the river–lake interaction in the middle Yangtze basin. While enhancing hydrological stability and reducing flood risk, it has concurrently heightened drought

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susceptibility. Future management should transition from a flood-control-centric paradigm toward an integrated flood–ecological–regulation framework, emphasizing coordinated Yangtze–Poyang scheduling, strengthened river–lake connectivity, and intelligent basin management to enhance regional water resilience and sustainability.

Data availability

All raw data can be provided by the corresponding authors upon request.

Author contributions

Biqing Tian wrote the manuscript draft. Hao Jia reviewed and edited the manuscript. Peng Gao and Xingmin Mu contributed review and commentaries on the manuscript.

Competing interests

The authors declare that they have no conflict of interest.

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