

Article

Flood Propagation Characteristics in a Plain Lake: The Role of Multiple River Interactions

Qiuqin Wu ^{1,2} , Zhichao Wang ^{1,2,*}, Xinfu Xu ^{1,2}, Zhiwen Huang ¹, Tianfu Wen ¹, Wensun You ^{1,2} and Yang Xia ¹¹ Jiangxi Academy of Water Science and Engineering, Nanchang 330001, China; doubleq2021@163.com (Q.W.)² Jiangxi Provincial Technology Innovation Center for Ecological Water Engineering in Poyang Lake Basin, Nanchang 330029, China

* Correspondence: pyhnszz@163.com

Abstract: Plain lakes play a crucial role in the hydrological cycle of a watershed, but their interactions with adjacent rivers and downstream water bodies can create complex river–lake relationships, often leading to frequent flooding disasters. Taking Poyang Lake as an example, this paper delves into its interaction with the Yangtze River, revealing the spatiotemporal patterns of flood propagation within the lake and its impact on surrounding flood control measures. The aim is to provide insights for flood management in similar environments worldwide. This study employs a comprehensive approach combining hydrological statistical analysis and two-dimensional hydrodynamic modeling, based on extensive hydrological, topographic, and socio-economic data. The results indicate that the annual maximum outflow from Poyang Lake is primarily controlled by floods within the watershed, while the highest annual lake water level is predominantly influenced by floods from the Yangtze River. The peak discharge typically reaches the lake outlet within 48 h, with the peak water level taking slightly longer at 54 h. However, water storage in the lake can shorten the time that it takes for the peak discharge to arrive. When converging with floods from the Yangtze River, the peak water level may be delayed by up to 10 days, due to the top-supporting interaction. Furthermore, floods from the “Five Rivers” propagate differently within the lake, affecting various lake regions to differing degrees. Notably, floods from the Fu River cause the most significant rise in the lake’s water level under the same flow rate. The top-supporting effect from the Yangtze River also significantly impacts the water surface slope of Poyang Lake. When the Yangtze River flood discharge significantly exceeds that of the “Five Rivers” (i.e., when the top-supporting intensity value, f , exceeds four), the lake surface becomes as flat as a reservoir. During major floods in the watershed, the water level difference in the lake can increase dramatically, potentially creating a “dynamic storage capacity” of up to 840 million cubic meters.

Keywords: plain lake; river–lake interactions; flood propagation; dynamic storage capacity; Poyang Lake



Citation: Wu, Q.; Wang, Z.; Xu, X.; Huang, Z.; Wen, T.; You, W.; Xia, Y. Flood Propagation Characteristics in a Plain Lake: The Role of Multiple River Interactions. *Water* **2024**, *16*, 1447. <https://doi.org/10.3390/w16101447>

Academic Editor: Matthew Therrell

Received: 9 April 2024

Revised: 10 May 2024

Accepted: 17 May 2024

Published: 19 May 2024



Copyright: © 2024 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

1. Introduction

The rainfall within watersheds generates runoff, which flows towards lowland plains under the influence of gravity, eventually collecting into lakes. Dramatic changes in terrain during this process lead to a reduction in flow velocity, causing sediment carried by the water to deposit at the entrance of a lake. This deposition promotes the formation of alluvial plains [1,2]. Over time, a complex network of waterways gradually develops around the lake (see Figure 1). As lake water flows further into downstream rivers, the lake becomes influenced by both internal and external rivers, giving rise to more complex hydrological phenomena. River-connected lakes are widely found in all continents of the world [3–10]. It is worth noting that, during the flood season, due to the special geographical features of these types of lakes and their surrounding areas, they often become flood-prone and disaster-stricken areas, suffering severe floods, which bring huge disasters to coastal residents [7–10].

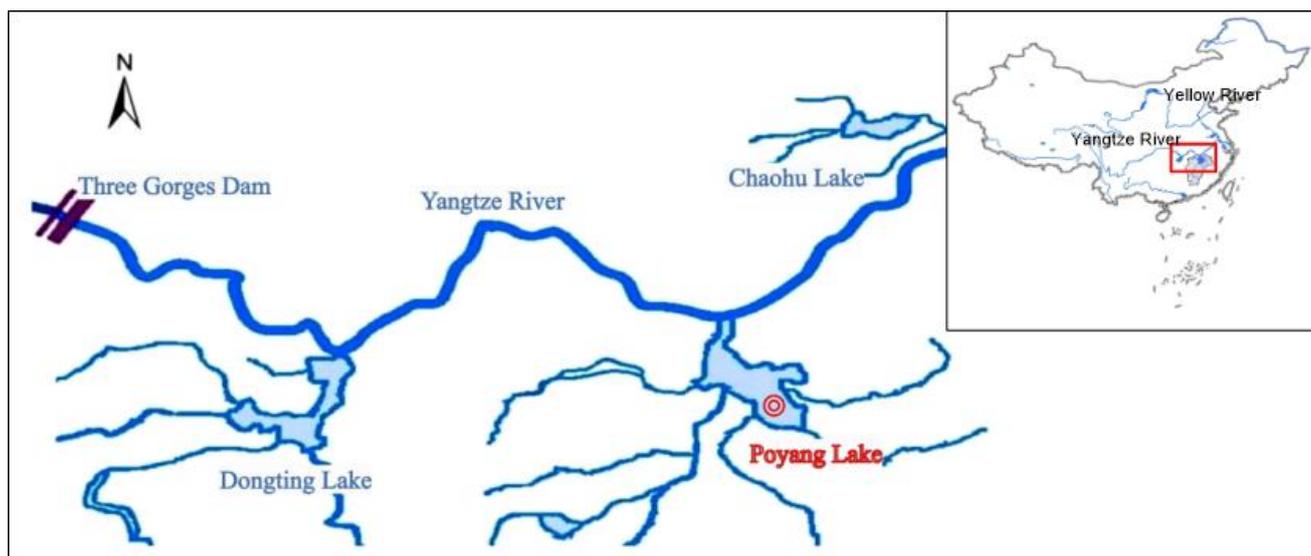


Figure 1. Illustration of river-connected lakes distributed in the middle and lower reaches of the Yangtze River.

Currently, 23% of the global population is under threat of experiencing flooding, with China being at the top of the list with 395 million people at risk [11]. The Poyang Lake region is one of the hardest-hit areas. As the largest connected lake in the Yangtze River basin, Poyang Lake's flood formation and development are jointly influenced by the inflow from five major rivers within the watershed (Gan River, Fu River, Xin River, Rao River, and Xiu River, collectively known as the "Five Rivers") and by floods from the Yangtze River. Under normal circumstances, the main flood season of the Poyang Lake watershed and the middle reach of the Yangtze River are staggered by 1 to 2 months, to avoid triggering major floods [12]. However, when floods from the river and the lake converge, they create a strong top-supporting effect, making it difficult for the lake to discharge, keeping Poyang Lake at a high water level for an extended period, and leading to flooding disasters. The flat terrain, vast water surface, and 2946 km of main dikes around Poyang Lake pose significant challenges to flood defense efforts in the region. Additionally, the fertile alluvial plains surrounding Poyang Lake are important grain-producing areas, with cultivated land accounting for 39% of the region's area. The region also includes economically developed and densely populated cities such as Nanchang and Jiujiang. Despite occupying only 30% of the province's area, the region is home to 50% of the population and generates over 60% of the province's economic output. These advantages bring prosperity, but also exacerbate flood risks and defense pressures. For example, the 1998 Poyang Lake flood affected 20.09 million people and damaged 15,840 square kilometers of crops in Jiangxi Province [9].

For a long time, scholars have been committed to studying the flood characteristics of and risk management in large plain lake areas to reduce flood losses in these regions [13–28]. For instance, K. Söderholm et al. [13] improved regional flood risk management by developing and applying the Watershed Simulation and Forecasting System (WSFS). Wang et al. [14] conducted a flood risk assessment for Poyang Lake using a context-aware LSTM algorithm. To determine water level changes in Amazon floodplain lakes, Douglas E. Alsdorf et al. [15] employed interferometric radar measurements for water level monitoring. Deng et al. [16] established a model to analyze the application strategies and flood diversion effects of flood diversion areas and single-withdrawal dikes around Poyang Lake, proposing corresponding optimized scheduling measures. To more accurately simulate and predict floods in Poyang Lake, experts have utilized various technical methods, including the water level–storage capacity curve and water balance method [17], hydrological models [18,19], hydrodynamic models [12,15], and machine learning models [20,21]. These studies were based on experts' understanding of lake flood characteristics. However, due to the intricate river–lake

interactions in plain lakes, flood characteristics and their influencing factors have been a focal point of research [22–26]. During flood seasons, multi-source lake water is influenced by multiple factors, leading to changes in the flood propagation characteristics, as observed in lakes like the Amazon floodplain lakes [27], Dongting Lake in the Yangtze River [10], and Poyang Lake [12]. Nevertheless, less attention has been paid to the detailed characteristics of flood propagation within plain lakes and they are often assumed to be giant reservoirs in practical flood analysis [17,28].

Through continuous efforts by scholars and governmental departments, significant progress has been made in the flood management of Poyang Lake. For example, during the historically largest flood in Poyang Lake in 2020, the number of affected people and the affected crop area in Jiangxi Province decreased by 66% and 53%, respectively, compared to 1998 [9]. However, the flood problem in Poyang Lake remains complex and is influenced by various factors, and further exploration is still needed to achieve precise forecasting. This article aims to determine phenomena and patterns by studying the spatiotemporal characteristics of flood propagation in Poyang Lake, providing assistance for the precise calculation of lake water storage capacity, studying the flood diversion effect of the Poyang Lake project, and optimizing scheduling in the future. It is hoped that it can provide valuable insights for regions facing similar flood threats, globally.

2. Data and Methods

2.1. Study Area

Poyang Lake is located in Jiangxi Province, on the south bank of the middle and lower reaches of the Yangtze River. Its basin converges five major rivers, namely, the Gan River, Fu River, Xin River, Rao River, and Xiu River (collectively referred to as the “Five Rivers”). These rivers flow from south to north and eventually merge into the Yangtze River at Hukou [17,18]. The scope of this study encompasses Poyang Lake and the connected section of the Yangtze River mainstream in Jiangxi (see Figure 2), covering a total area of 3606.6 square kilometers. Within this range, Poyang Lake specifically refers to the vast water area from the estuaries of the “Five Rivers” to Hukou, with an area of 3219.1 square kilometers, which has been determined through comprehensive analysis of remote sensing images of flood inundation over the years, as well as the surrounding embankment data. The Yangtze River mainstream section refers to the main river segment between Jiujiang and Pengze, covering an area of 387.5 square kilometers.

Table 1. Information on relevant hydrological stations in the study area.

Number	Hydrological Station	River System	Data
①, ②	Qiu Jin, Wanjiabu	Xiu River	Flow rate, water level
③	Waizhou	Gan River	Flow rate, water level
④	Lijiadu	Fu River	Flow rate, water level
⑤	Meigang	Xin River	Flow rate, water level
⑥, ⑦	Hushan, Dufengkeng	Rao River	Flow rate, water level
⑧, ⑨	Jiujiang, Hukou	Yangtze River	Flow rate, water level
⑩	Pengze		Water level
⑪, ⑫, ⑬, ⑭, ⑮, ⑯, ⑰, ⑱	Xingzi, Wucheng, Duchang, Tangyin, Longkou, Kangshan, Sanyang, Poyang	Poyang Lake	Water level

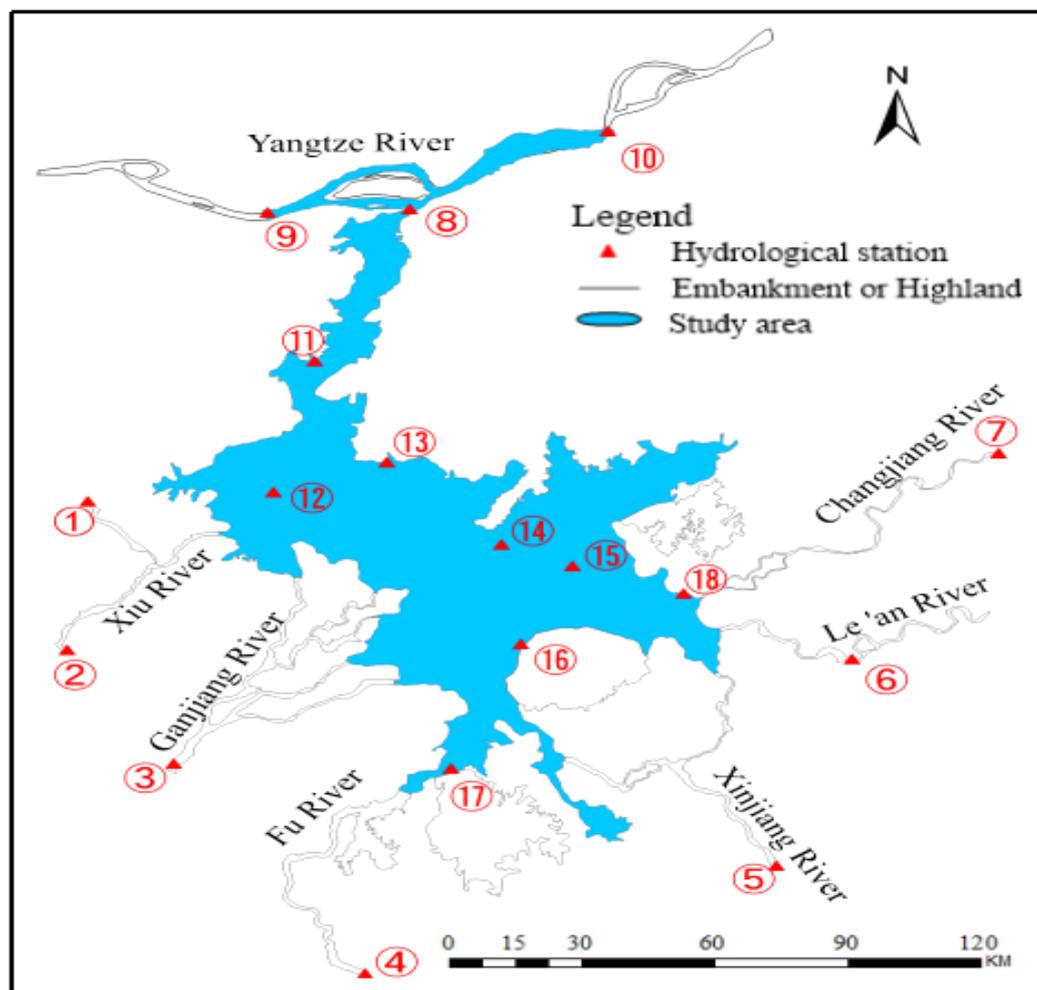


Figure 2. Schematic diagram of the research scope (see Table 1 for interpretation of symbols in the diagram).

2.2. Data and Analysis

This study adopts a significant amount of key data, provided by the Jiangxi Provincial Institute of Water Sciences, including detailed hydrological data from hydrological stations over the years (hydrological stations are shown in Figure 2 and Table 1), precise embankment information for Poyang Lake (Figure 2), high-resolution digital topographic maps of Poyang Lake (Figure 3), and comprehensive records of flooded areas over the years. Additionally, the core data on natural resources and socio-economics that are cited in the text originate from two important planning documents, “Ecological Economic Zone Planning of Poyang Lake” and “The Rise of Poyang Lake Ecological Economic Zone Construction to National Strategy,” ensuring the authority and accuracy of the research data.

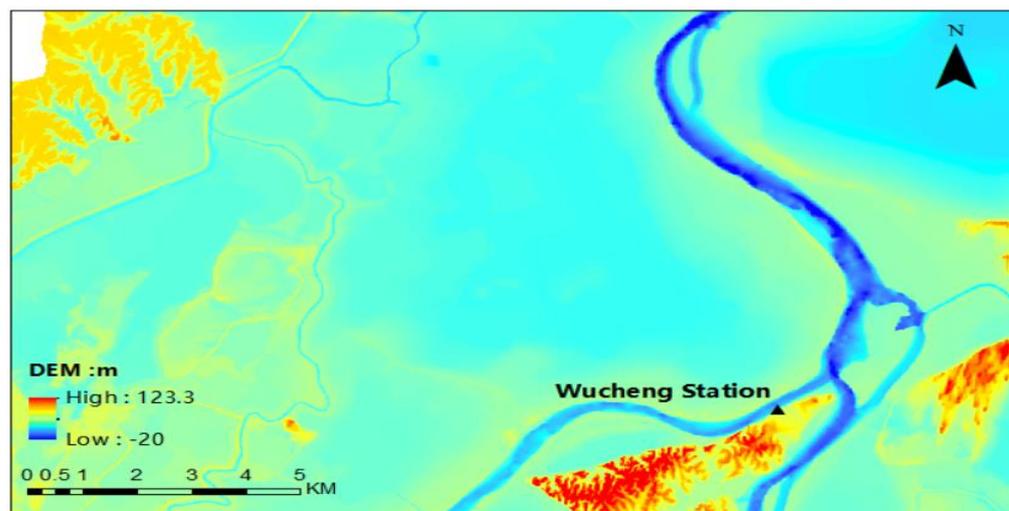


Figure 3. Digital terrain of the downstream local area of Wucheng Station ⑫ in Poyang Lake.

2.2.1. Hydrological Data

As the largest freshwater lake in China, changes in the hydrological characteristics of Poyang Lake are of great significance to the ecological environment and regional development. To monitor these changes in real time, multiple hydrological monitoring stations have been carefully arranged in the Poyang Lake basin. Table 1 and Figure 2 detail the information of 18 key hydrological stations in the study area, which play an indispensable role in data collection and monitoring.

Among these stations, Xingzi Hydrological Station ⑪ stands out due to its unique geographical location. It is situated on a key passage after the convergence of the Five Rivers in the lake area and is located on the left bank of the waterway from Poyang Lake to the Yangtze River, making it a landmark hydrological station of Poyang Lake. This location enables Xingzi Station to accurately capture important changes in the lake's hydrological characteristics.

Meanwhile, Hukou Hydrological Station ⑧ and Jiujiang Hydrological Station ⑨ also play crucial roles. Hukou Hydrological Station, located at the foot of Shizhong Mountain in Hukou County, Jiujiang City, serves as the control station for the Poyang Lake basin's entrance into the Yangtze River. Jiujiang Hydrological Station, located on the Yangtze River mainstream, is a key hydrological station connecting the middle and lower reaches of the Yangtze River. The water level and flow rate data from these two stations during the flood season are extremely valuable for studying the complex relationship between Poyang Lake and the Yangtze River.

In addition, the data presented in this study on the inflow of the "Five Rivers" into the lake originate from the hydrological data collected by the corresponding control stations ①~⑦. These data provide accurate information about the river's flow rates. Meanwhile, monitoring data from other stations in the lake area, especially water level data, are widely used in the calibration of hydrodynamic models to ensure their accuracy and reliability.

2.2.2. Topographic Data

This study adopts high-precision topographic data on Poyang Lake and the Yangtze River mainstream, provided by the Jiangxi Provincial Institute of Water Sciences. Specifically, the topographic data on Poyang Lake are based on a 10 m × 10 m resolution digital terrain model created in 2011, while the topographic data on the Yangtze River mainstream are derived from 1:1000 high-resolution scattered elevation data obtained in 2017. It is worth emphasizing that comprehensively measuring the lake basin topography of Poyang Lake is an extremely challenging task due to its vast area. Therefore, the topographic data adopted in this study are the latest available information. In fact, only when significant erosion and deposition changes occur in the lake basin will a complete re-measurement

be considered. Currently, uninterrupted terrain monitoring of key sections of the lake is still ongoing.

Recent studies have shown that the erosion of Poyang Lake is mainly concentrated in the tail channels of the lake and the northern lake area's waterway to the Yangtze River, manifesting as a phenomenon of deep channel incision [29–31]. This incision phenomenon has a relatively small impact on wide and shallow cross-sections. Meanwhile, the bedrock of Shizhong Mountain at the entrance of Poyang Lake into the Yangtze River possesses excellent erosion resistance, maintaining relative stability in recent years [32]. Furthermore, with the gradual strengthening and improvement of Poyang Lake's protection measures, the direct impact of human activities on the lake basin's topography has been significantly reduced [33]. According to the latest research results on the evolution of erosion and deposition, the main lake area of Poyang Lake has basically maintained a balance between erosion and deposition, with relatively little impact on the lake basin's topography [34]. In summary, using the 2011 topographic data on Poyang Lake for recent flood process simulation in this study fully meets the accuracy requirements.

2.2.3. Tributary Diversion Ratios

As the river winds its way into the Poyang Lake delta region, its many tributaries spread like vines, forming a complex network of waterways. This unique topographical feature not only endows Poyang Lake with rich ecological value, but also poses unprecedented technical challenges for the construction of flood models. Especially in relatively narrow and steep areas, floods propagate much faster in the river channels than on the open lake area, increasing the complexity and difficulty of simulation.

To balance the accuracy and efficiency of the model, this study appropriately simplifies the simulation area. Specifically, we move the model's entries to the estuaries of various tributaries. The adjusted model entries will allocate the inflow of upstream hydrological stations based on actual measured diversion ratio data, to ensure the accuracy and validity of the simulation.

2.3. Methods

2.3.1. Implementing a Special Open Boundary Condition

When two rivers converge, their flows generate a top-supporting effect in the confluence zone and the strength of this effect directly affects the degree of water level rise. This top-supporting phenomenon is particularly notable during the confluence of floods from Poyang Lake into the Yangtze River. When a massive flow exceeding 80,000 m³/s surges into a river channel that is less than 2 km wide, the intense top-supporting effect and the resulting extremely high water level rise are incredible. This was one of the main reasons for the historic floods encountered by Poyang Lake in 2020. Records show that on July 11 of that year, the combined flow at Hukou and Jiujiang Stations reached a staggering 85,900 m³/s. Furthermore, this interaction between the lake and the river is not limited to the confluence zone, with its influence extending up to 200 km downstream [35]. As a result, in downstream areas that are close to such confluence zones, the water level is directly affected by the top-supporting interaction, exhibiting an irregular and uncertain "loop" phenomenon in relation to the flow rate [36].

Although this hydrological phenomenon is common in estuarine areas, hydrodynamic models face methodological limitations when dealing with such open boundary conditions. Traditional methods, such as presetting water levels or defining "water level–flow rate relationships" based on semi-empirical formulas, are not applicable in these confluence zones, because, in these regions, while the designed flood flow rate may be known, the water level cannot be determined beforehand. Therefore, these methods cannot effectively simulate combined flood problems under the influence of top-supporting dynamics.

To overcome this limitation, this study innovatively introduces the concept of "water level correlation", which is commonly used in hydrology, into the hydrodynamic model. For large, deep rivers with gentle slopes, the wave speed of floods is significantly faster

than the flow speed, resulting in a close correlation between upstream and downstream water levels (see Figure 4). Based on this principle, using flood data from 2003 to 2020, we successfully fitted a water level relationship Formula (1) between Jiujiang Station and Pengze Station. This formula serves as the lower boundary condition for the hydrodynamic model, enabling a more effective simulation and prediction of flood behavior in rivers' confluence zones.

$$Z_{pz} = 0.97 \times Z_{jj} - 0.6754 \quad (1)$$

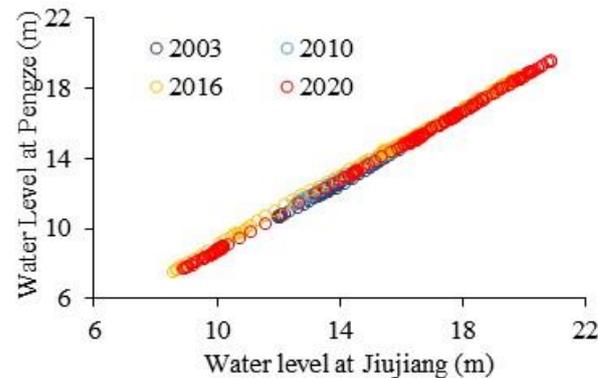


Figure 4. Water level correlation between Jiujiang Station and Pengze Station in different years.

In the formula, Z_{pz} and Z_{jj} represent the water levels of Pengze Station and Jiujiang Station, respectively.

2.3.2. The Construction of the Hydrodynamic Flood Evolution Model

In this study, the commercial software DHI MIKE (2017) was used to draw grids for different regions in the study area, such as deltas, deep troughs, and shoals. To ensure the continuity and integrity of the grids, the self-developed grid-editing software “Grid Manager 1.0” was further utilized for grid stitching operations. Considering the complex and changing terrain, the grid size was set in the range of 100~600 m. The final constructed model contained 27,944 grids and a corresponding number of nodes.

To reasonably establish the open boundary conditions of the model under the top-supporting effects, we developed the “Poyang FS 1.3” software, using the FORTRAN language. This software not only adopts the classic finite volume method to efficiently solve the two-dimensional shallow water equations [37], but also innovatively integrates the setting function of the “water level correlation” open boundary.

Given the top-supporting and emptying effects, as well as significant water level fluctuations in the lake system during the flood fluctuation process in Poyang Lake, we selected the flood event from 21 June 2016 to 16 July 2016, for simulation verification. Figure 5 shows the measured water level data during this period, while Figure 6a compares the simulated discharge at Hukou Station (dashed line) with the measured discharge (solid line). Similarly, Figure 6b compares the simulated water level at Xingzi Station (dashed line) with the measured water level (solid line). The comparison between the simulation results and the measured data showed a high degree of consistency, with a correlation coefficient R^2 of 0.998. Specifically, the average relative error of the simulated outflow from the lake was only 6.55% and the root mean square error (RMSE) of the water level was as low as 0.04 m. These simulation results fully comply with the industry specifications, which require a water level error of less than 0.1 m and a flow error of less than 10%, demonstrating the excellent accuracy and reliability of the model.

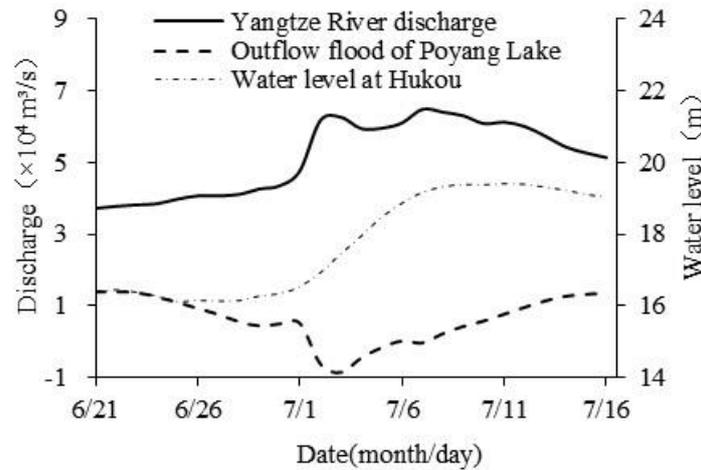


Figure 5. Flood situation at Jiujiang and Hukou during the selected flood event.

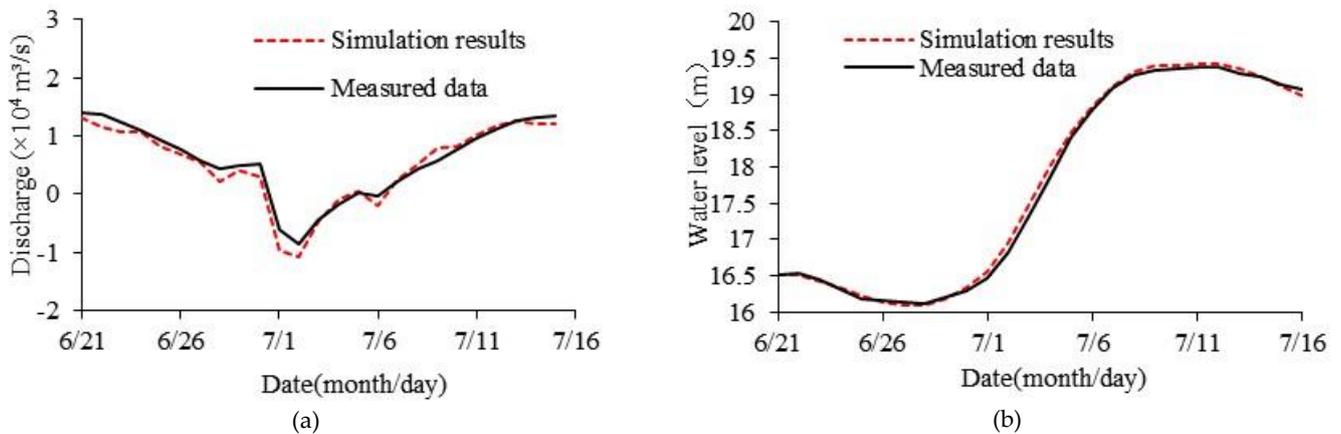


Figure 6. Simulation results. (a) Lake outflow of HuKou Station. (b) Lake’s water level of Xingzi Station.

2.3.3. Combined Flooding

In large shallow lakes, the diversity of flood propagation paths can lead to significant differences in water level distribution. This is an important reason for establishing numerous hydrological stations in Poyang Lake. However, despite these observation points, it remains a challenge to accurately set a realistic and continuous initial water level distribution on the hydrodynamic model. To effectively study combined flood problems, we adopted an innovative approach—superimposing typical flood peak processes on a steady flow. Specifically, we selected a relatively balanced period of the Yangtze River and the “Five Rivers”. Using the time-averaged flow rates of various inflow hydrological stations during this period as steady inflow conditions and the “water level correlation” open boundary as the outflow condition, we simulated the water flow until it reached a steady state. Subsequently, typical flood peak processes were superimposed on different river entrances to analyze the dynamic effects of flood propagation.

To implement this method, we first calculated the key parameters in a stable state using hydrological data from 23 May to 2 June 2016, whereby the inflow rate into the lake was $11,150 \text{ m}^3/\text{s}$, the Yangtze River flow rate was $35,500 \text{ m}^3/\text{s}$, the outflow rate from the lake was $11,150 \text{ m}^3/\text{s}$, and the water level at Hukou was 15.5 m. Then, we selected the flow rate data from Waizhou Station from 7 to 16 July 2020 as a typical flood process and superimposed it on the inflow of the “Five Rivers” for the simulation.

3. Analysis of Results

3.1. Interaction between River and Lake Floods

The flood propagation process in plain-type river-connected lakes is profoundly influenced by the combined effects of the scale of inflow floods and the strength of river–lake top-supporting interactions. Through an in-depth analysis of historical hydrological data, this study aims to explore the mechanisms of river–lake top-supporting interactions and reveal the dominant factor in flood propagation. Figure 7 details the frequency of the annual maximum discharge and the highest water level at Hukou station from 1955 to 2020. Notably, the highest water level and maximum discharge in Poyang Lake do not occur simultaneously. Specifically, the maximum discharge is mainly concentrated in June, coinciding with the main flood season of Poyang Lake, indicating that floods within the Poyang Lake basin play a dominant role in determining the annual maximum outflow from the lake. In contrast, the highest water level mainly occurs in July, aligning with the main flood season of the Yangtze River, suggesting that the Yangtze River floods predominantly influence the highest annual lake water level.

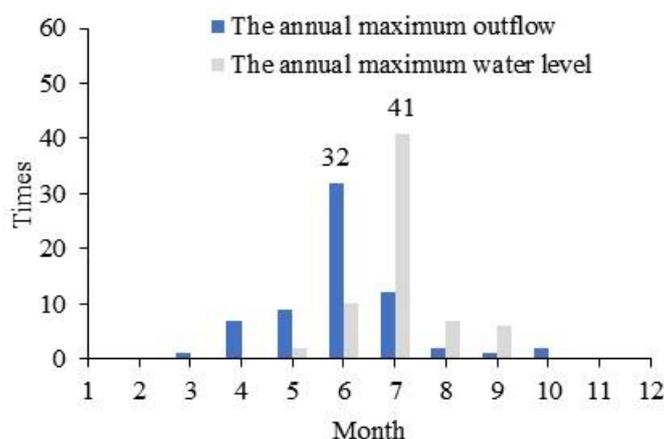


Figure 7. Monthly occurrence of the annual maximum outflow and highest water level at Hukou station from 1955 to 2020.

To further validate these observations, we conducted an in-depth analysis of historical major flood events from 1998 to 2020. The data in Table 2 show that the interval between the time of the incoming flood peak (T1) and the time of the peak outflow (T2) is less than or equal to 2 days. This suggests that the incoming flood peak can reach the lake outlet in a very short time, further supporting the view that floods within the Poyang Lake basin dominate the outflow. Additionally, the water volume that is stored in the lake enhances the outflow, potentially reducing the time that it takes for the peak outflow to occur (T2–T1).

Table 2. Statistics of peak flood occurrence times for typical years with maximum flood events.

Year	Time of Incoming Flood Peak T1 (month/day)	Time of Peak Outflow T2 (month/day)	T2–T1 (days)	Time of Water Level Peak T3 (month/day)	T3–T1 (days)
1998	6/26	6/26	0	7/1	5
2010	6/21	6/23	2	6/29	8
2017	6/26	6/28	2	7/6	10
2020	7/10	7/11	1	7/12	2

However, changes in the peak water level time exhibit more complex characteristics compared to those in the outflow. The interval between the time of the water level peak at Hukou (T3) and the time of the incoming flood peak (T1) can reach up to 10 days, primarily due to the influence of river–lake top-supporting interactions. This interaction prolongs

the residence time of floods in the lake, resulting in a significant lag in the water level peak relative to the incoming flood peak.

Based on this, we discuss two scenarios of river–lake flood interactions.

A stable inflow from the Yangtze River: Taking July 2020 as an example (see Figure 8), the Yangtze River flood was maintained within the range of $59,200 \text{ m}^3/\text{s}$ to $64,900 \text{ m}^3/\text{s}$. In this case, the stable top-supporting effect of the Yangtze River on Poyang Lake makes the floods of the “Five Rivers” the main factor leading the lake flood process, including changes in the outflow and water level of the lake. Therefore, the time of peak outflow, T2, in this flood is very close to the time of water level peak, T3 (see Table 2).

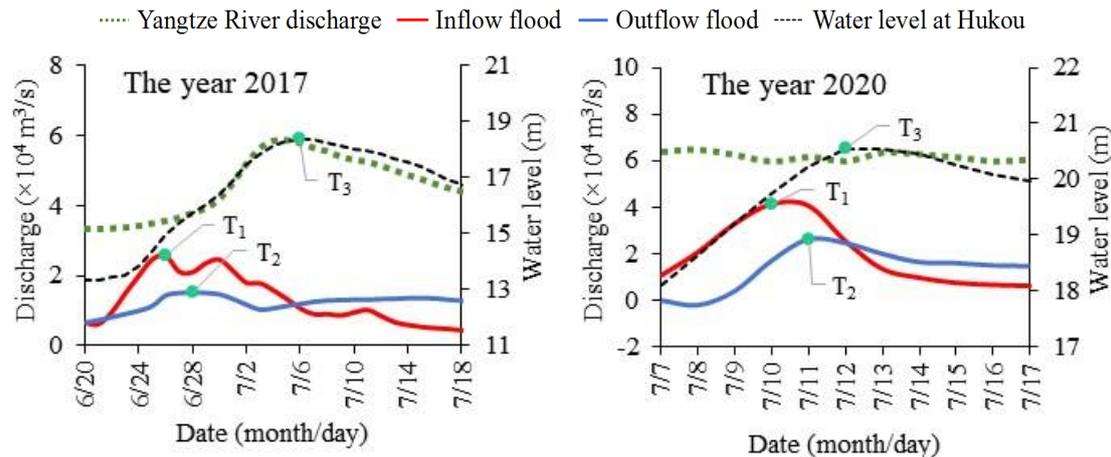


Figure 8. Flood process of Poyang Lake in a typical year.

Increasing the inflow from the Yangtze River: Using July 2017 as an example (see Figure 8), as the floods into the lake gradually weakened, the Yangtze River discharge continuously increased, causing the lake’s water level to rise. In this scenario, the Yangtze River floods became the key factor influencing changes in the lake water level. Therefore, the time of water level peak, T3, lags significantly behind the time of the peak outflow, T2.

3.2. Changes in the Lake’s Water Level under River–Lake Interaction

When the Yangtze River and the “Five Rivers” become the dominant factors influencing the flood process in Poyang Lake, the lake’s water level exhibits distinct variation characteristics. Specifically, the Yangtze River flood significantly raises the water level in the river–lake confluence zone through its strong top-supporting effect, thus effectively controlling the lake’s outlet. In this context, if the inflow from the “Five Rivers” decreases, the lake’s water level is mainly influenced by its outlet water level, resulting in a relatively flat lake surface, resembling a reservoir. Conversely, an increase in inflow from the “Five Rivers” causes varying degrees of surface slope within the lake.

The Three Gorges Reservoir, located upstream of the confluence of the Yangtze River and Poyang Lake (Figure 1), was fully completed in 2009 and has effectively regulated the Yangtze River floods since then. To investigate the relationship between the lake’s surface slope and river–lake top-supporting effects, we analyzed hydrological data during periods when Poyang Lake’s water level exceeded the flood warning level, after 2010 (Figure 9). We used the water level difference between Tangyin and Xingzi Stations (dz) to represent the lake’s surface slope and the ratio of the Yangtze River’s discharge to the “Five Rivers” discharge (f), to measure the strength of the top-supporting effect. The results show that, when the f value exceeds four, indicating that the Yangtze River’s flood discharge is more than four times that of the “Five Rivers”, Poyang Lake’s surface remains relatively flat. Otherwise, the lake’s surface slope increases rapidly.

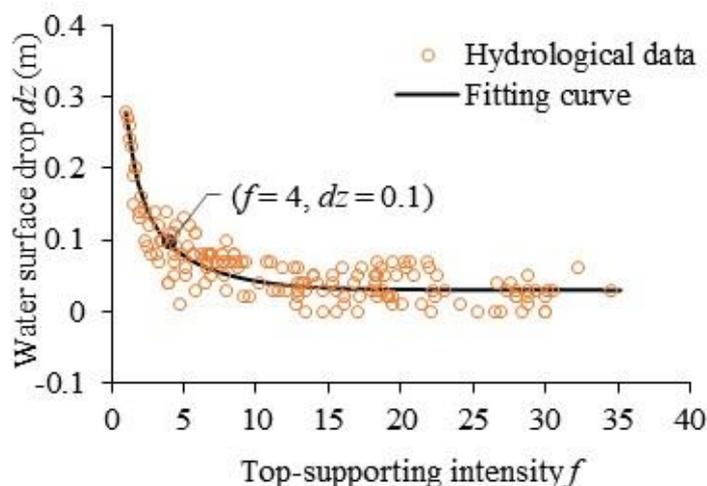


Figure 9. Variation in water surface drop, dz , within Poyang Lake when the lake exceeds the warning water level.

In flood analyses of Poyang Lake, researchers often use the relationship curve between the water level at Xingzi and the lake’s water storage capacity, known as the “water level–storage capacity curve” [38]. However, this curve is typically based on the assumption of a flat lake surface. Therefore, once the lake surface slope increases, the lake’s actual storage capacity exceeds the calculated value based on the curve. The excess water storage capacity, defined as the “dynamic storage capacity”, reflects the additional water volume due to surface slope changes. These data are crucial for accurate flood predictions in Poyang Lake and for assessing the actual benefits of flood control.

To further analyze the characteristics of “dynamic storage capacity” changes, we applied the same method of drawing the “water level–storage capacity curve” and obtained the research area’s curve (Figure 10). Additionally, we used the Poyang Lake flood evolution model to simulate the hydrological process from May to September in typical years (2010, 2012, 2016, and 2020). Based on the simulation results, we plotted a scatter plot showing the correlation between the water level at Xingzi and the lake’s water storage capacity (Figure 10). The simulation dataset for the Yangtze River’s flood season from July to September shows a clear band distribution, closely matching the “water level–storage capacity curve”(Figure 10a). This emphasizes the critical role of the Xingzi water level in representing the “water level–storage capacity” relationship in Poyang Lake and verifies the accuracy of the correlation curve method during this period. However, the simulation data points for Poyang Lake from May to June are significantly lower than the correlation curve, indicating that the “dynamic storage capacity” affects the accuracy of the correlation curve method during this period. Further analysis of the simulation results revealed that the average “dynamic storage capacity” of the lake reaches 840 million cubic meters during the main flood season of the “Five Rivers”. Influenced by the strength of the river–lake top-supporting effect, the variation range of this “dynamic storage capacity” can be as high as 2.2 billion cubic meters(Figure 10b).

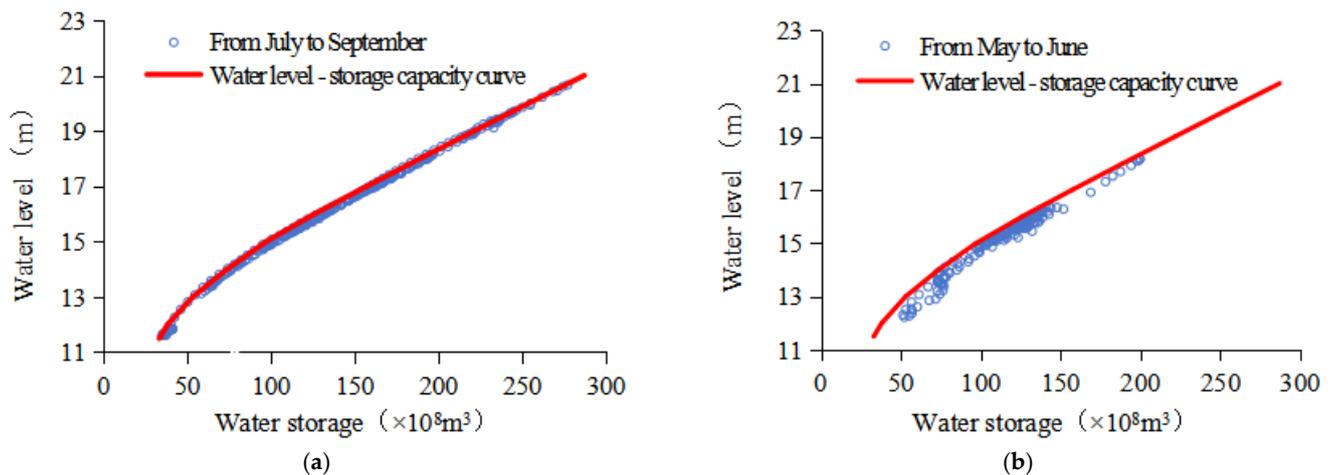


Figure 10. The relationship between the water level of Xingzi station and the water storage capacity of the lake. (a) From July to September. (b) From May to June.

3.3. Propagation Characteristics of Floods from the “Five Rivers” into the Lake

In addition to the significant influence of the river–lake top-supporting effects on flood propagation in Poyang Lake, the differences in flood propagation paths from different rivers into the lake cannot be ignored. These differences result in inconsistent flood peak propagation times and varying degrees of water level rise in different parts of the lake. To delve deeper into these impacts, typical flood processes were superimposed onto the Five Rivers and added into the Poyang Lake flood model for simulation.

Based on the simulation results, we plotted the flow field diagram of Poyang Lake at 48 h after the flood peak of the “Five Rivers” (Figure 11). Based on the flow field information, this study connected areas with high and concentrated flow velocities, delineated the mainstream line, and measured its length as the flood propagation path. Among them, the Xiu River flood enters the lake, passes through Wucheng, and flows directly into the northern waterway leading to the lake outlet, with the shortest propagation distance, the fastest flood peak reaching the lake outlet, and the time to the water level peak taking only 50 h (Table 3).

Table 3. Time of the water level peak at each station (unit: h).

Flood Source	Lake Outlet	Xingzi	Duchang	Wucheng	Tangyin	Kangshan
Gan River	52	50	48	48	48	46
Xiu River	50	48	47	46	49	50
Fu River	56	55	54	55	51	47
Xin River	56	55	54	55	51	48
Rao River	56	54	52	52	49	48

The Gan River diverges into four tributaries before entering Poyang Lake in Nanchang, namely, the “Main Branch, North Branch, Middle Branch, and South Branch”. The South Branch converges with the waters of the Fu River and the West Branch of the Xin River at Kangshan, then flows northward through Tangyin and Duchang, and finally merges into the waterway leading to the lake outlet from the north side of Songmen Mountain. This propagation path is longer compared to the Xiu River and covers a wider area. The Main Branch exhibits similar characteristics to the Xiu River, while floods from the North and Middle Branches enter the lake along the delta region. Due to the combined effects of topographical inclination and lake water level support, these floods rapidly spread towards the central lake area. Consequently, during the propagation of the Gan River floods to

Hukou, their influence, scope, and distance exceed those of the Xiu River, resulting in a longer propagation time for the water level peak (Table 3).

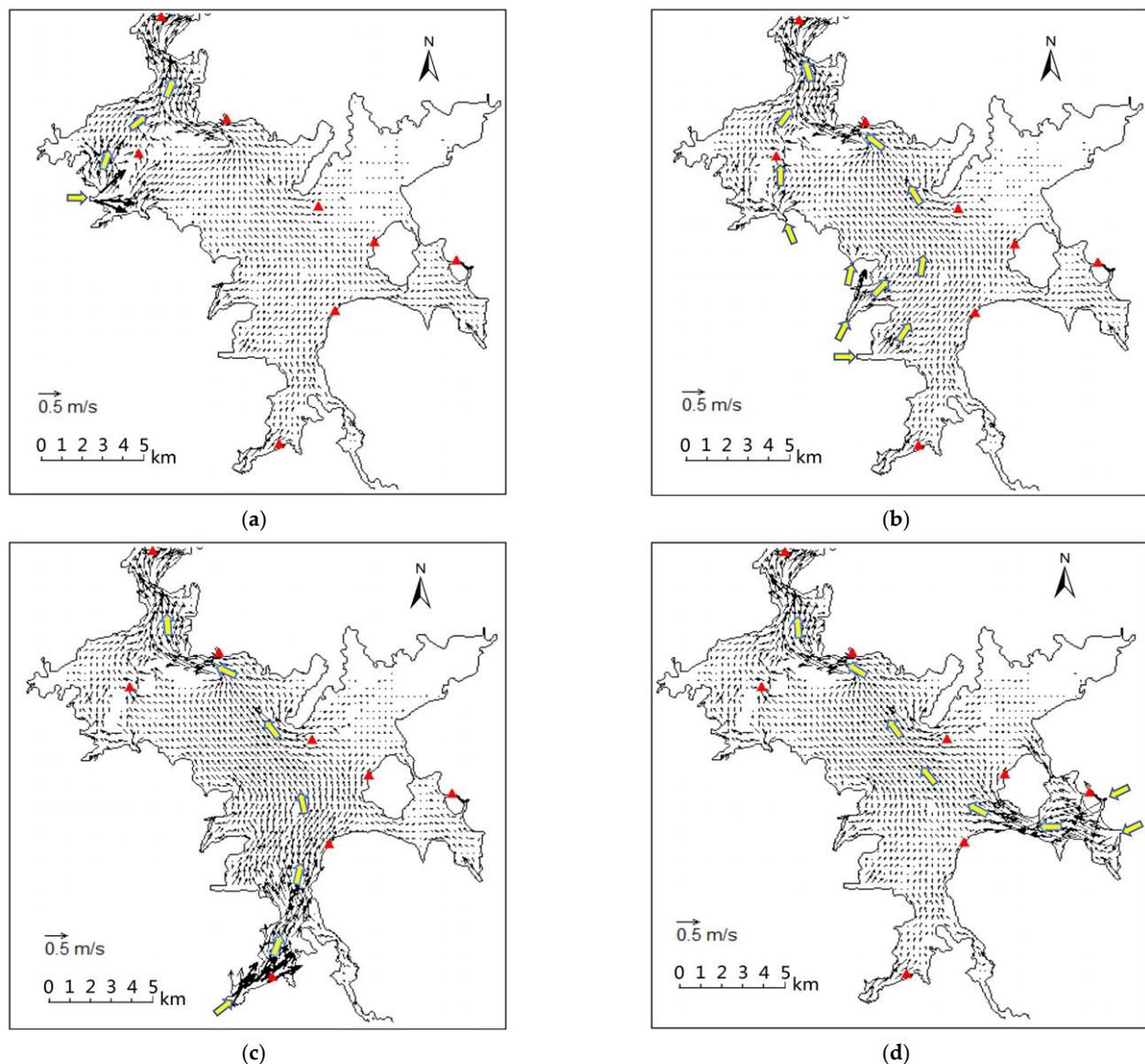


Figure 11. Flow field diagram of the lake area at the 48th hour after the flood peak. (a) Xiu River Flood. (b) Gan River Flood. (c) Fu River Flood. (d) Rao River Flood.

The Fu River, due to its considerable distance from the lake outlet, requires its flood wave to pass through Sanyang and Kangshan before entering the main lake area of Poyang Lake and propagating to the waterway leading into the Yangtze River. Its influence and propagation range are more extensive compared to the Gan River. The Rao River converges into Poyang Lake via its two major tributaries, the Chang River and the Le'an River, and then flows from east to northwest through the main lake area, significantly impacting the eastern region of the lake, with a more prominent effect compared to other rivers. The Xin River enters Poyang Lake through two branches, east and west. The flood propagation paths of the two branches are similar to those of the Rao and Fu Rivers, respectively. Despite differences in the flood propagation paths of these three rivers, the lake areas that they impact are all quite extensive. Consequently, the regulation and storage of lakes have a particularly significant impact on the flooding of these rivers, resulting in a relatively more significant energy dissipation during the propagation of flood waves. As a result, the peak

water levels of the Fu, Rao, and Xin Rivers all reach the lake outlet at 56 h, lagging behind the Xiu and Gan Rivers (Table 3). This phenomenon reflects the significant impact of the complexity of the Poyang Lake hydrological system and the diversity of flood propagation paths from various rivers into the lake.

There is a clear proportional relationship between the time that it takes for the peak discharge and water level of each river to reach the lake outlet and their respective distances to the outlet. Detailed data can be found in Tables 3 and 4. It is worth noting that the regulation and storage function of Poyang Lake influences the time of the water level peak at the lake outlet, causing a certain lag that is relative to the time of the peak outflow. A comprehensive data analysis reveals that the average propagation time for the peak discharge of the “Five Rivers” is 48.4 h, while the peak water level propagates relatively slower, with an average time of 54 h.

Table 4. Flood propagation distance of each river and time of peak outflow.

Name	Xiu River Flood	Gan River Flood	Fu River Flood	Xin River Flood	Rao River Flood
Time of Peak Outflow (h)	44	46	52	51	49
Propagation Distance (km)	99	102–162	177	166	155

Differences in flood propagation paths can lead to varying degrees of water level rise at monitoring stations (see Table 5). Specifically, the broader the flood wave’s propagation range is, the higher the water level rise is at the stations that it passes through. This is because, as the propagation range expands, the kinetic energy of the flood wave gradually dissipates and converts into potential energy. Regarding the influence of various flood sources in the basin, the northern lake region experiences comparatively minimal effects. For instance, the maximum water level rise recorded at the Xingzi station varies by less than 0.02 m. However, the central and southern lake areas are more significantly impacted, especially by floods from the Fu River, which surpass the influence of the Xiu River and Gan River. Taking the Tangyin and Kangshan stations as examples, floods from different sources cause maximum water level rise variations of up to 0.06 m and 0.09 m in the central and southern lake areas, respectively.

Table 5. Maximum water level rise caused by flood propagation at each station (unit: m).

Flood Source	Xingzi Station	Tangyin Station	Kangshan Station
Gan River	1.05	1.11	1.11
Xiu River	1.05	1.08	1.07
Fu River	1.07	1.14	1.16
Xin River	1.07	1.14	1.15
Rao River	1.06	1.14	1.14

4. Discussion and Suggestions

4.1. Reasonableness of the Results

Under the influence of the “Five Rivers” runoff, the water level of Poyang Lake exhibits significant periodic fluctuations [24]. When subjected to the backwater effect from the Yangtze River floods, the water level of Poyang Lake rises rapidly [26]. This study reveals that the annual maximum outflow from Poyang Lake is primarily influenced by floods within the watershed, while the annual highest lake water level is determined by floods from the Yangtze River outside the watershed. This result further clarifies the dominant factors of floods under different circumstances and quantitatively reveals the impact of these factors, building upon previous research.

Poyang Lake plays a significant role in regulating and maintaining floods within the watershed. However, its regulation and storage capacity significantly decrease when floods from the Yangtze River and Poyang Lake converge [16,25]. This study indicates that, if the lake is affected by the backwater effect before the arrival of a flood peak within the watershed, it can lead to a rapid rise in the water level, reducing the duration of the flood peak's stay in the lake. Additionally, as the backwater effect increases, the "dynamic storage capacity" contained in the lake's water surface slope decreases significantly. This result confirms the lake's flood regulation characteristics from the perspectives of the flood detention time and "dynamic storage capacity."

4.2. Limitations and Applications

(1) Application of "Dynamic Storage Capacity" in Flood Calculations:

The inherent "dynamic storage capacity" in the water surface slope of plain lakes is often overlooked in traditional hydrological forecasting. Taking Poyang Lake as an example, currently, the Jiangxi Provincial Hydrology Bureau [35] predicts lake water levels based on the water level–volume curve (Figure 10a). However, this method assumes a flat lake surface and inadequately considers the impact of lake water level fluctuations on storage capacity (Figure 10b).

In the future, statistical methods can be employed to thoroughly explore the intrinsic relationship and variation patterns between the strength of the river–lake backwater effects (f) and the lake's surface slope (dz). Based on this understanding, we can apply these insights to traditional hydrological forecasting [17,38]. Specifically, by continuously monitoring and evaluating the strength of river–lake backwater effects (f), we can accurately determine the corresponding water surface slope's value (dz). Subsequently, by multiplying this dz value by the lake area (A), we can precisely calculate the "dynamic storage capacity" ($V_{dynamic}$). This approach provides a more accurate and scientific basis for calculating and revising the actual water storage capacity of such lakes.

(2) Application of Hydrodynamic Models with Free Open Boundaries in Lake Flood Scheduling and Benefit Analysis: The ability to freely simulate different design floods is fundamental for models to perform flood predictions. However, traditional open boundary calculation methods [39] no longer meet computational needs in the face of river–lake backwater interference. This is one of the reasons why most studies on flood simulation for such lakes use hydrodynamic models for inversion [13].

When a plain lake is, itself, a vast floodplain, utilizing the surrounding flood diversion areas for flood regulation and storage becomes a crucial means of reducing flood damage in the region. To effectively respond to major floods, 4 flood diversion areas and 229 single-retreat embankments have been established around Poyang Lake, capable of storing 2.5 billion cubic meters and 2.6 billion cubic meters of floodwater, respectively. Currently, the water level at hydrological stations near the flood diversion areas is used as the boundary condition for flood diversion calculations [16,40] to analyze the effectiveness of flood diversion. However, this study finds that when the river–lake backwater effect strength (f) is below four, the overall water surface drop (dz) of the lake can reach 0.28 m (Figure 9). Additionally, the time interval between peak water level arrivals at various stations can be up to 9 h (Table 3). This can interfere with the accuracy of the original flood diversion calculation scheme to some extent.

Therefore, for such connected lakes, the free open boundary method proposed in this study (as shown in Figure 4 and Formula (1)) can be utilized to establish a hydrodynamic model and simulate different design flood scenarios. Specifically, simulations can be conducted for different flood encounter situations between rivers and lakes, allowing for the formulation of flood prevention plans. Furthermore, the hydrodynamic model can provide more accurate data on the outer lake water level process in flood diversion areas. For example, it can offer corresponding outer lake water level processes for sparsely distributed micro-flood diversion areas like single-retreat embankments. Large-scale flood storage and detention areas can also be incorporated into the hydrodynamic model to

achieve dynamic calculations of the flood diversion process. This fully considers the impact of dynamic adjustments on river–lake backwater effects on the outer lake water level in flood storage and detention areas after flood diversion.

5. Conclusions

(1) Flood propagation characteristics in Poyang Lake

As a typical plain lake connected to rivers, Poyang Lake's annual maximum outflow is mainly influenced by floods within the watershed, while its annual highest water level is determined by floods from the Yangtze River outside the watershed. Based on historical hydrological data and simulation analysis, the flood peak discharge usually reaches the lake outlet within 48 h, while the flood peak water level takes an average of 54 h to propagate. It is worth noting that the lake's pre-existing water storage can accelerate the arrival time of the peak discharge. However, when lake floods encounter Yangtze River floods, the peak water level's arrival time may be extended by up to 10 days due to river–lake top-supporting effects.

(2) Flood propagation paths and their impacts

Floods from different sources follow distinct propagation paths after entering Poyang Lake. These paths not only affect the travel time of floods, but also directly relate to the degree of impact on the lake area. Specifically, after the floods from the "Five Rivers" enter the lake, the flood peak transmission distances are ordered as Xiu River < Gan River < Rao River < Xin River < Fu River, resulting in the flood peak of the Xiu River reaching the lake outlet 8 h earlier than that of the Fu River. Additionally, the propagation paths have a greater impact on the central and southern lake areas, especially floods from the Fu River, which cause the highest water level rise in the lake compared to other rivers under the same flow rate, by far.

(3) Poyang Lake's water surface slope and Yangtze River top-supporting effects

The water surface slope of Poyang Lake is significantly influenced by the top-supporting effects of the Yangtze River. When the flood flow rate of the Yangtze River reaches more than four times that of the "Five Rivers" (i.e., the top-supporting intensity value, f , exceeds four), the lake water's surface remains relatively flat, exhibiting reservoir-like characteristics. Conversely, during major floods within the watershed, the water surface slope in the lake rises rapidly and the inherent "dynamic storage capacity" of the surface slope can reach up to 840 million cubic meters. This important factor may not have received sufficient attention in traditional hydrological forecasting.

Author Contributions: Writing—original draft preparation, Q.W. and Z.W.; writing—review and editing, Z.W. and Z.H.; supervision, X.X. and W.Y.; funding acquisition, T.W. and Y.X. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the National Key R&D Program of China (Grant Nos. 2022YFC3201804, 2022YFC3202603), the Major Science and Technology Program of the Ministry of Water Resources of China (Grant No. SKS- 2022010), the Jiangxi Province Key R&D Program Projects (Grant No. 20213AAG01012, 20203BBGL73224), and the Science and Technology Project of the Water Resources Department of Jiangxi Province (Grant Nos. 202124ZDKT02, 202224ZDKT13, 202325ZDKT04, 202426ZDKT33).

Data Availability Statement: All data of the model used in this research can be requested from the corresponding author through the indicated e-mail.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Dou, H.; Jiang, J. *China's Five Largest Freshwater Lakes*; University of Science and Technology of China Press: Beijing, China, 2003.
2. Gierlowski-Kordesch, E.; Rust, B.R. *The Jurassic East Berlin Formation, Hartford Basin, Newark Supergroup (Connecticut and Massachusetts): A Saline Lake Playa Alluvial Plain System*; AAPG: Tulsa, OK, USA, 1994.
3. Knowlton, M.F.; Jones, J.R. Trophic status of Missouri River Floodplain Lakes in Relation to Basin Type and connectivity. *Wetlands* **1997**, *17*, 468–475. [[CrossRef](#)]

4. Besemer, K.; Moeseneder, M.M.; Arrieta, J.M.; Herndl, G.J.; Peduzzi, P. Complexity of Bacterial Communities in a River-Floodplain system (Danube, Austria). *Appl. Environ. Microbiol.* **2005**, *71*, 609–620. [[CrossRef](#)] [[PubMed](#)]
5. Lesack, L.F.; Marsh, P. River-to-Lake Connectivities, Water Renewal, and Aquatic Habitat Diversity in the Mackenzie River Delta. *Water Resour. Res.* **2010**, *46*, 439–445. [[CrossRef](#)]
6. Kumm, M.; Tes, S.; Yin, S.; Adamson, P.; Jozsa, J.; Koponen, J.; Richey, J.; Sarkkula, J. Water Balance Analysis for the Tonle Sap Lake-Floodplain System. *Hydrol. Process.* **2014**, *28*, 1722–1733. [[CrossRef](#)]
7. Bhave, A.G.; Bulcock, L.; Dessai, S.; Conway, D.; Jewitt, G.; Dougill, A.J.; Kolusu, S.R.; Mkwambisi, D. Lake Malawi's threshold behaviour: A stakeholder-informed model to simulate sensitivity to climate change. *J. Hydrol.* **2020**, *584*, 124671. [[CrossRef](#)]
8. Opere, A.; Ogallo, L.A. *Natural Disasters in Lake Victoria Basin (Kenya): Causes and Impacts on Environment and Livelihoods*; United Nations Environment Programme (UNEP): Nairobi, Kenya, 2006; pp. 135–148.
9. Lei, S. Review and Reflection on the Floods of Poyang Lake in 2020. *Water Resour. Prot.* **2021**, *37*, 7–12.
10. Liu, Y.; Yang, S.-Q.; Jiang, C.; Sivakumar, M.; Enever, K.; Long, Y.; Deng, B.; Khalil, U.; Yin, L. Flood mitigation using an innovative flood control scheme in a large lake: Dongting Lake, China. *Appl. Sci.* **2019**, *9*, 2465. [[CrossRef](#)]
11. McDermott, T.K.J. Global exposure to flood risk and poverty. *Nat. Commun.* **2022**, *13*, 3529. [[CrossRef](#)] [[PubMed](#)]
12. Zhang, G.; Wang, Z.; Wu, L. Wu, Q.; Huang, Z.; Deng, S. Hydrodynamic simulation of Poyang Lake under flooding in rivers and lakes. *China Rural Water Resour. Hydropower* **2023**, *11*, 69–77.
13. Söderholm, K.; Pihlajamäki, M.; Dubrovin, T.; Veijalainen, N.; Vehviläinen, B.; Marttunen, M. Collaborative planning in adaptive flood risk management under climate change. *Water Resour. Manag.* **2018**, *32*, 1383–1397. [[CrossRef](#)]
14. Wang, X.; Chen, W.; Yin, J.; Wang, L.; Guo, H. Risk assessment of flood disasters in the Poyang lake area. *Int. J. Disaster Risk Reduct.* **2024**, *100*, 104208. [[CrossRef](#)]
15. Alsdorf, D.E.; Melack, J.M.; Dunne, T.; Mertes, L.A.K.; Hess, L.L.; Smith, L.C. Interferometric radar measurements of water level changes on the Amazon flood plain. *Nature* **2000**, *404*, 174–177. [[CrossRef](#)] [[PubMed](#)]
16. Deng, S.; Wu, Q.; Wang, Z.; Wu, L.; Huang, Z.; Zhang, G. Investigating Flood Characteristics and Mitigation Measures in Plain-Type River-Connected Lakes: A Case Study of Poyang Lake. *Water* **2024**, *16*, 281. [[CrossRef](#)]
17. Xu, G.; Qin, Z. Calculation method for flood in the Poyang Lake section. *Lake Sci.* **1998**, *10*, 31–36.
18. Setegn, S.G.; Srinivasan, R.; Dargahi, B. Hydrological modelling in the Lake Tana Basin, Ethiopia using SWAT model. *Open Hydrol. J.* **2008**, *2*, 49–62. [[CrossRef](#)]
19. Alaminie, A.A.; Amarnath, G.; Padhee, S.K.; Ghosh, S.; Tilahun, S.A.; Mekonnen, M.A.; Assefa, G.; Seid, A.; Zimale, F.A.; Jury, M.R. Nested hydrological modeling for flood prediction using CMIP6 inputs around Lake Tana, Ethiopia. *J. Hydrol. Reg. Stud.* **2023**, *46*, 101343. [[CrossRef](#)]
20. Li, G.; Liu, Z.; Zhang, J.; Han, H.; Shu, Z. Bayesian model averaging by combining deep learning models to improve lake water level prediction. *Sci. Total Environ.* **2024**, *906*, 167718. [[CrossRef](#)] [[PubMed](#)]
21. Ozdemir, S.; Yaqub, M.; Yildirim, S.O. A systematic literature review on lake water level prediction models. *Environ. Model. Softw.* **2023**, *163*, 105684. [[CrossRef](#)]
22. Li, X.; Zhang, Q. Variation of floods characteristics and their responses to climate and human activities in Poyang Lake, China. *Chin. Geogr. Sci.* **2015**, *25*, 13–25. [[CrossRef](#)]
23. Sun, Z.; Huang, Q.; Lotz, T. Evolution of flood regulation capacity for a large shallow retention lake: Characterization, mechanism, and impacts. *Water* **2020**, *12*, 2853. [[CrossRef](#)]
24. Hu, Z.; Fu, J. Quantitative analysis of the hydrological relationship and evolution between the Yangtze River and Poyang Lake. *J. Water Resour.* **2018**, *49*, 570–579.
25. Liu, Z.; Ni, Z. The Development and Evolution of Poyang Lake and the Impact of Changes in Jianghu Relations. *J. Environ. Sci.* **2015**, *35*, 1265–1273.
26. Wang, Z.; Zhu, L.; Wang, J.; Fan, H.; Chen, H.; Liu, B. Quantitative indicators for the causes and occurrence conditions of Yangtze River backflow into Poyang Lake. *Prog. Water Sci.* **2020**, *31*, 203–213.
27. Lesack, L.F.; Melack, J.M. Flooding Hydrology and Mixture Dynamics of Lake Water Derived from Multiple Sources in an Amazon Floodplain Lake. *Water Resour. Res.* **1995**, *31*, 329–345. [[CrossRef](#)]
28. Wang, X.; Lu, J.; Chen, X.; Li, Y. Flood mitigation effects of lake-reservoir group on the Poyang Lake watershed based on runoff-weighted model from multi-satellite weekly observation. *J. Hydrol. Reg. Stud.* **2022**, *44*, 101265. [[CrossRef](#)]
29. Bai, Y.C.; Li, X.W.; Xu, H. Effects of topographic changes on the water dynamics in flood season in the tail of Ganjiang River network. *J. Hydropower Eng.* **2022**, *41*, 9–21.
30. Zhang, L.; Tan, Z.; Li, K. Influence of sand mining on river bed in middle and lower reaches of Ganjiang River. *Hydropower New Energy* **2010**, *5*, 63–65.
31. Huang, Z.; Xu, X.F.; Wang, Z.C. Analysis of the influence of the evolution of the water channel into the river of Poyang Lake on the water level of the lake. *Water Power* **2021**, *47*, 37–40.
32. Wang, Z.C.; Xu, X.F.; Huang, Z.W.; Wu, N.H.; Zhou, S.F. Siltation characteristics of the tail reach of Ganjiang river under the regulation of estuary gates. *Water Sci. Technol. Water Supply* **2020**, *20*, 3707–3714. [[CrossRef](#)]
33. Wu, D.Y.; Li, R.F.; Wang, Y.W. Analysis of flood control and disaster reduction situation in Poyang Lake District after removing embankments and returning farmland to the lake. *Hydrology* **2004**, *6*, 26–31.

34. Hu, Z.P.; Wang, S.G. Evolution of erosion and deposition in Poyang Lake and its hydrological and ecological effects. *Water Resour. Hydropower Technol.* **2022**, *53*, 66–78.
35. Wang, F.; Hu, T. A study on the relationship between water level and flow rate at the mouth of Poyang Lake. *China Rural Water Resour. Hydropower* **2023**, *11*, 112–118.
36. Gao, B.Y.; Li, Z.Z. Direct fitting of water level flow relationship rope loop curve during flood season. *Hydrology* **1998**, *5*, 27–30.
37. Jiang, C.; An, X.; Zhang, Q. Finite element parallel numerical simulation of two-dimensional shallow water flow. *J. Water Resour.* **2002**, *5*, 65–68.
38. Li, G.; Yu, Z.; Chen, J. Study on the relationship between dynamic water level and area, water level and volume of Poyang Lake. *Jiangxi Water Conserv. Sci. Technol.* **2015**, *41*, 21–26.
39. Keramidas, G.A. A hydrodynamic model for open channel flow problems. In *Finite Elements in Water Resources*; Springer: Berlin/Heidelberg, Germany, 1982; pp. 269–282.
40. Wan, Z.; Lei, S.; Wen, T. Simulation and Analysis of Flood Evolution in the Lianbei Dike Area of Poyang Lake under Active Flood Diversion. *China Flood Drought Manag.* **2024**, 1–6.

Disclaimer/Publisher’s Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.