

Article

Investigating Flood Characteristics and Mitigation Measures in Plain-Type River-Connected Lakes: A Case Study of Poyang Lake

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Abstract: The flow of plain-type river-connected lakes is affected by both upstream and downstream rivers, and the hydrological conditions are very complex. Poyang Lake, situated in Jiangxi Province, is the largest river-connected lake in the Yangtze River Basin. Its unique geographical features and complex hydrological conditions have made it a heavy disaster area and a frequent area of floods since ancient times. As typical mitigation measures of Poyang Lake, semi-restoration polder areas and flood storage and detention areas play a crucial role in the flood control of Poyang Lake. Taking Poyang Lake as an example, this article studies the flood characteristics of Poyang Lake based on the measured hydrological data. Furthermore, by using the weir (gate) outflow formula to construct the hydraulic model of semi-restoration polder areas and DHI MIKE to construct the hydrodynamic model of Kangshan flood storage and detention area, the flood diversion capacity of the two, and the flood diversion effect under the super-historical flood in 2020 are analyzed. The results show that compared with the non-use of mitigation measures, the maximum cumulative reduction in Xingzi water level can be reduced by 0.68 m and 0.48 m when semi-restoration polder areas and Kangshan flood storage and detention areas are used alone. Finally, the article puts forward some thoughts and suggestions on the flood control of Poyang Lake. The research results can offer some reference to the flood risk management of plain-type river-connected lakes.

Keywords: plain-type river-connected lakes; flood characteristics; mitigation measures; Poyang Lake; flood control



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1. Introduction

Plain-type river-connected lakes, influenced by the intricate dynamics of upstream and downstream rivers, possess highly complex hydrological conditions. These lakes, shaped by their unique geographical features and hydrological complexities, are particularly prone to flooding, often resulting in catastrophic consequences for surrounding areas. Notable examples include Lake Malawi in Africa, Lake Victoria in Kenya, and China's Poyang Lake, which have all experienced devastating floods in recent decades, causing immense hardship for coastal residents. Globally, 1.81 billion people—a staggering 23% of the world's population—face the direct threat of once-in-a-century floods [1]. Notably, 1.24 billion of these individuals reside in South Asia and East Asia, with China and India alone accounting for over one-third of the worldwide population at risk. Annually, natural disasters cause asset losses exceeding USD 300 billion globally. Recent floods in countries like Iraq [2], Italy [3], Nigeria, Bangladesh, Vietnam, the United States, and the United Kingdom underline the universality of this challenge.

Located within the Yangtze River Delta plain, Poyang Lake is a dynamic system influenced by the inflow of Five Rivers—the Ganjiang, Fu, Xin, Rao, and Xiu—as well as the fluctuating waters of the Yangtze River itself. Characterized as a water-passing, throughput-type, seasonal river-connected shallow lake, it features a vast lake surface

area interspersed with alluvial plains and river deltas, forming an intricate network of crisscrossing waterways [4]. Typically, Poyang Lake's flood season precedes that of the Yangtze River by 1 to 2 months. However, when the Yangtze River flood arrives early and the flood season of the Five Rivers is delayed or extended, the lake and river floods converge, leading to a prolonged period of high water levels in the lake area under the combined influence of incoming waters from the Five Rivers and the backflow of the Yangtze River [5].

Historically, Poyang Lake has been a hotspot for flood disasters in the middle and lower reaches of the Yangtze River due to its low-lying terrain and limited flood discharge capacity [6]. Statistics reveal that major floods in the lakeside area occurred in 1954, 1973, 1998, and 2020. Notably, in 1998, the lake's water level surpassed its historical record by 22.59 m, causing extensive damage to polder areas and significant losses. Following this disaster, Jiangxi Province embarked on a comprehensive flood control program that included embankment removal for floodwater drainage, restoration of lakes, abandonment of cultivated farmland, and relocation of towns. Although these measures significantly reduced risks and disasters during the 2020 flood—which exceeded the historic 1998 event—the impact was still severe. In 2020 alone, the flood inundated 1961.95 km² of the Poyang Lake area, with Poyang County being the hardest hit, affecting 625,886 people and damaging 335 km² of crops, resulting in direct economic losses of USD 7.75 million. Figure 1 shows that in 2020 the flood inundated Wuxing Village, Sanjiao Township, and Yongxiu County.



Figure 1. The 2020 flood inundated Wuxing Village, Sanjiao Township, and Yongxiu County.

From late June to early July 2020, the Yangtze River's middle and lower reaches and the Poyang Lake Basin experienced intense rainfall concentrations. The rainfall in the middle and lower reaches of the Yangtze River was 1.5 times higher than the multi-year average. Jiangxi Province recorded an unprecedented average rainfall from 1 to 10 July—four times higher than usual—marking it as the highest in recorded history. Notably, on 8–9 July, the Poyang Lake Basin received record-breaking rainfall, with an average provincial rainfall of 108 mm—the highest since complete meteorological records began in 1961 [5]. Studies by Wang Han et al. [7] further reveal that the extreme rainfall indices during the 2020 flood season were significantly higher than those in 1998. This rainfall was characterized by its wide distribution range, prolonged duration, high intensity, and elevated extreme indices, all contributing factors to Poyang Lake's high water level and large water volume which, when combined with the high water level of the Yangtze River, sustained elevated water levels in Poyang Lake leading to a major flood disaster.

On 13 July 2020, the Jiangxi Provincial Flood Control Command mandated that all Semi-Restoration Polders (SR Polders) within the lake vicinity actively initiate sluice opening to accommodate floodwaters and robustly fend off floods.

The fertile alluvial plain of Poyang Lake is situated in the lakeside area, where floodwaters fluctuate. The flat terrain, coupled with intensive human activities, including agriculture, industry, and daily life, preclude the construction of flood control reservoirs in this area. Therefore, optimal scheduling of flood control measures for flood storage in Poyang Lake, especially during river and lake flood events, has garnered significant attention in flood risk management research. Fu Chun [8] utilized the multi-level fuzzy optimization method within the variable fuzzy optimization theory to refine the scheduling plan for the SR Polders in Poyang Lake. Their findings suggest that when the water level at the Hukou hydrological station reaches 22.05 m, exceeding 6.6 km² of the SR Polders should be opened for flood storage which is 0.37 m higher than the original scheme's 21.68 m. Fu Dianlong [9] employed the "clipping the level head" approach to planning the SR Polders and proposed a basic framework for the control and application of these areas but did not develop a specific operational scheduling program. Duan Caobin [10] optimized and adjusted the existing flood storage area of Poyang Lake by selecting a subset of SR Polders for modification and incorporating them as new flood storage zones to form a comprehensive flood storage system integrating both existing and newly designated areas. Liu Wenbiao [11] devised three construction plans for the Kangshan flood storage and detention area (Kangshan Zone) in Poyang Lake, considering factors such as opening flexibility, flood diversion reliability, project investment, and operational management of flood diversion gates. The analysis concluded that a scheme featuring 1/2 flood diversion gates combined with 1/2 breaches is most suitable.

The utilization of SR Polders and flood detention areas in Poyang Lake offers a robust approach to counter over-standard floods and alleviate the impact of regional inundation and waterlogging disasters. The primary objective of this article is to explore strategies for enhancing the efficiency of engineering utilization to optimize flood control benefits. Initially, a comprehensive examination of Poyang Lake's flood characteristics is conducted through the analysis of historical hydrological data obtained from key hydrological stations. Subsequently, based on current situation of the SR Polders and the physical model test results of Kangshan Zone, hydraulic and hydrodynamic models are established to assess the flood diversion capabilities. Finally, this paper concludes with a set of insights and recommendations pertaining to flood control management in Poyang Lake. The research results can not only provide scientific suggestions for the flood dispatch work related to Poyang Lake, but also offer valuable reference for flood risk management in plain-type river-connected lake systems globally.

2. Materials and Methods

2.1. Study Area

Poyang Lake (115°47'~116°45' E, 28°22'~29°45' N) is situated on the southern bank of the middle and lower reaches of the Yangtze River, in northern Jiangxi Province. It receives water from five major tributaries: the Ganjiang, Fuhe, Xinjiang, Raohe, and Xiuhe rivers (collectively known as the "Five Rivers") and their respective tributaries. Downstream, it connects to the Yangtze River through Hukou, making it the largest river-connected lake in the Yangtze River basin. The surface area and volume of Poyang Lake vary drastically between flood and dry seasons. During the flood season, the water level rises, expanding the lake's surface area. For instance, in 2020, the Xingzi Hydrological Station recorded a maximum water level of 22.63 m, corresponding to a dynamic lake area of 4903.08 km² and a volume of 38.762 billion m³. Conversely, in the dry season, the water level drops, exposing sandbars and reducing the lake's area. In 2022, the lowest water level recorded at Xingzi was 6.46 m, which corresponded to a dynamic lake area of 217.84 km² and a volume of 674 million m³. High water levels in Poyang Lake typically persist from April to September. Although April to June marks the main flood season of the "Five Rivers", July

to September sees reduced inflow from these rivers and increased inflow from the Yangtze River as it enters its main flood season. This can lead to backwater effects and even reverse flow, causing rapid rises in Poyang Lake’s water level and increasing the risk of flooding disasters. The study area is shown in Figure 2.

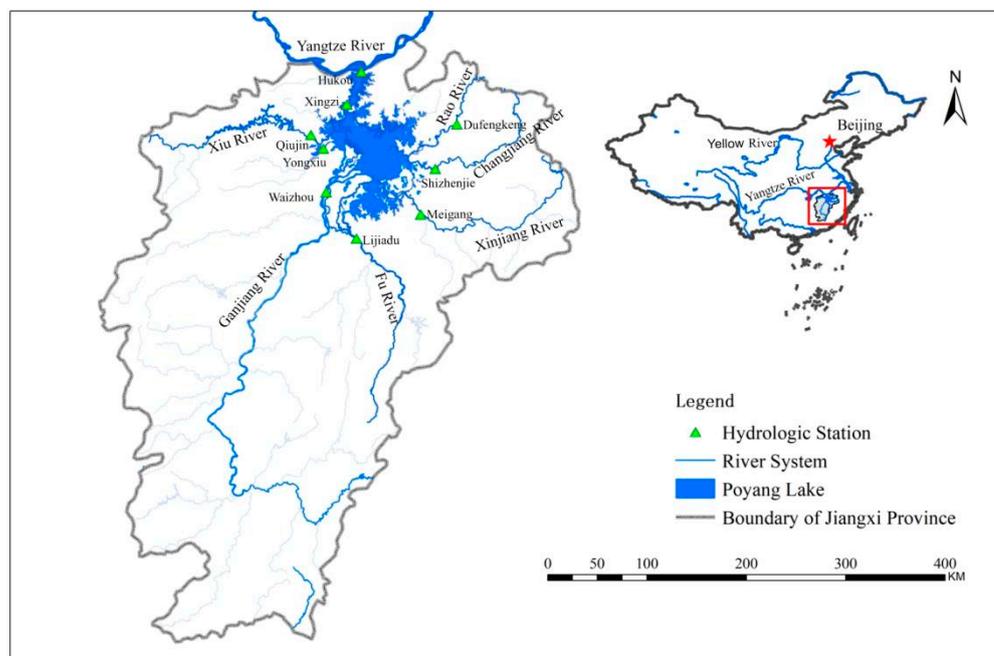


Figure 2. Geographic location of Poyang Lake and relevant hydrological control stations.

2.2. Data and Analysis

The data utilized in this study comprise historical hydrological records from hydrological stations in the Poyang Lake basin, current survey data on SR Polders in Poyang Lake, topographic information on the Kangshan Zone, and results from the physical model test on newly constructed flood diversion sluices. All data were provided by the Jiangxi Academy of Water Science and Engineering.

2.2.1. Historical Hydrological Data of Poyang Lake

As China’s largest freshwater lake, Poyang Lake has a network of hydrological monitoring stations to monitor changes in its hydrological characteristics in real time [12] (as shown in Figure 2). Table 1 outlines the basic information for the control stations located at the estuaries of the Five Rivers.

Table 1. Seven exports of Five Rivers in Poyang Lake Basin.

Name	Flow Direction	Control Area (km ²)	Hydrological Stations
Ganjiang River	From southwest to northeast	80,948	Waizhou station
Xin River	From east to west	15,535	Meigang station
Fu River	From southeast to northwest	15,811	Lijiadu station
Rao River	From northeast to southwest	11,387	Hushan station, Dufengkeng station
Xiu River	From west to east	13,462	Qiujiu station, Wanjiabu station

The Xingzi Hydrological Station, situated at a key juncture where the Five Rivers converge within the lake area, serves as a benchmark station for monitoring fluctuations in water levels of the lake and is commonly used to represent the lake's transition between wet and dry seasons. Meanwhile, the Hukou Station is situated at the outlet of the lake under Shizhong Mountain in Hukou County. As a control station for the entrance of the Poyang Lake basin into the Yangtze River, its water level and discharge data during flood periods are frequently utilized in studies examining the relationship between Poyang Lake and the Yangtze River. To analyze the characteristics of floods in Poyang Lake, this paper collected historical hydrological data from numerous hydrological stations, including the daily average water level and flow data from 1951 to 2022 of the major hydrological stations.

2.2.2. Current Status of SR Polders in the Poyang Lake Area

Following the catastrophic flooding in 1998, China initiated the "Lake Floodplain Restoration" project in the middle and lower reaches of the Yangtze River. Within this framework, Jiangxi Province adopted two approaches for transforming farmland and restoring lakes: "semi-restoration" and "full-restoration" polders. Completed in 2007, these polders have undergone changes over a decade of use. Therefore, the historical data collection and on-site surveys were conducted in 2021 to analyze the current status of SR Polders.

There are 185 SR Polders in the Poyang Lake area, of which 155 polders protect over 2 km² areas. These include 46 key polders and 109 general polders, with a total length of 2460 km, safeguarding 3866.6 km² of farmland and 6.94 million people. These polders primarily rely on overflow weirs, floodgates, manual breaches or ruptures, and a limited number of flood intake culverts to divert and store floodwaters. After decades of operation, the flood control facilities of the polders are seriously aged and damaged, and their actual capacity of them are changed whereas there are different degrees of safety hazards.

2.2.3. Physical Model Testing of the Kangshan Flood Diversion Gate

The Kangshan Zone, located on the southeastern shore of Poyang Lake and downstream of the confluence of the southern branch of the Gan River, the Fu River, and the Xin River, serves as a critical flood retention area for Poyang Lake [13]. It is tasked with diverting up to 1.57 billion m³ of excess floodwater from the Yangtze River. According to the "Flood Control Scheme for the Yangtze River" approved by the State Council in 2015 [5], the Kangshan Zone is activated when the forecasted water level at Hukou reaches 22.50 m and continues to rise.

The Kangshan Flood Diversion Gate is designed to handle 10,673 m³/s of floodwater when the Kangshan station's water level reaches 20.68 m. A physical model, with a geometric scale of 1:100, was used to study its performance. This model covering an area of 5.51 km² and following gravity similarity principles is shown in Figure 3. During the model tests, the upstream water level of the model is maintained at 20.68 m, several sets of test conditions are obtained by adjusting the downstream water level. The relationship between the downstream water level and the flood diversion flow when the 28 gates are fully opened is shown in Figure 4.

As depicted in Figure 4, the Kangshan Flood Diversion Gate attains a maximum flood diversion flow of 10,694 m³/s when all 28 gates are fully opened at an upstream water level of 20.68 m. When the downstream water level remains below 18.74 m, this impressive diversion flow is sustained at a constant rate, exhibiting characteristics of free outflow. However, as the downstream water level rises above 19.35 m, a notable shift occurs. The coefficient of outflow inundation steadily diminishes with the progressive increase in downstream water depth. Consequently, the diversion flow exhibits a persistent downward trend, signifying a transition from free outflow to inundation outflow. These observations strongly suggest that the critical downstream water level marking this transition lies close to 18.74 m. This insight is crucial for understanding and optimizing the flood diversion capabilities of the Kangshan Flood Diversion Gate.

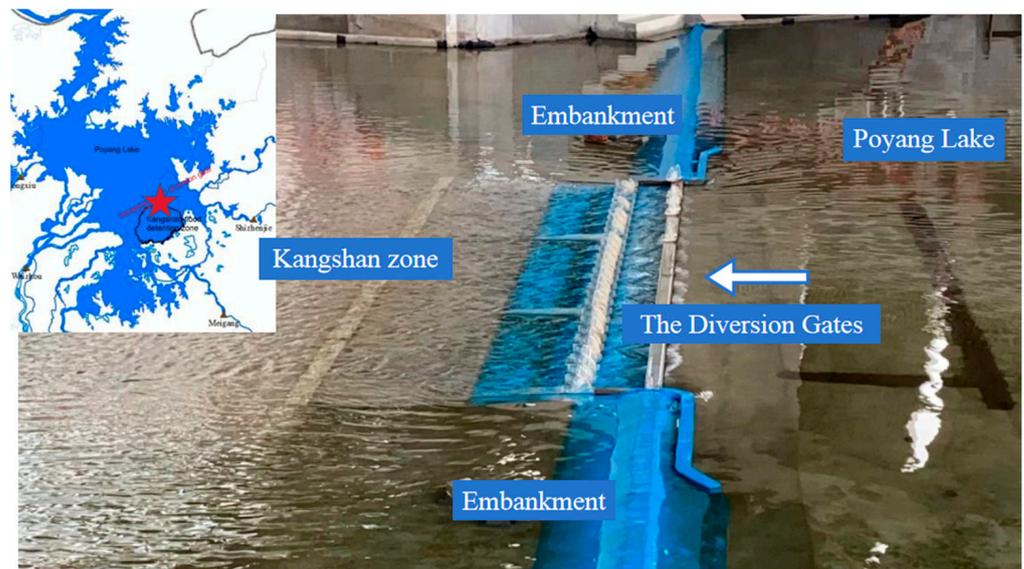


Figure 3. The physical model of flood diversion gates.

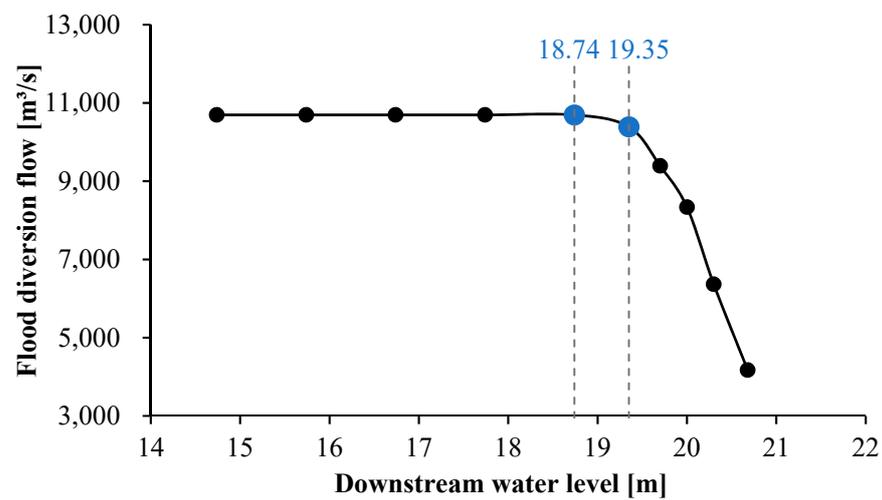


Figure 4. The model test result about the downstream water level and the flood diversion flow with the 28 gates fully opened.

2.3. Research Method

2.3.1. Research Methods for Assessing Flood Diversion Capacity of SR Polders

Based on the basic data of the 185 SR Polders in Poyang Lake, a hydraulic model is constructed by using the formulas of weir flow and gate outflow [14,15] to simulate the flooding processes of various flood control facilities. By analyzing the water level~volume relationships specific to each polder, the time~water level~cumulative flood diversion process curves are generated. Subsequently, a comprehensive statistical analysis of the flood diversion processes across all polders is conducted to determine the flood diversion capacity of SR Polders in 2020.

The formula for weir flow that is used in the hydraulics model is as follows:

$$Q = \sigma_s \sigma_c m n b \sqrt{2gH_0^3/2} \tag{1}$$

In the formula, b represents the net width of each open gate opening; n represents the number of gate openings; H_0 represents the upstream water head including the approaching flow velocity head, $H_0 = H + v_0^2/2g$, the water head at the upstream end of the weir;

V represents the approaching flow velocity; m represents the free overflow discharge coefficient, which is related to the type and height of the weir; σ_s represents the side contraction coefficient; and σ_c represents the submergence coefficient.

The formula for gate discharge that is used in the model is as follows:

$$Q = \sigma_s \mu \epsilon n b \sqrt{2g(H_0 - \epsilon e)} \quad (2)$$

In the formula, e represents the opening height of the gate; ϵ represents the vertical contraction coefficient; μ represents the free discharge coefficient of the gate opening, and other symbols have the same meaning as those mentioned above.

To validate the accuracy and applicability of this hydraulic model, this study selects the actual flood diversion conditions observed in the Lianbei and Liannan polders. Specifically, data from 5 July 2020, 0:00 to 25 July 2020, 0:00 are utilized as a representative case study for simulating and analyzing the flood diversion process.

The water level in front of the weir is set to the measured water level of the Poyang station. The flow coefficient, lateral contraction coefficient, and submergence coefficient are given according to the calculation formula of overflow weir and flood discharge gate. The initial water levels in the Lianbei polder and Liannan polder are set to 13 m and 14 m, respectively. The comparison between the actual flood process and the simulation results is shown in Table 2.

Table 2. The comparison between the actual flood process and the simulation results.

Name	Type	Date of Flood Diversion		Flood Diversion Duration [h]	Cumulative Diversion Volume [10^4 m^3]	The Relative Errors	
		Gate, Weir	Man-Made Breaches			Diversion Duration	Diversion Volume
Lianbei polder	Actual process	9 July	10 July, 12 July	60	25,510	5%	14%
	Simulation results	9 July	10 July, 12 July	57	29,066		
Liannan polder	Actual process	10 July	11 July	60	8150	5%	17%
	Simulation results	10 July	11 July	57	9544		

As indicated in Table 2, the simulation results are satisfactory, with the inflow process closely aligning with real-world conditions. Both the relative errors of inflow duration and flood volume are less than 20%, meeting the standards set out in the “*Hydrological Information and Forecasting Specification (GB T 22482-2008)*” [16]. This indicates that the hydraulic model of the SR Polders is designed reasonably.

2.3.2. Research Methods for Assessing Flood Diversion Capacity in the Kangshan Zone

To assess the flood diversion capacity of the Kangshan flood detention area, this paper constructs a two-dimensional hydrodynamic model for the Kangshan Zone, based on DHI MIKE 2014 software, considering the main dikes and newly built flood diversion gates. Then, combined with the results of the hydraulic model test of the flood diversion gates, several typical operating conditions are used to calibrate the discharge capacity of the hydrodynamic model. Finally, taking the flood diversion water level as the control condition, the flood diversion process under different enabling conditions is studied.

The Kangshan dike, 9 separation dikes, 6 passes, and the natural highland watershed line between the Kangshan dike and Xinrui Levee are used as the boundaries of the simulation area. Considering simulation accuracy and operational efficiency, the hydrodynamic model adopts unstructured grids, with quadrilateral grids as the main and triangular grids as the auxiliary. The simulation range is about 340.39 km^2 , and the side length of the overall grid is between 10 and 130 m. The grids near the gates are locally encrypted, with a side length of 10 m, and a total of 50,794 grids. The measured topographic data and the linear interpolation method are adopted to generate temporary topographic files. Finally,

according to the design data of the flood diversion gate, its terrain is corrected, and the modified final grid terrain is shown in Figure 5.

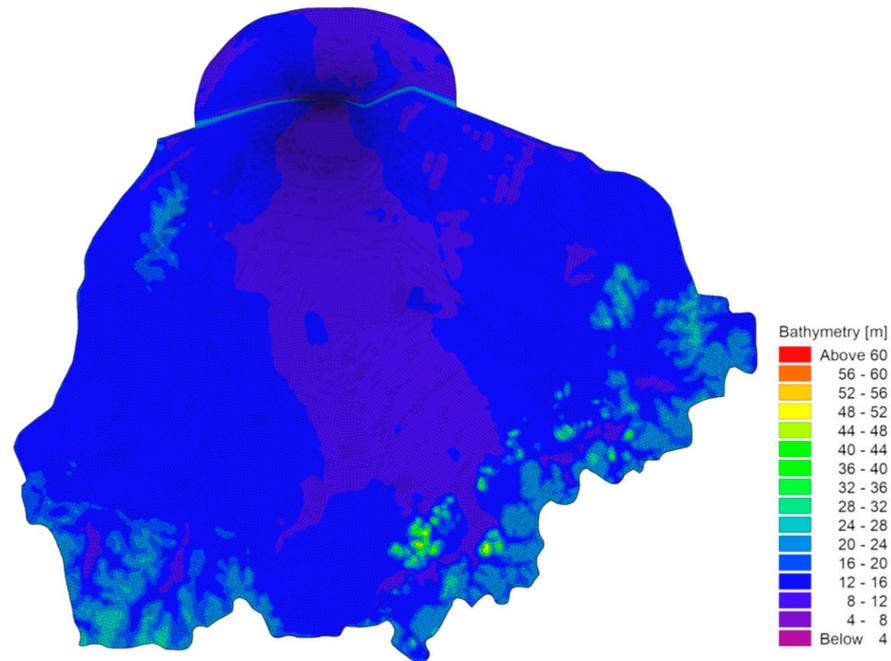


Figure 5. The mathematical model of Kangshan Zone.

Without considering the influence of factors such as tide, wind force, temperature, etc., consistent with the Physical Model Test, the upper boundary of the hydrodynamic model is given as the water level. Several typical operating conditions are adopted to verify the discharge capacity of the mathematical hydrodynamic model. The verification results are shown in Figure 6 below.

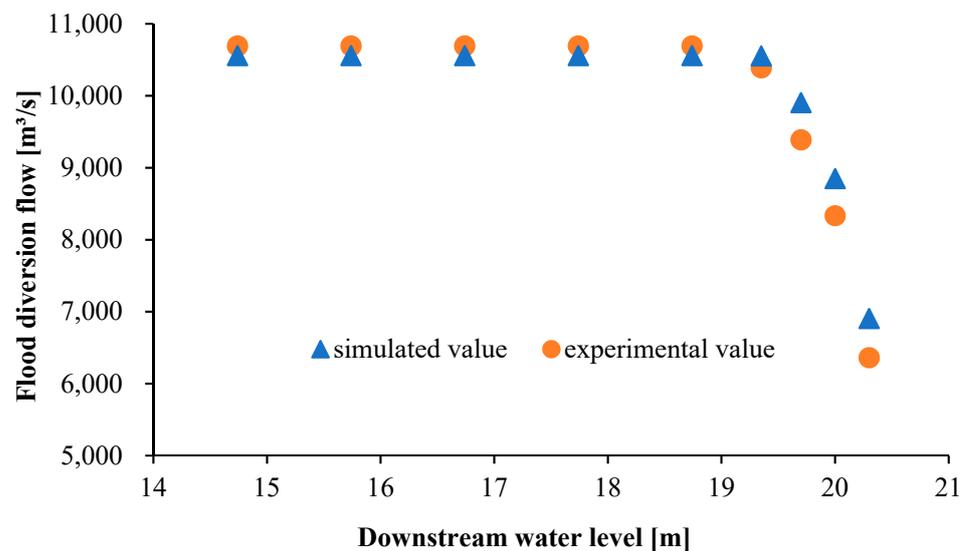


Figure 6. The experimental and simulated values of flood diversion flow under different downstream water levels.

Figure 6 reveals that the hydrodynamic model performs well in validation exercises, as indicated by a relative error well below 20%. These results confirm that the model meets the requirements outlined in the “Hydrological Information and Forecasting Specification

(GB T 22482-2008)" [16] and can be reliably used to assess flood diversion capacity in the Kangshan Zone.

3. Results

3.1. Analysis of Flood Characteristics of Poyang Lake

Climate change and human interventions have significantly altered Poyang Lake's hydrology [17], leading to frequent floods that threaten lives, property, and socio-economic stability. Analyzing the changes in flood characteristics in the past 70 years is crucial for the study of flood disaster management.

As illustrated in Figure 7, it can be seen that in the past 70 years, the annual maximum water level of Poyang Lake mainly appeared in July, accounting for 62.12%; the annual maximum outflow was mainly concentrated in June, and it appeared 32 times in the 66 years of statistics, accounting for 48.48%. The annual maximum water level lags behind the occurrence of the annual maximum outflow. The occurrence time of the maximum outflow from Hukou mainly depends on the size of the flow into the lake and the time when the Five Rivers form a big flood, whereas the occurrence time of the maximum water level mainly depends on the size of the incoming water from the Yangtze River and the corresponding height of the water level [18].

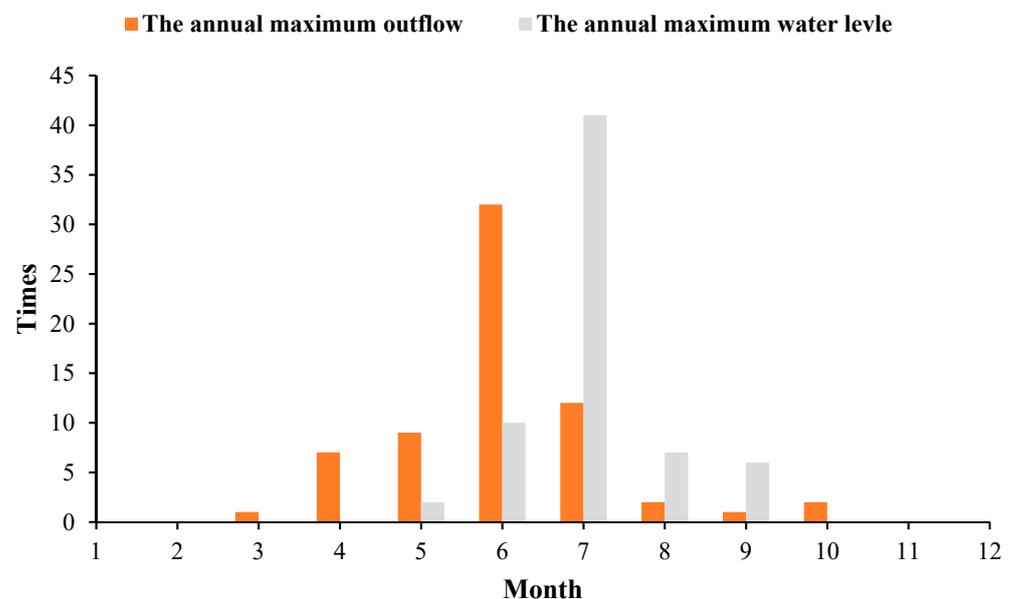


Figure 7. Monthly times of the annual maximum outflow and water level at Hukou hydrological station from 1955 to 2020.

The prerequisite for the jacking of rivers and lakes is the disparity in inflow between the Five Rivers and the Yangtze River. Furthermore, the manifestation of this extreme phenomenon is evident in the backflow of the Yangtze River into the lake. The influx of Yangtze River water into the lake serves a dual purpose: it mitigates the water volume of the Yangtze River while simultaneously impeding the inflow of the Poyang Lake water system [19]. Notably, the occurrence of river backflow can be consistently observed and documented through the daily flow data recorded at the Hukou hydrological station over an extended period.

According to the statistics of the daily average flow data of Hukou hydrological station from 1951 to 2020, out of a total of 70 years, only in 15 years has backflow not occurred, accounting for 21.43% of the total number of years, with an average of 4 out of 5 years with backflow occurring. The time of river water backflow in different years is different, but it mainly occurs from July to September each year, which is basically consistent with the main flood season of the Yangtze River.

From 1951 to 2020, the total number of backflow days was 765 days, and the total number of backflow times was 141. As shown in Figure 8, the number of backflow days in July, August, and September was 221 days, 185 days, and 252 days, respectively, accounting for 28.89%, 24.18%, and 32.94% of the total days.

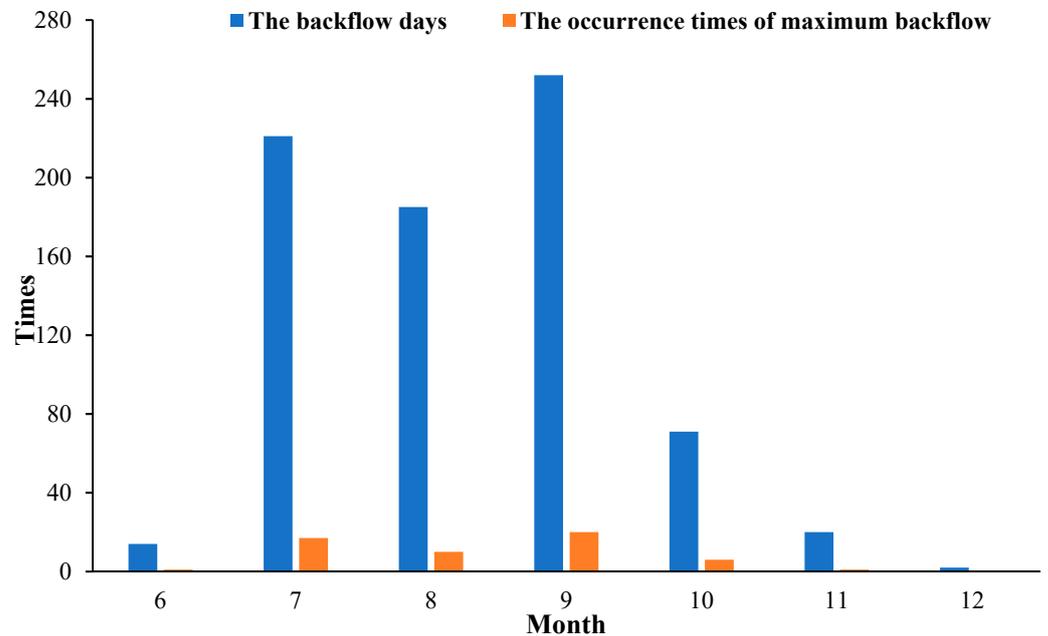


Figure 8. The backflow days and the occurrence times of maximum backflow in each month of the Yangtze River flood from 1951 to 2020.

Analysis of the backflow discharge data reveals that the highest frequency of maximum backflow occurrences took place in July, August, and September, with 17, 10, and 20 events, respectively. These events constitute 30.91%, 18.18%, and 36.36% of the total recorded incidents for each respective month. Furthermore, the most prolonged period of backflow was observed in 1958, lasting for 47 days. The peak discharge rate during a backflow event was recorded at a staggering 13,700 m³/s on 12 July 1991. Additionally, the year 1991 saw the greatest amount of backflow volume, totaling 113.9 billion m³.

The amount and the number of days of backflow in different years reflect the strength of the interaction between the Yangtze River and Poyang Lake [20]. Table 3 shows the statistics of backflow of the Yangtze River from 1951 to 2019 by age. The number of days, times, and amount of backflow by the Yangtze River floods in different years showed an alternating pattern of one less and one more. It can be seen from the table that the backflow in the 1960s and 1980s was the most frequent, and the Yangtze River water backflow occurred every year during this period, which indicated that the inflow from the middle and upper reaches of the Yangtze River had a relatively strong jacking action on the flood of Poyang Lake. In the 1970s and 1990s, the number of days and times of backflow was less, which reflected that the inflow from the middle and upper reaches of the Yangtze River had a weak jacking action on the flood of Poyang Lake, and the frequency of backflow increased in the first 10 years of the 21st century.

Table 3. The statistics of backflow of the Yangtze River from 1951 to 2019 by age.

Age	All Years [Year]	Backflow Years [Year]	Backflow Days [Day]	Backflow Times [times]	Backflow Volume [10 ⁸ m ³]
1951–1959	9	8	105	12	214
1960–1969	10	10	172	30	356.4

Table 3. Cont.

Age	All Years [Year]	Backflow Years [Year]	Backflow Days [Day]	Backflow Times [times]	Backflow Volume [10 ⁸ m ³]
1970–1979	10	8	99	25	112.7
1980–1989	10	10	194	36	350.3
1990–1999	10	4	54	10	147
2000–2009	10	8	106	19	228
2010–2019	10	6	33	8	49.22

3.2. Analysis of Flood Diversion Capacity of SR Polders in Poyang Lake Area

The Poyang Lake area is home to numerous SR Polders, each with its unique characteristics and conditions. Therefore, adjusting the flood control parameters within the hydraulic model presents a significant challenge. SR Polders were first activated under the super-historic flood in 2020, and we collected the data on the actual activation time, flood process, and engineering parameters of each SR Polder through field research, literature collection, discussion, and recycling of research forms. Based on these data, we chose the super-historic flood process in 2020 as a typical working condition to analyze the flood diversion capacity of SR Polders.

In order to analyze the flood diversion capacity of SR Polders under the 2020 flood, 185 SR Polders in the Poyang Lake area are arranged in the model, and the water flow boundary condition of each polder area is set as the actual water level of the corresponding hydrological station, so as to calculate the flood diversion flow and volume from 5 July to 25 July 2020. The statistics of the calculation results are shown in Table 4 and Figure 9.

Table 4. Statistics on the simulation results of flood diversion volume of SR Polders in 2020 in Poyang Lake area.

Type	Designed Flood Diversion Volume [10 ⁸ m ³]	Simulated Flood Diversion Volume [10 ⁸ m ³]	Flood Diversion Account	Amount	Number of Unused SR Polders	Number of Over-Designed SR Polders
SR Polders	26.14	22.04	84.3%	185	57	113

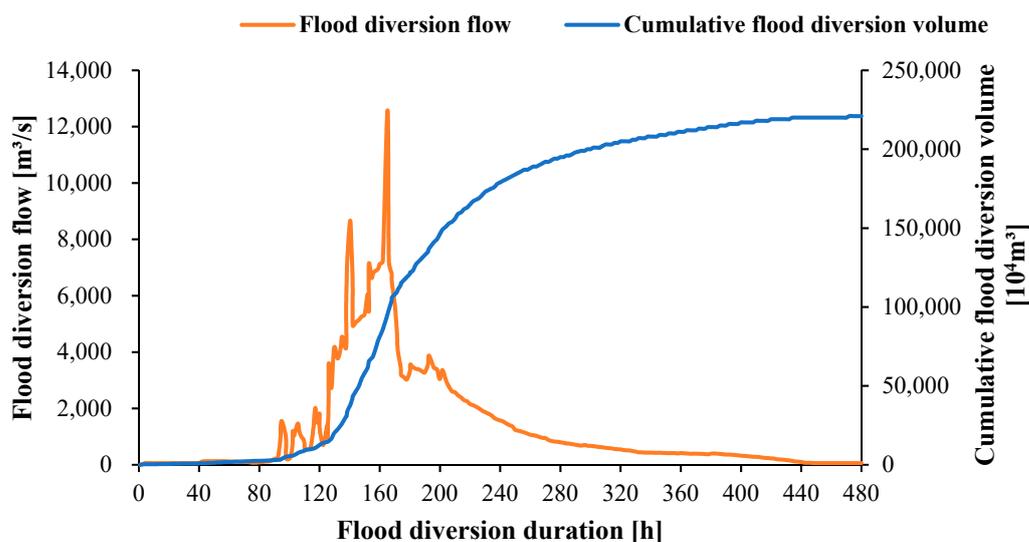


Figure 9. The simulated process of flood diversion of SR Polders in 2020.

From the analysis of statistical results, it can be seen that:

- (1) During the super-historical flood in 2020, the utilization rate of SR Polders was not high, and the polder areas that have been used are basically in the state of over-designed flood diversion and storage. Within the lake area, there were 185 SR Polders in total, out of which only 128 (constituting 69.2% of the total) were effectively utilized for flood diversion. Furthermore, it was observed that 113 polder areas, accounting for 88.3% of the total SR Polders, exhibited signs of over-design in terms of their flood diversion capabilities.
- (2) The flood diversion process extended over a considerable duration. Specifically, the principal flood diversion window occurred within 3–4 days following the deployment of SR Polders, during which the effective flood diversion volume comprised 68.1% of the cumulative flood diversion volume. In 2020, SR Polders were engaged in flood diversion for a total of 480 h (spanning 20 days). During this period, the maximum flood diversion flow reached 12,170 m³/s, resulting in a cumulative flood diversion volume of 2204.05 million m³. The peak flood period, from 10 July to 13 July, witnessed a cumulative flood diversion volume of 150.73 million m³, equivalent to 68.1% of the total flood volume. This period was characterized by several flood diversion peaks in the section, primarily attributed to breaches in numerous polders or the excavation of grilles due to excessive flood flows. Subsequent to 15 July, the water levels inside and outside the polder areas stabilized, leading to a sharp decline in flood diversion flow and gradual stabilization of the cumulative flood diversion volume.

3.3. Analysis of Flood Diversion Capacity of the Kanshan Zone

As the physical model solely focuses on scenarios where the upstream water level stands at 20.68 m, its outcomes are inherently limited in scope. To gain a more nuanced understanding of the flood diversion capabilities within the Kanshan Zone, we have established distinct working conditions based on varying flood diversion thresholds. A detailed breakdown of these conditions is presented in Table 5. Utilizing the hydrodynamic model tailored for the Kanshan Zone, we conducted a simulation spanning 48 h to assess flood diversion performance. Figure 10 illustrates the correlation between flood diversion duration and flood diversion flow under each specified condition, whereas Figure 11 delves into the relationship between flood diversion duration and cumulative flood diversion volume.

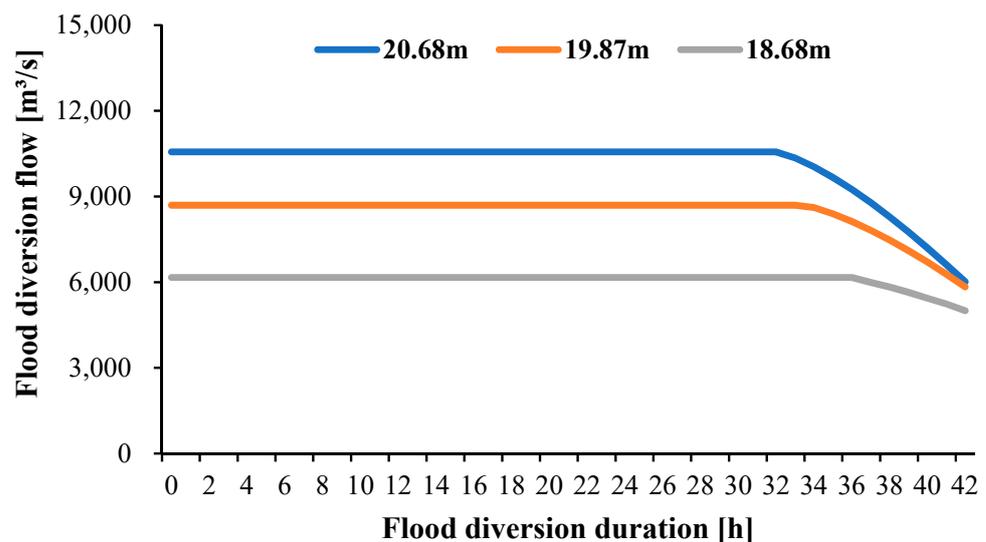


Figure 10. The relationship between flood diversion duration and flood diversion flow under each working condition.

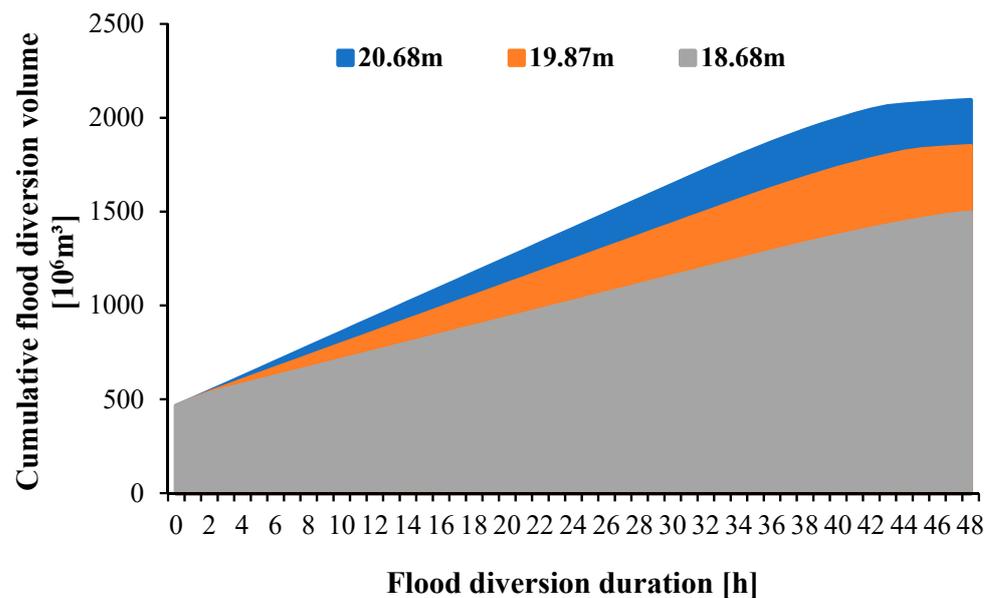


Figure 11. The relationship between flood diversion duration and cumulative flood diversion volume under each working condition.

Table 5. Conditions of different flood diversion levels.

	Condition	Flood Diversion Level [m]
Condition one	The water level of SR Polders under 1647 acres controlled by lake flood	18.68
Condition two	The water level of SR Polders above 1647 acres controlled by lake flood	19.87
Condition three	The opening water level of Kanshan Zone	20.68

It can be seen from Figure 10 that the higher the flood diversion level, the stronger the maximum diversion capacity. When the flood level is 18.68 m, 19.87 m, and 20.68 m, the maximum diversion flow is 6165 m³/s, 8693 m³/s, and 10,560 m³/s respectively. With the increase in flood diversion time, the water level in the flood storage and detention area gradually increases. When the flood diversion duration of working conditions 1, 2, and 3 is 36, 33 and 32 h, respectively, the flood diversion flow begins to decrease gradually due to the influence of the downstream water level, and the flow pattern gradually changes from free outflow to submerged outflow.

Under different working conditions, the higher the flood level, the faster the flood diversion speed, the more the flood diversion volume in the same period, and the shorter the time to complete the flood storage task. As shown in Figure 11, the duration of flood diversion and the cumulative flood volume are approximately linearly increasing under various conditions in the early stage of flood diversion. In the later period, with the gradual increase in water level in the flood storage and detention area, the upward trend of cumulative flood diversion volume gradually slows down. Under the condition of a flood diversion water level of 20.68 m, the water storage capacity of the flood storage and detention area is close to saturation when the flood diversion was about 42 h.

3.4. Analysis of Flood Diversion Effect of SR Polders and Kanshan Zone under Typical Flood

In 2020, Poyang Lake encountered a super-historical flood. In the face of an unusually severe flood control situation, after the scheduling of the reservoirs, 185 SR Polders were opened for flood storage, effectively reducing the water level of Hukou by 0.25–0.3 m, which greatly alleviated the flood control pressure in the lower reaches of the Yangtze River.

As typical mitigation measures of Poyang Lake, SR Polders and flood storage and detention areas are an important part of the flood control system [13]. The study of the flood diversion effect of SR Polders and Kanshan Zone under a typical flood will provide a certain reference for solving the problem of how to jointly use the typical mitigation measures of Poyang Lake to minimize the loss of flood disaster while resisting the flood in the future when encountering the excessive flood.

3.4.1. Analysis of Flood Diversion Effect of SR Polders

Based on the previous research results on the dynamic water level–area and water level–volume relationship of Poyang Lake [21], according to the flood diversion process of SR Polders in Poyang Lake area simulated in Section 3.2 from 5 July to 25 July 2020, using Xingzi hydrological station as the representative station of Poyang Lake water level, the water level change process of Xingzi hydrological station before and after the opening of SR Polders is calculated as Figure 12.

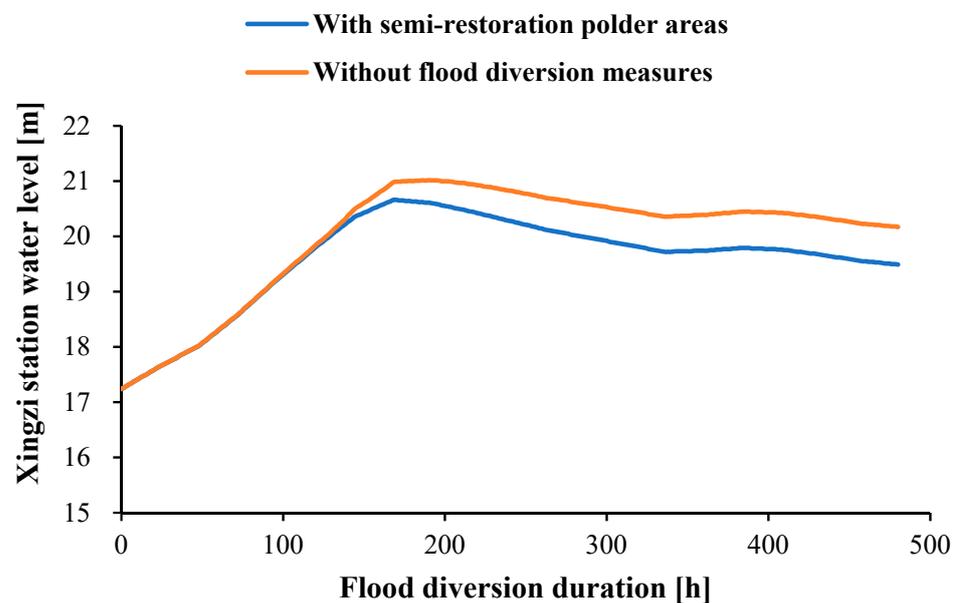


Figure 12. The water level change process of Xingzi hydrological station before and after the opening of SR Polders.

From 29 June to 10 July 2020 is the second rainfall concentration period in Poyang Lake during the year. As shown in Figure 12, during this period, the flood diversion capacity of SR Polders is weak, and the water level decline is not significant compared with that without flood diversion. The water level of Poyang Lake is still on the rise. Around 10 July–13 July 2020 is the main flood diversion period, the water level decreases significantly, but the water level still shows a rising trend. After 13 July, the water level of Poyang Lake shows a continuous downward trend, in which the local increase in water level around 20 July is mainly due to the rainfall in the basin. Over time, compared with the non-activation of SR Polders, the water level of Xingzi can be decreased by 0.68 m in total.

3.4.2. Analysis of Flood Diversion Effect of Kanshan Zone

As shown in Figure 11, it takes about 42 h for the Kanshan Zone to store 1570 million m^3 water under the working condition of the flood diversion level of 20.68 m, which meets the design requirement of 48 h.

According to Figure 12, the water level of Xingzi will exceed 20.60 m after 11 July if SR Polders are not used for flood diversion. According to the “Yangtze River flood prevention plan” [5] and the characteristic water level relationship of the representative station in the Poyang Lake area [21], the Kanshan Zone has the conditions for flood diversion in 2020.

It is assumed that the Kanshan Zone is used for flood diversion on 11 July, and the flood diversion period is from 6:00 on 11 July to 0:00 on 13 July. According to the water storage process line of Kanshan Zone, and the relationship between the water level and volume of Poyang Lake, the water level change process of Xingzi hydrological station before and after the opening of flood storage and detention area is enabled can be calculated, as shown in Figure 13.

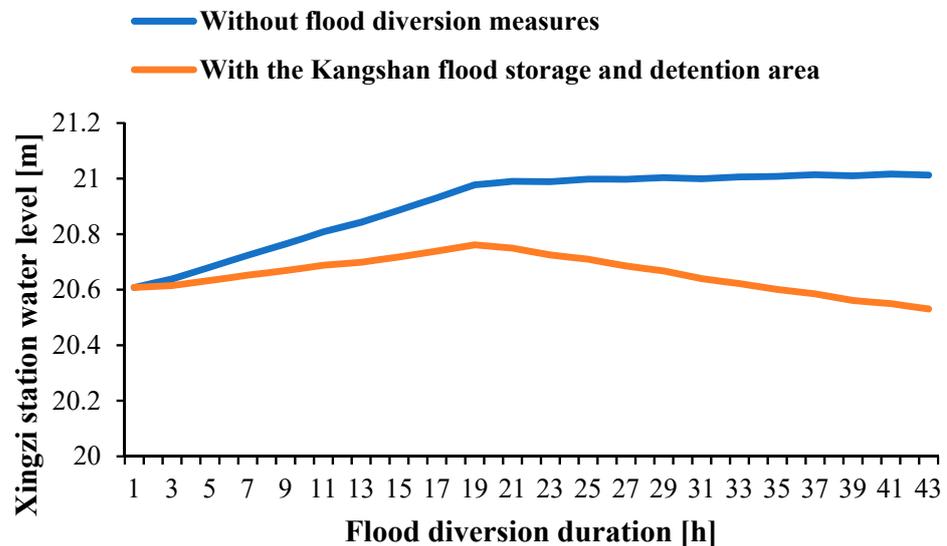


Figure 13. The water level change process of Xingzi hydrological station before and after the opening of Kanshan Zone.

Upon analyzing Figure 13, it becomes evident that, during the initial stages of flood diversion, the water level at the Xingzi hydrological station continued to ascend; however, this increase occurred at a slower rate compared to scenarios where no mitigation measures were implemented. Approximately 19 h into the flood diversion process, a notable decline in the water level at Xingzi hydrological station became apparent. Over the subsequent 24 h, this downward trend persisted, ultimately resulting in a water level reduction to 20.53 m after a total duration of 43 h. The implementation of flood diversion measures in the Kanshan Zone has proven effective in lowering the water level of Poyang Lake by a significant margin of 0.48 m. Furthermore, by integrating the utilization of SR Polders, the flood control pressure on both Poyang Lake and the Jiujiang section of the Yangtze River can be substantially alleviated.

4. Discussion

The Poyang Lake area has initially formed a flood control and disaster reduction system based on dikes, supplemented by reservoirs, flood storage and detention areas, river regulation projects, and non-engineering measures for flood control. In 2020, Poyang Lake encountered super-historical floods, and the flood control engineering system in the lake area played an important role in effectively reducing the flood control pressure in the Poyang Lake area and the estuary of the Yangtze River.

According to the practice of flood control in the Poyang Lake area in 2020, combined with the analysis of the flood diversion effect of SR Polders and flood detention area, the following suggestions are put forward for flood control in the Poyang Lake area:

- (1) Implement an effective management and operation mechanism. It has been more than ten years since the establishment of SR Polders in Jiangxi Province. Most of them are aging and in disrepair or partially damaged. Due to the failure to establish the daily operation and management mechanism, they cannot be maintained in time, resulting in the actual use of effective flood control during the super-historical flood period in 2020, accounting for 69.2% of the total number of SR Polders in the lake area,

and the actual cumulative flood diversion volume accounts for 84.3% of the designed value. Due to the large number of SR Polders in the lake area and different standards, achieving comprehensive defense and overall consideration in both construction and flood control seems to be difficult. It is more effective to classify the defense according to the importance of the protected area and necessary to improve the defense level for the key SR Polders. Moreover, enhancing routine maintenance of polder areas and reinforcing standardized management are essential undertakings.

- (2) Deepen the adjustment and optimization research of SR Polders. There are a large number of SR Polders built along the riverside of Poyang Lake, and they can effectively reduce the passive breach by taking the initiative to flood diversion at the key time. However, in 2020, although SR Polders in the lake area were fully used, the drop in water level was still limited, and the measured maximum water level was only 1 cm short of the utilization standard of the flood storage and retention area. In the face of over-standard floods, it is suggested that further work should be carried out from the following two aspects: First, according to the different protection of cultivated land area of SR Polders divide into different use of water level scheduling research, that is, to adjust the existing opening water level, improve the existing flood storage and detention area operating conditions. For example, the opening water level below 1647 acres is still 20.5 m, the SR Polders of 1647 to 4942 acres are adjusted from 21.68 m to 22.00 m, the SR Polders of 1647 to 8235 acres is set to 22.50 m, and the operation standard of the four flood storage and detention areas is adjusted from 22.50 m to about 23.0 m, so as to realize different application schemes for floods of different magnitudes. Secondly, in order to deal with regional super-standard floods, the zoning application schemes of SR Polders at different tails are studied.
- (3) Explore the joint scheduling and hierarchical application program of lake flood control under super standard flood. Existing SR Polders in Poyang Lake are mainly cultivated, and since there are no residents and important facilities, the cost of flood diversion per unit of flood storage is much lower than that of the flood storage and detention area. When there are small and medium-sized floods, Poyang Lake reservoir and polder areas can play a better role, but when facing larger floods, SR Polders are not enough to store the excess flood in a short time, and the loss is extremely heavy in case of collapse. It can be considered to use the flood storage and detention areas to allocate excess flood in advance and reduce the flood peak water level and flood peak flow. Through the overall arrangement of SR Polders and flood storage and detention areas, rationally determine the timing and sequence of flood diversion, so as to minimize the disaster loss while ensuring the flood control safety of key dikes in the lake area.

5. Conclusions

- (1) During the 2020 flood, the 185 SR Polders in Poyang Lake area had significant flood diversion, with a total actual flood inflow of about 2204 million m³ and a flood inflow ratio of 84.03%. The SR Polders with effective flood diversion account for 69.2% of total SR Polders in lake area. Without flood diversion, the highest water level of Xingzi station can reach 22.98 m, which is 0.41 m higher than the characteristic water level (22.57 m) and lasts for nearly 5 days. After the flood diversion, the water level of Xingzi Station is controlled at 22.63 m.
- (2) During the 2020 flood, if no measures are taken for flood diversion by SR Polders, the water level at Hukou station will reach the activation standard of Kangshan Zone on 11 July. Under the task of bearing 1.57 billion m³ of excessive flood water, using the Kangshan Zone for flood diversion can reduce the water level of Xingzi station from 22.98 m to 22.73 m. Subsequently, combined with the application of SR Polders, it can further alleviate the flood control pressure of Poyang Lake and the Jiujiang section of the Yangtze River.
- (3) To enhance the flood control engineering system in the Poyang Lake area, it is advisable to expedite the implementation of efficient SR Polders management and

operation mechanisms. This includes promptly undertaking dike reinforcement and strengthening measures, bolstering routine engineering maintenance, refining existing norms and management frameworks, clarifying dike positioning and defense levels, and ultimately achieving scientific and orderly graded flood control during crucial moments.

- (4) It is recommended to optimize flood control dispatching and deepen the research on the adjustment and optimization of SR Polders. Given the flood storage characteristics of various projects, we coordinate the flood control projects such as reservoirs, SR Polders groups, and flood detention areas to achieve fine joint dispatching of the flood control engineering system in the Poyang Lake area.

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