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Research on Joint Operation of Flood Diversion and Storage Measures: A Case Study of Poyang Lake

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Abstract: In recent years, flood hazards have occurred increasingly worldwide, posing significant threats to the safety of life and property in lacustrine and riverine environments. To mitigate the devastating impacts of floods, it is crucial to explore optimal strategies for joint flood diversion of flood diversion and storage measures (FDSM). The FDSM management of Poyang Lake in China focuses on studying semi-restoration polder areas (SR Polders) and flood storage and detention areas (FS Detentions), which are subjects of ongoing research. Existing studies primarily focus on SR Polders or FS Detentions, with limited research on the joint flood diversion potential of these two measures, particularly regarding optimal scheduling. This study takes 185 SR Polders and the Kangshan flood storage and detention area (KS Detention) as the primary research objects. By integrating hydraulic theory, numerical simulation techniques, and survey data, we develop a hydraulic model for the SR Polders and a hydrodynamic model for the KS Detention to carry out flood diversion simulation. The 1998 flood is chosen as a typical case to simulate and analyze their flood diversion processes under various schemes. The results indicate that altering the operation criteria for FDSM influences both the maximum diversion discharge and the timing of the main diversion period. For the SR Polders, under the current flood control scheme, raising the operation water level (OWL) of SR Polders-I by 1.0 m increases the maximum diversion discharge by 894 m^3/s. Additionally, raising the OWL of SR Polders-II by 0.37 m delays the main diversion period by one day. For the KS Detention, higher flood diversion water levels correspond to greater discharge capacities. Furthermore, a fuzzy optimization method is applied to optimize nine joint schemes of the SR Polders and KS Detention. The results indicate that the optimal joint flood diversion strategy for Poyang Lake is operating SR Polders-I, SR Polders-II, and KS Detention at a Hukou water level of 21.65 m, 22.05 m, and 22.50 m, respectively. Finally, the study provides insights and recommendations for flood control management at Poyang Lake. The results of this study not only have important guiding significance for flood control management of large plain lakes but also provide references for the joint operation of flood diversion and storage areas in other regions.

Keywords: flood diversion and storage measures (FDSM); joint operation; optimal strategy; Poyang Lake

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1. Introduction

In recent years, extreme rainfall events leading to flooding have occurred with increasing frequency, driven by the intensifying effects of climate change and rapid urbanization [1,2]. Flooding has had devastating global impacts, with global losses estimated at USD 651 billion between 2000 and 2019, affecting 1.6 billion people [3]. It has become one of the most frequent, widespread, and economically damaging natural disasters, posing a significant threat to human life [4]. Flooding events in countries such as China [5], Vietnam [6], Germany [7], and Pakistan [8] highlight the universal and severe nature of this phenomenon.

With its vast territory and numerous rivers and lakes, China is particularly vulnerable to flooding. Poyang Lake, the largest freshwater lake in China, is located in the Yangtze River Delta plain and is influenced by the floods of the five rivers (Gan River, Fu River, Xin River, Rao River, and Xiu River) as well as the Yangtze River [9]. Due to the low-lying topography of the lake area and inefficient flood diversion, Poyang Lake has long been a hotspot for flood disasters in the middle and lower reaches of the Yangtze River [10]. These flood disasters pose a serious threat to the lives and property of people in the lakeside area, which covers about 18% of the province's total land area, supports 26% of its population, and accounts for 41% of its economic output [11]. This area is the core economic zone of Jiangxi Province, underscoring the critical importance of improving its flood control system to enhance disaster resilience. Over several decades of water conservancy construction, Jiangxi Province has established a flood control engineering system primarily consisting of reservoirs, Polders, and FS Detentions [12].

As the typical FDSM in the Poyang Lake area, the current research mainly focuses on the individual operation of SR Polders or FS Detentions. However, studies on the joint flood diversion operation of these two measures remain insufficient. Scholars such as Min Qian [13] and Jiang Lugang [14] focused on the role of SR Polders in flood control, investigating the flood diversion capacity of Poyang Lake after returning farmland to lake areas and addressing issues related to polders management. Lei Sheng [12], Ma Qiang [15], and Wan Zhihao [16] analyzed the practical application of SR Polders in flood diversion during the 2020 floods. Yan Hong, Fu Chun [17], and Wen Tianfu [18] conducted in-depth studies on the flood control optimization scheduling strategy of SR Polders using fuzzy optimization theory. Jiang Shuihua [19] applied the MIKE 21 model to develop a loss assessment method based on flood evolution and inundation data from FS Detentions, accurately estimating the potential life and property losses caused by a breach of the Kangshan embankment in Poyang Lake. Chen Yubin [20] proposed a flood regulation model that integrates the River–Lake–Detention system, creating flood simulation schemes that consider the impact of FS Detentions and conducting real-time scheduling simulations for the operation of SR Polders during the 2020 floods. Most of the above-mentioned studies are mainly based on the macroscopic perspective of water balance in the lake area, focusing on the total volume and impact of using FDSM for flood diversion, and the research methods are mostly based on spatial data analysis or statistical models. However, the research on systematic simulation and comprehensive analysis of FDSM for flood diversion, especially joint flood diversion still needs to be strengthened.

Few studies have explored the joint operation of the two. Zou Jiayu [21] developed a hydrodynamic model of Poyang Lake using Mike 21, which couples SR Polders and FS Detentions and then simulated the joint operation of flood diversion under different schemes. The model constructed in [21] was constructed by merging the same type of SR Polders into a whole. However, this generalization method still needs to be improved from the verification results of the model. In order to explore the potential of joint flood diversion operation and optimize the flood control scheduling strategy of SR Polders and

FS Detentions, this study takes 185 SR Polders and the KS Detention in Poyang Lake as research objects. First, a hydraulic model for the SR Polders and a hydrodynamic model for the KS Detention are developed using hydraulic theory, numerical simulation techniques, and survey data to carry out flood diversion simulation. Then, the 1998 flood is selected as a typical case to simulate the flood diversion under different operational schemes for SR Polders and the KS Detention, respectively. Subsequently, a fuzzy optimization method is employed to optimize the nine schemes of the joint flood diversion operation by evaluating three key aspects: the reduction in maximum water level at the Xingzi Station (WL Reduction), the duration of exceeding KS Detention OWL (EL Duration), and the total flood diversion volume (FD Volume). Finally, this paper discusses insights and recommendations for improving the flood control management of Poyang Lake. The innovation of this study lies in the first systematic evaluation and optimization of different strategies for the joint operation of SR Polders and KS Detention for flood diversion under the 1998 flood, filling the gap in the research on the joint operation of flood diversion and storage measures in the Poyang Lake. The objectives of this study are (a) to investigate the effects of different operation criteria on the flood diversion capacities of SR Polders and KS Detention under the current status and (b) to evaluate and optimize the joint operation schemes of SR Polders and KS Detention by adopting a fuzzy optimization method.

2. Materials and Methods

2.1. Study Area

Poyang Lake, located on the southern bank of the middle and lower reaches of the Yangtze River in northern Jiangxi Province, consists of the main lake area and the tails of five rivers. The basin area of Poyang Lake is 162,200 km^2, accounting for about 94% of the area of Jiangxi Province. After receiving water from the five rivers, the lake stores and regulates it before discharging it into the Yangtze River through Hukou, as shown in Figure 1. From April to June, the main flood season for the five rivers, the increased upstream discharge causes the water level in the lake to rise, expanding the areas of lake. From July to September, the inflow from the five rivers decreases, while the Yangtze River enters the main flood season, with the increased Yangtze inflow causing backflow into the lake, hindering outflow and resulting in a rapid rise in the water level of Poyang Lake, which increases the risk of flooding disasters. Since the 20th century, the frequency and severity of flooding disasters in Poyang Lake have significantly increased [22,23]. In 1998, the water level at the Poyang Lake Hukou Station reached 22.59 m, surpassing the WWL (19.50 m) by 3.09 m, and the OWL of FS Detentions (22.50 m) by 0.09 m. In 2020, the water level at the same station peaked at 22.49 m and the average water levels during the period of July to August were 20.41 m, with water level variations ranging from 17.91 m to 22.49 m. The frequent occurrence of flooding disasters in Poyang Lake poses a severe threat to the safety of life and property for the people living in the lakeside areas.

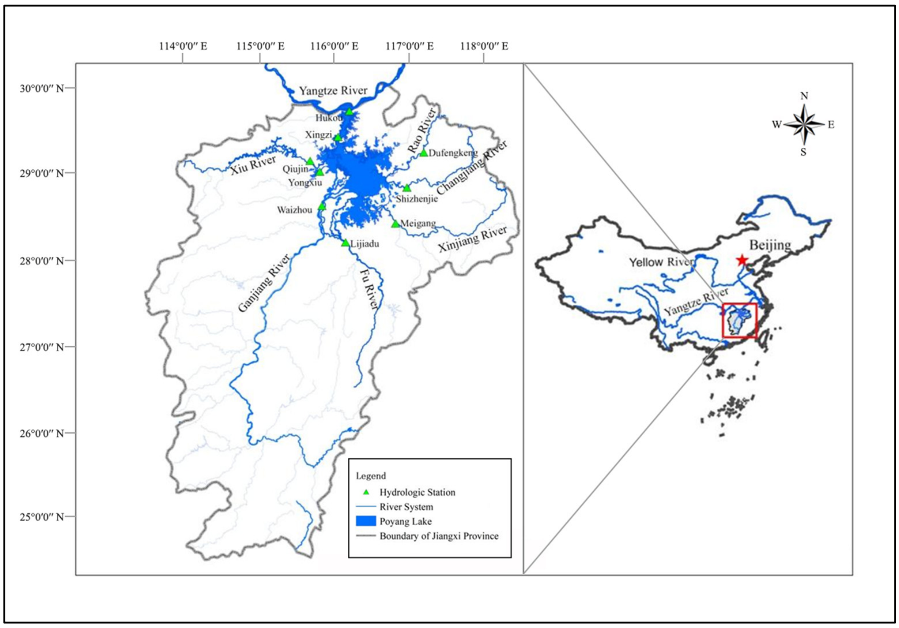

Figure 1. Geographic location of Poyang Lake and relevant hydrological stations [10].

The SR Polders and KS Detention are critical components of the flood control system in Poyang Lake. According to the 'Regulations on the Relocation of Villages and Restoration of Lakes for Flood Discharge in Jiangxi Province' [12], the OWL of SR Polders with less than 6.67 km^2 of crop cultivation (SR Polders-I) is 20.50 m, and the OWL of SR Polders with more than 6.67 km^2 of crop cultivation (SR Polders-II) is 21.68 m. However, studies indicate that current operation water levels are significantly lower [17,18]. According to the "Flood Control Scheme for the Yangtze River", the OWL of the KS Detention is 22.50 m. In 2023, Jiangxi Province started to advance the construction project of FS Detentions, along with the reinforcement and improvement of flood diversion facilities. In this context, it is crucial to study the joint flood diversion operation of the SR Polders and KS Detention under typical flood conditions.

2.2. Data and Analysis

The data from the main hydrologic stations of Poyang Lake in 1998, along with the survey data of each SR Polder, as well as the physical model testing data of the flood diversion sluice in the KS Detention, were all provided by the Jiangxi Academy of Water Science and Engineering.

2.2.1. Current Status of SR Polders in the Poyang Lake

SR Polders are areas where crops are cultivated within the dikes that surround polders when the water level outside the dikes is lower than the OWL, and which are used for flood storage when the water level outside the dikes rises above the OWL. Figure 2 shows the Zenglong SR Polder located in Zenglong Village, Jiangyi Town, Gongqingcheng County, Jiujiang City, Jiangxi Province. By collecting historical data, reading literature, and conducting a field survey in 2021, relevant data, such as the detailed and newest data of flood diversion facilities, the location of each polder, and the area of crop cultivation, was compiled and analyzed to study the current status of the SR Polders.

There are a total of 240 SR Polders in Jiangxi Province, distributed across 18 counties (cities, districts) in the three cities of Nanchang, Shangrao, and Jiujiang. Among these, Nanchang has 7 SR Polders, Jiujiang has 194, and Shangrao has 39. In terms of river basins, 185 of these SR Polders are located in the Poyang Lake area, while 55 are situated along the Jiangxi area of the Yangtze River [10]. The dikes surrounding 185 SR Polders with an area of 4697.35 km^2 of crop cultivation are 604.13 km in total length. Among these, 152 SR Polders are classified as SR Polders-I, whereas 33 SR Polders fall under the category of SR Polders-II. According to flood diversion statistics from the 2020 flood, the 185 SR Polders utilize various facilities for flood storage, including weirs, sluices, breaches, and a small number of culverts. The specifics of these facilities are shown in Figure 3. As seen in Figure 3, the most commonly used facility is the sluice, followed by the weir. Over the years, many facilities have experienced aging, lack of maintenance, or partial damage. Due to the absence of a regular management and maintenance system, timely repairs are not carried out, leading to a decrease in their flood diversion capacity and a reduction in efficiency [10,24].

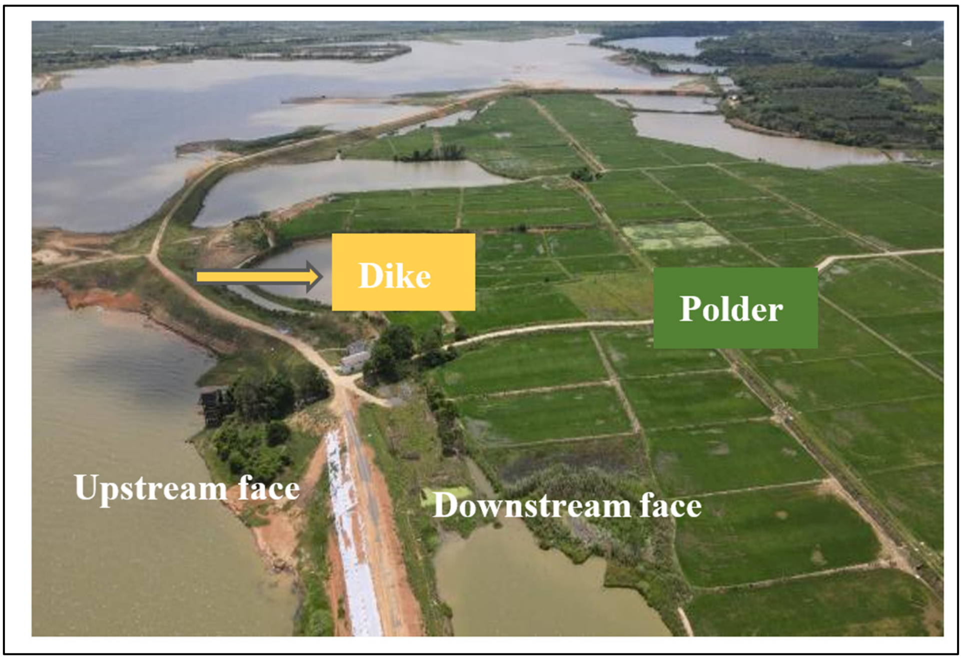

Figure 2. The Zenglong SR Polder located in Zenglong Village, Jiangyi Town, Gongqingcheng County, Jiujiang City, Jiangxi Province.

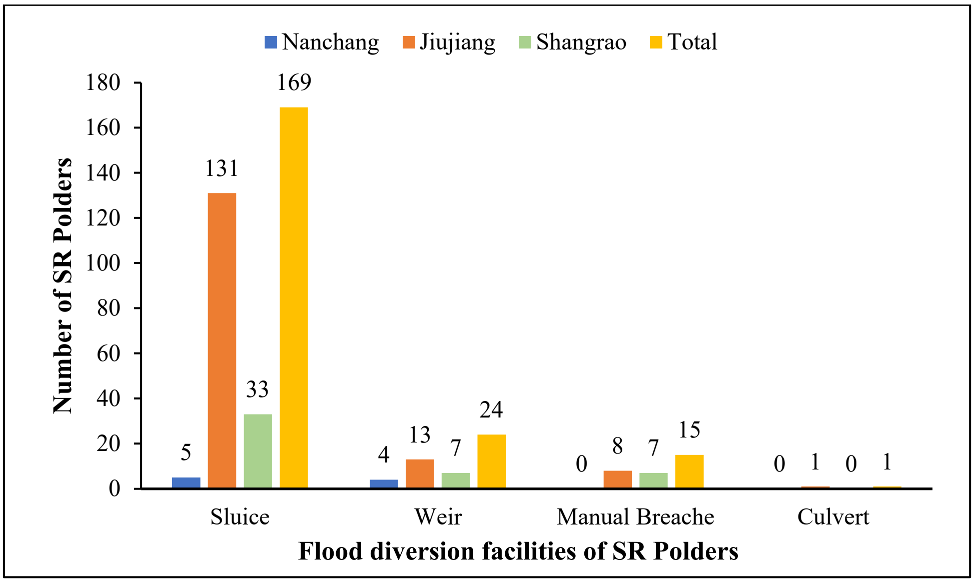

Figure 3. Statistics of flood diversion facilities of SR Polders in three cities.

2.2.2. Physical Model Testing of the Kangshan Flood Diversion Sluice

Situated on the southeastern shore of Poyang Lake and positioned downstream of the confluence of the southern branch of the Gan River, the Fu River, and the Xin River, the KS Detention functions as a vital flood detention area for Poyang Lake, with the responsibility of diversion 1.57 billion m^3 of floods from the Yangtze River [10].

On 10 May 2023, the construction project of KS Detention officially started. The designed flood diversion discharge of the sluice is 10,673 m^3/s, with a total of 28 gates, each having a clear width of 14 m. The sluice is operated when the water level of the Kangshan Station reaches 20.68 m. The physical model was designed and built according to the Froude's similarity, with a total area of about 551 m^2 and a geometric scale of 1:100. The model is shown in Figure 4. With the upstream water level maintained at 20.68 m, various experimental conditions were obtained by adjusting the downstream water level. The relationship between the downstream water level and the flood diversion discharge when all 28 gates are fully open is illustrated in Figure 5.

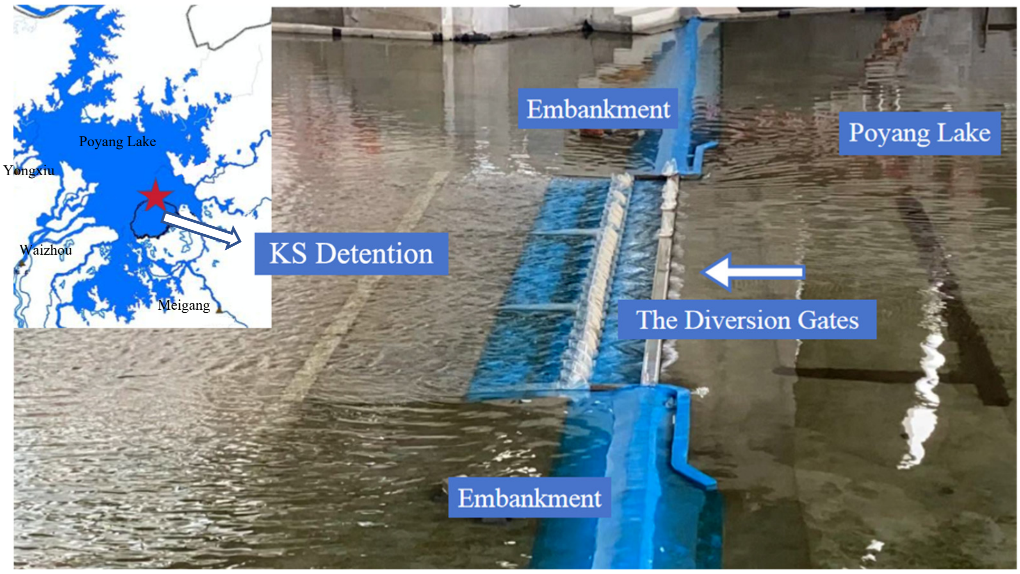

Figure 4. The physical model of flood diversion gates of KS Detention [10].

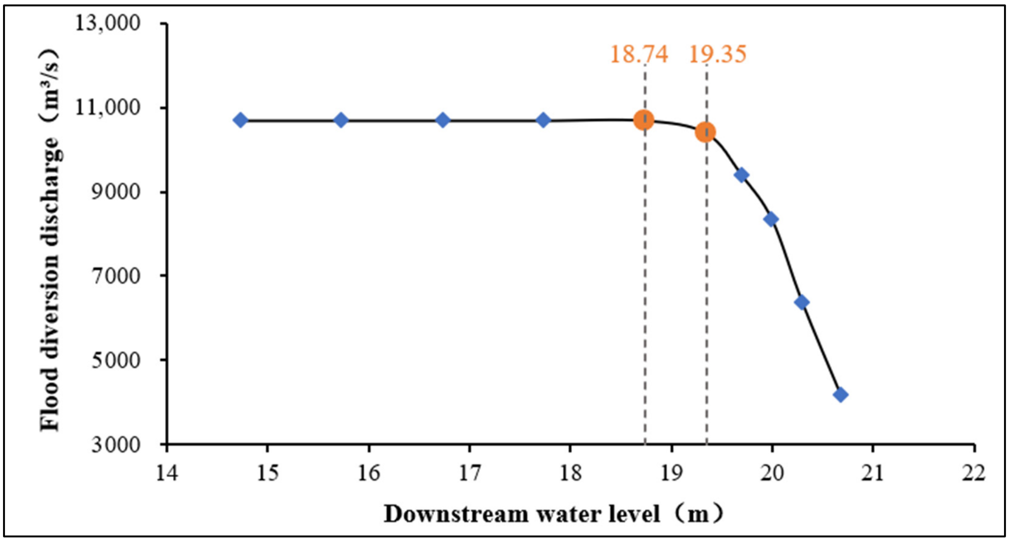

Figure 5. The model testing results about the downstream water level and the flood diversion discharge with the 28 gates fully opened, where orange points indicate test results under two notable conditions.

As depicted in Figure 5, the Kangshan flood diversion sluice achieves a peak discharge of 10,694 m^3/s with all 28 gates in full operation at an upstream water level of 20.68 m. This substantial diversion discharge remains constant when the downstream water level is maintained below 18.74 m, indicating characteristics typical of free flow. However, a significant shift is observed when the downstream water level exceeds 19.35 m. Specifically, the coefficient of discharge progressively decreases with the rising downstream water level, leading to a consistent decline in the diversion discharge. This decline marks a transition from free flow to submerged flow. Importantly, our findings suggest that the critical threshold for this transition in the downstream water level is approximately 18.74 m. This understanding is crucial for the comprehension of the flood diversion capacity of the KS Detention.

2.3. Research Method

2.3.1. Methods for Flood Diversion Simulation of SR Polders

To simulate and analyze the flood diversion process of SR Polders, this study optimizes the hydraulic model of SR Polders established in [10]. The optimization includes the flow calculation method for sluice and the selection of water level reference stations. The specific details of the model design and calculations are as follows.

Upon thorough investigation and rigorous analysis, it has been established that when the SR Polders use weirs for flood diversion, it can be classified as a broad-crested weir equipped with a sill, whereas the manual breach can be generalized as a broad-crested weir devoid of a sill. The flow calculation of sluice is based on the maximum opening. The flow calculation of open-type sluice can use the flow calculation formula of the weir, while the culvert-type sluice requires the formula of the weir or culvert. When the flow pattern is non-pressurized, it can be calculated according to the flow calculation formula of weir; when the flow pattern is pressurized or culvert outflow, the flow calculation formula of the culvert is used. The specific calculation formulas are as follows.

The flow calculation formula of weir, breach, open-type sluice, and culvert-type sluice without pressure that is used in the hydraulic model is as follows [25]:

$$Q = \sigma \varepsilon m n b \sqrt{2g} H_0^{3/2} \quad (1)$$

In the formula, σ represents the submergence coefficient; ε represents the side contraction coefficient; m represents the discharge coefficient, which is related to the type and height of the weir; n represents the number of gates; b represents the net width of each gate; H_0 represents the upstream water head including the approach velocity head, $H_0 = H + \alpha v^2/2g$; H represents the water head at the upstream end of the weir; α represents the kinetic energy correction coefficient; and v represents the approach velocity.

The flow calculation formula for while the flow pattern of sluice is pressurized or culvert outflow that is used in the model is as follows [26]:

$$Q = \mu w \sqrt{2g(H_0 + iL - h)} \quad (2)$$

In the formula, μ represents the discharge coefficient; w represents the cross-sectional area of the outlet; H_0 represents the sum of the elevation difference between the upstream water surface and the outlet of the culvert, as well as the approach velocity head; i represents the slope of the culvert; L represents the length of the culvert; and h represents the water depth in downstream.

The calculation process of flood diversion in the hydraulic model of SR Polders includes basic data input, condition judge, external data access, intermediate process, and result output. Firstly, the basic hydrological data and flood diversion facility data are input into the model. Then, the program judges the flood diversion conditions and flow patterns of each facility. The intermediate process includes dynamically adjusting various parameters in the flow calculation formula in real-time. At the same time, based on the water level-capacity curve of SR Polder, it determines whether the flood diversion has ended. Finally, the program statistically outputs the changes in the flood diversion discharge (Q) and cumulative flood diversion volume (V) of each facility. The specific calculation process of the model is shown in Figure 6.

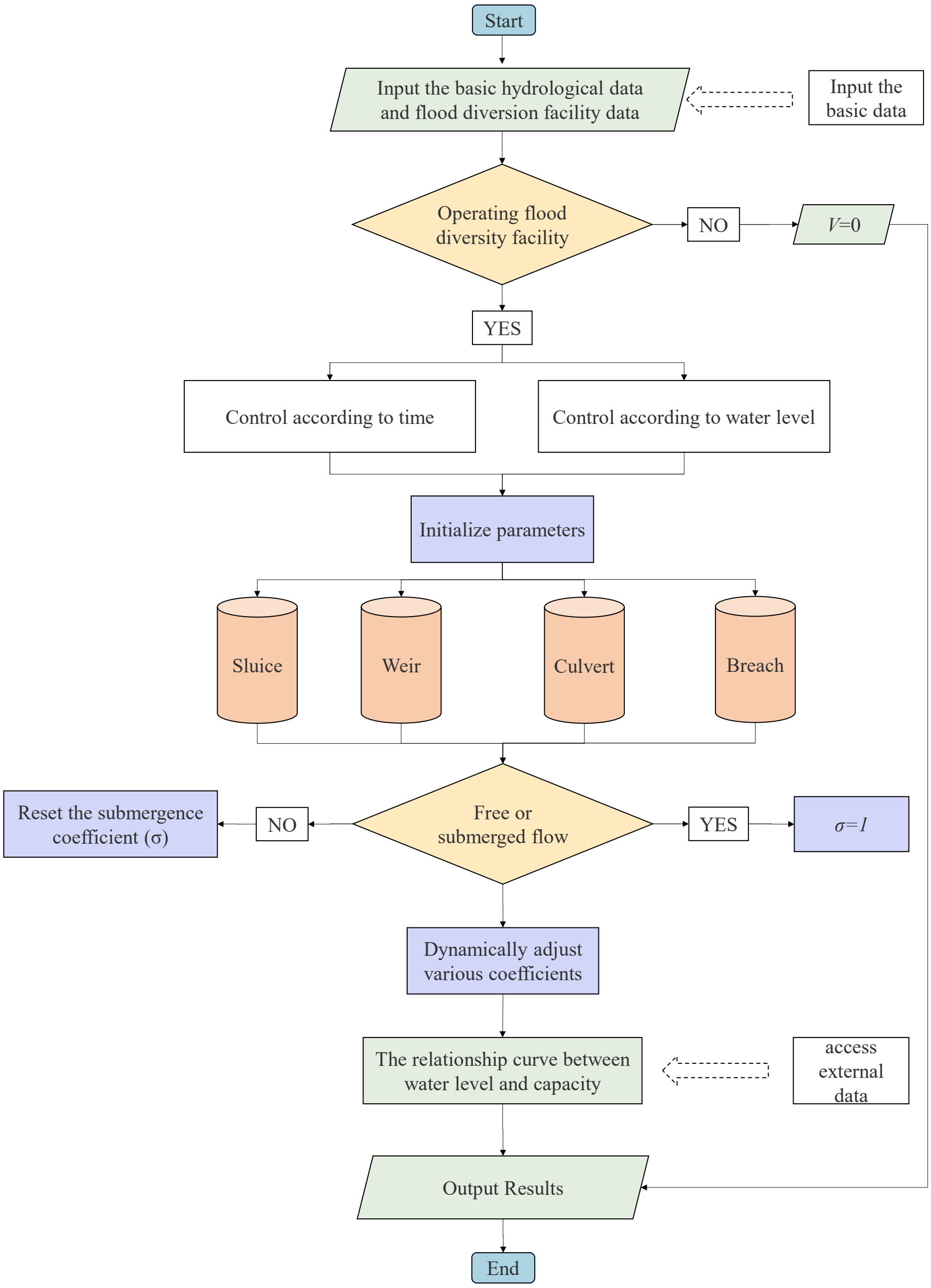

Figure 6. The flood diversion calculation process of hydraulic model for SR Polders.

The operation of each SR Polder is closely related to Hukou Station. Due to the different distances from Hukou Station, in actual use, the relevant Polders need to be operated accordingly when the adjacent stations (reference stations) reach the OWL. The water level stations selected in this model mainly include Hukou, Xingzi, Duchang, Tangyin, Poyang, Sanyang, Kangshan, and other stations. Among them, Hukou Station is the representative station, and the other water level stations are reference stations.

To verify the rationality of the model design and the accuracy of calculations, this study selected Nanbei Port Polder, Shuilanzhou Polder, Lianbei Polder, and Liannan Polder as typical examples. The data of flood diversion facilities corresponding to each Polder into the model was inputted, and the boundary conditions were set to the observed water levels of Hukou Station (Nanbei Port Polder), Sanyang Station (Shuilanzhou Polder), and Poyang Station (Lianbei Polder and Liannan Polder). The parameters such as the discharge coefficient and submergence coefficient are dynamically and automatically adjusted during the calculation process, and the comparison between the simulated results and the survey results is shown in Table 1.

Table 1. The comparison between the flood diversion survey results and simulation results of SR Polders in the 2020 flood.

Name	Type	Date of Operation		Flood Diversion Duration (h)	Cumulative Diversion Volume (10^8 m^3)	The Absolute Value of Relative Errors (%)	
		Gate, Weir	Breaches			Diversion Duration	Diversion Volume
Nanbei Port Polder	Survey results	9 July	-	216	1.78	1.85	1.12
	Simulated results	9 July	-	220	1.76		
Shuilanzhou Polder	Survey results	9 July	-	82	0.25	7.32	0
	Simulated results	9 July	-	76	0.25		
Lianbei Polder	Survey results	9 July	10 July, 12 July	60	2.92	3.33	0.34
	Simulated results	9 July	10 July, 12 July	58	2.91		
Liannan Polder	Survey results	10 July	11 July	60	0.96	3.33	1.04
	Simulated results	10 July	11 July	58	0.95		

According to the "Hydrological Information and Forecasting Specification (GB T 22482-2008)" [27], combined with Table 1, it can be seen that the accuracy of this flood diversion simulation meets the requirements. The selected Polder has a flood diversion duration and diversion volume relative error of less than 20% of the allowable error. The flood diversion process of the Polder is basically consistent with the actual situation. It can be considered that the design of the hydraulic model of SR Polders is reasonable, and the calculation is accurate.

2.3.2. Methods for Flood Diversion Simulation of KS Detention

A hydrodynamic model was constructed based on DHI MIKE software 2014 to carry out a flood diversion simulation of KS Detention. The model adopts unstructured grids, mainly quadrilateral grids supplemented by triangular grids. The study area of the hydrodynamic model is approximately 340.39 km^2, with the grid length ranging from 10 to 130 m. The model has a total of 50,794 grids, notably the grid near the sluice is densified. The hydrodynamic model of KS Detention is shown in Figure 7.

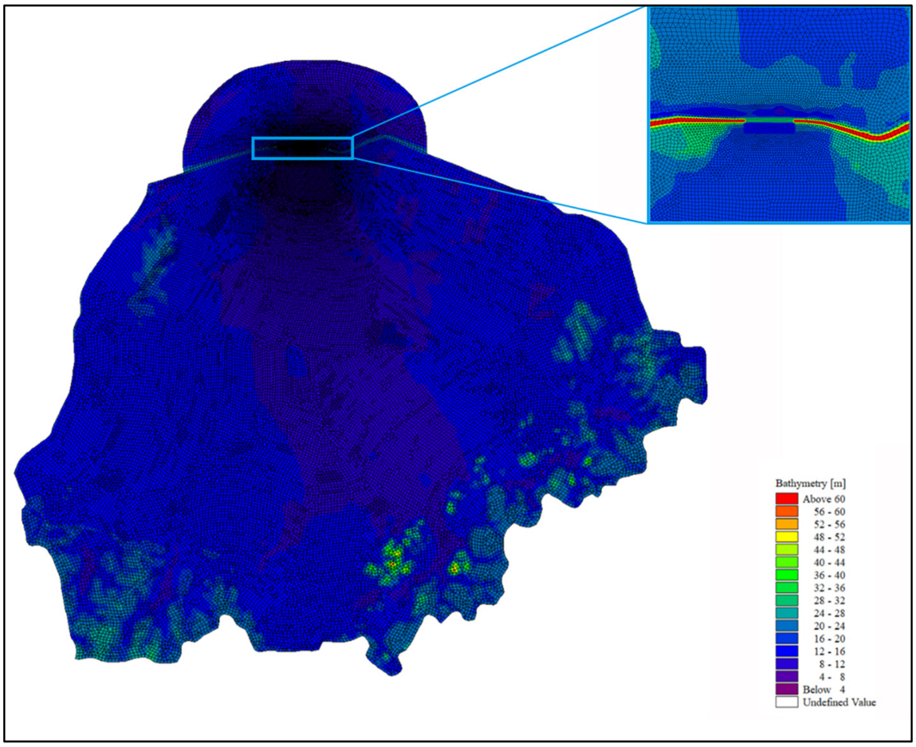

Figure 7. The hydrodynamic model of KS Detention [10].

Without considering the influence of factors, such as tide, wind force, temperature, etc., several typical conditions to verify the discharge capacity of the hydrodynamic model are the various downstream water levels of gates which are 14.74 m, 15.74 m, 16.74 m, 17.74 m, 18.74 m, 19.35 m, 19.7 m, 20.0 m, and 20.3 m. Consistent with the physical model testing, the upstream boundary of the hydrodynamic model is given as the water level which is 20.68 m. The downstream boundary condition of the model is Land (zero normal velocity) due to the Xinrui and Kangshan embankments. The verification results are shown in Figure 8, below.

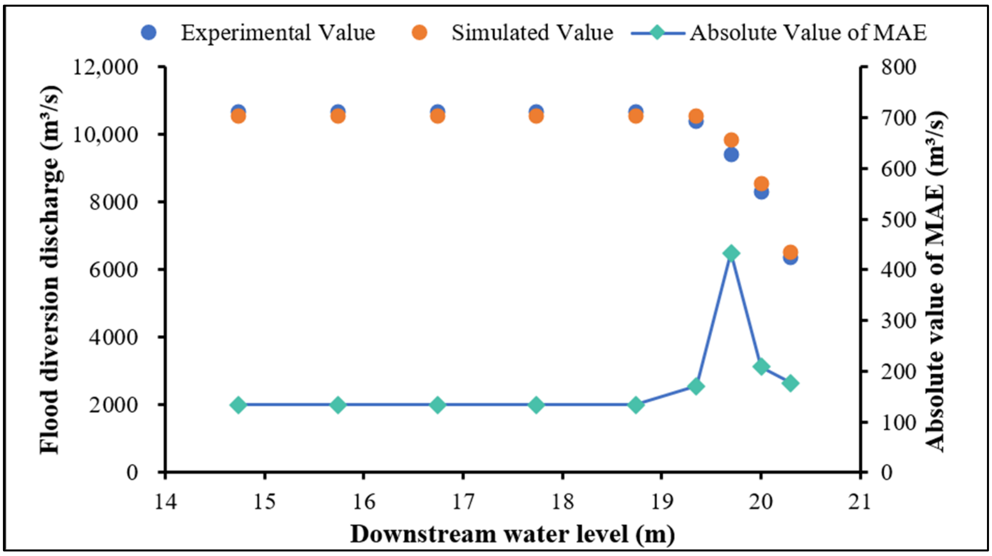

Figure 8. The experimental and simulated values of flood diversion discharge under different downstream water levels.

From Figure 8, it can be observed that the mean absolute error (MAE) of the flood diversion discharge under various conditions is 184.22 m^3/s, the root mean square error

(RMSE) is 205.68 m^3/s, the coefficient of determination (R^2) is 0.85, and the Nash–Sutcliffe efficiency coefficient (NSE) is 0.98. According to the "Hydrological Information and Forecasting Specification (GB/T 22482-2008)" [27], this model demonstrates certain feasibility and can accurately simulate the flood diversion of KS Detention.

2.3.3. Fuzzy Optimization Methods for Joint Flood Diversion Operation Schemes of Flood Diversion and Storage Measures

Flood control optimization scheduling poses a complex, multi-objective decision-making challenge. In the process of selecting and identifying the optimal scheme, there is no absolute distinction between its advantages and disadvantages. This process exhibits an intermediate transitional nature, embodying a fuzzy concept.

In this study, we applied the fuzzy optimization theory to develop a fuzzy optimization model for the joint operation schemes of SR Polders and KS Detention based on the methods and theories described in [28]. The process of solving the optimal scheme is as follows.

(1) Calculating the relative superiority degree matrix of quantitative targets

The quantitative objectives were selected as the reduction in maximum water level at the Xingzi station (WL Reduction, ΔH), the duration of exceeding KS Detention OWL (EL Duration, T) and the total flood diversion volume (FD Volume, V).

Assuming there are m flood control targets and n scheduling schemes, the relative superiority degree (RSD) of the *i-th* target (i = 1, 2, 3, . . ., m) and *j-th* scheme (j = 1, 2, 3, . . ., n) is denoted as r_{ij}. When calculating the RSD, it is necessary to first analyze whether the eigenvalue of quantitative target belongs to the "larger, better" type, "smaller, better" type, or "intermediate" type. Since the WL Reduction belongs to the "larger, better" quantitative target, the EL Duration belongs to the "smaller, better" quantitative target, and the FD Volume belongs to the "intermediate" quantitative target, Equations (3)–(5) are used to calculate their RSD.

$$r_{ij} = \frac{x_{ij} - \min\limits_{j} x_{ij}}{\max\limits_{j} x_{ij} - \min\limits_{j} x_{ij}}, \forall j \tag{3}$$

$$r_{ij} = \frac{\max\limits_{j} x_{ij} - x_{ij}}{\max\limits_{j} x_{ij} - \min\limits_{j} x_{ij}}, \forall j \tag{4}$$

$$r_{ij} = 1 - \frac{\left|x_{ij} - \overline{x_i}\right|}{\max\limits_{j} \left|x_{ij} - \overline{x_i}\right|}, \forall j \tag{5}$$

In the Equations, r_{ij} represents the RSD of target i in scheme j; $\max\limits_{j} x_{ij}$ denotes the maximum eigenvalue of target i in the scheme set; $\min\limits_{j} x_{ij}$ indicates the minimum eigenvalue of target i in the scheme set; and $\overline{x_i}$ signifies the intermediate optimal value of target i in the scheme set.

By calculating the RSD of each target under each scheme, the relative superiority degree matrix (RSDM, $\boldsymbol{R}$) for quantitative targets is obtained.

$$\boldsymbol{R} = \begin{bmatrix} r_{11} & r_{12} & \cdots & r_{1n} \\ r_{21} & r_{22} & \cdots & r_{2n} \\ \cdots & \cdots & & \cdots \\ r_{m1} & r_{m2} & \cdots & r_{mn} \end{bmatrix} = \left(r_{ij}\right) \tag{6}$$

(2) Determining the weights of quantitative targets

The determination of quantitative target weight typically involves a combination of subjective and objective methods. However, in practical applications, objective methods are often used to achieve satisfactory accuracy [17,18]. The process of objectively determining the target weight vector ($\boldsymbol{w}$) begins by ranking the importance of each target in descending order. Next, the fuzzy linguistic modifier (FLM) is determined according to importance, and then the relative membership degree (RMD) is calculated by the FLM. The RMD is normalized to obtain the weight for each target.

$$\boldsymbol{w} = \left(w_1 \quad , w_2 \quad , \cdots \quad , w_m\right) \tag{7}$$

In the Equation, w_m represents the weight of the *m-th* quantitative target.

(3) Solving the optimal relative membership degree matrix

The level of superiority or inferiority of the scheme is determined based on target eigenvalues, categorized into c levels ranging from superiority to inferiority. For any target, the standard value vector of RSD ($\boldsymbol{s}$) for each level from level 1 to level c is shown in Equation (8).

$$\boldsymbol{s} = \left(1, \quad \tfrac{c-2}{c-1}, \quad \tfrac{c-3}{c-1} \quad , \cdots \quad , 0\right) = (s_h) \tag{8}$$

In the Equation, h = 1, 2, 3, . . ., c.

After comparing the r_{1j}, r_{2j}, . . ., r_{mj} of the m targets in scheme j with the $\boldsymbol{s}$ shown in Equation (8) one by one, it is found that the RMD of the m targets in scheme j fall within the adjacent level intervals [a_{1j}, b_{1j}], . . ., [a_{mj}, b_{mj}]. Consequently, the upper limit b_j and lower limit a_j for scheme j are determined.

$$\begin{cases} a_j = \min\limits_i a_{ij} \\ b_j = \max\limits_i b_{ij} \end{cases} \tag{9}$$

In order to solve for the optimal relative membership degree (ORMD) of level h in scheme j (u_{hj}), the objective function is established as Equation (10), shown below. Meanwhile, since the sum of u_{hj} of each scheme is 1, the constraint is expressed by Equation (11), shown below.

$$\min\left\{F\left(u_{hj}\right) \quad = \sum_{h=a_j}^{b_j} u_{hj}^2 \left\{\sum_{i=1}^{m} \left[w_{ij}\left(r_{ij} - s_h\right)\right]^2\right\}\right\} \tag{10}$$

$$\sum_{h=1}^{c} u_{hj} = 1, \forall_j \tag{11}$$

The Lagrange function $L\left(u_{hj}, \lambda_j\right)$ is constructed according to Equation (10) and Equation (11), as shown in Equation (12), where λ_j is the Lagrange multiplier. When Equation (12) takes a partial derivative of 0 for u_{hj} and λ_j, the u_{hj} can be solved, as shown in Equation (13).

$$L\left(u_{hj}, \lambda_j\right) = \sum_{h=a_j}^{b_j} u_{hj}^2 d_{hj}^2 - \lambda_j \left(\sum_{h=a_j}^{b_j} u_{hj} - 1\right) \tag{12}$$

$$u_{hj} = \begin{cases} 0; h < a_j \text{ or } h > b_j \\ \dfrac{1}{\sum_{k=a_j}^{b_j} \dfrac{\sum_{i=1}^{m}\left[w_i\left(r_{ij} - s_h\right)\right]^2}{\sum_{i=1}^{m}\left[w_i\left(r_{ij} - s_k\right)\right]^2}}; a_j \leq h \leq b_j, d_{hj} \neq 0 \\ 1; d_{hj} = 0 \end{cases} \tag{13}$$

In the Equations, $d_{hj} = \left\{ \sum_{i=1}^{m} \left[w_i \left(r_{ij} - s_h \right) \right]^2 \right\}^{\frac{1}{2}}$.

After calculating the u_{hj}, the optimal relative membership degree matrix (ORMDM, $\boldsymbol{U}$) can be established.

$$\boldsymbol{U} = \begin{bmatrix} u_{11} & u_{12} & \cdots & u_{1n} \\ u_{21} & u_{22} & \cdots & u_{2n} \\ \cdots & \cdots & & \cdots \\ u_{c1} & u_{c2} & \cdots & u_{cn} \end{bmatrix} = \left(u_{hj} \right) \tag{14}$$

In the Equation, h = 1, 2, 3, . . ., c; j = 1, 2, 3, . . ., n.

(4) Selecting the optimal flood control operation scheme.

The vector expression of the level eigenvalue ($\boldsymbol{H}$) is as follows:

$$\boldsymbol{H} = \begin{pmatrix} 1 & ,2 & ,\cdots & ,c \end{pmatrix} \left(u_{hj} \right) = \begin{pmatrix} H_1 & ,H_2 & ,\cdots & ,H_n \end{pmatrix} \tag{15}$$

Equation (15) can be used to optimize the scheme set, wherein the scheme corresponding to the smallest level eigenvalue $\left(H_{min} \right)$ represents the optimal scheme.

2.3.4. Design of Flood Control Schemes and Calculation of Target Eigenvalues

(1) Design of Flood Control Schemes

This study selected the 1998 flood from previous years of major floods, with the highest water level and relatively complete hydrological data at Hukou Station, as a typical case to carry out research on optimal operation of FDSM in Poyang Lake. The OWL of SR Polders-I and SR Polders-II as well as the KS Detention were changed. At the same time, the operation time of the KS Detention was limited to 48 h, and three schemes for the operation of Polders were set, denoted A, B, and C. There are three schemes for KS Detention, denoted I, II, and III, as shown in Tables 2 and 3 below. After cross-combination, a total of 9 joint flood diversion schemes were obtained, as shown in Table 4 below.

Table 2. Flood diversion operation schemes of SR Polders.

Scheme Name	Hukou Water Level of Operating SR Polders/m	
	SR Polders-I	SR Polders-II
A	20.50	21.68
B	21.50	21.68
C	21.65	22.05

Table 3. Flood diversion operation schemes of KS Detention.

Scheme Name	Hukou Water Level of Operating KS Detention/m
I	22.50
II	21.68
III	20.50

Table 4. Joint flood diversion operation schemes of SR Polders and KS Detention.

Scheme Name	Hukou Water Level of Operating SR Polders/m		Hukou Water Level of Operating KS Detention/m
	SR Polders-I	SR Polders-II	
1	20.50	21.68	22.50
2	20.50	21.68	21.68
3	20.50	21.68	20.50
4	21.50	21.68	22.50
5	21.50	21.68	21.68
6	21.50	21.68	20.50
7	21.65	22.05	22.50
8	21.65	22.05	21.68
9	21.65	22.05	20.50

(2) Calculation of Target Eigenvalues

The quantitative target eigenvalues are solved utilizing the hydraulic model developed for SR Polders in Section 2.3.1 alongside the hydrodynamic models built for the KS Detention in Section 2.3.2. These calculations adhere to the schemes outlined in Tables 2 and 3, simulating the flood diversion processes. The cumulative flood diversion volume changes are denoted V_1—T for the Polder and V_2—T for the Detention. Subsequently, with a time interval ΔT set at one hour, the incremental volumes ΔV_1 and ΔV_2 from the same period are summed to derive the cumulative flood diversion changes (V_3—T), representing the joint operation of the Polders and Detention. Ultimately, adopting the water level-capacity relationship of Poyang Lake and the observed water level data (Z_1—T) at Xingzi Station, the water level changes (Z_2—T) at Xingzi Station, before the joint operation of the Polders and Detention, are meticulously calculated.

(a) WL Reduction (ΔH)

$$\Delta H = Z_{2max}|_{T=T_0} - Z_1|_{T=T_0} \quad (16)$$

In the Equation, $Z_{2max}|_{T=T_0}$ represents the maximum water level of Xingzi Station before the implementation of the Polders and Detention at time T = T_0; and $Z_1|_{T=T_0}$ represents the observed water level of Xingzi Station at time T = T_0.

(b) EL Duration (T)

The operation of the KS Detention corresponds to a water level of 22.50 m at Hukou Station. According to the correlation between the water level at Hukou Station and Xingzi Station, it can be inferred that the water level at Xingzi Station corresponds to 22.57 m at a water level of 22.50 m at Hukou Station [29]. Assuming that the water level before the implementation of the Polders and Detention at Xingzi Station is greater than 22.57 m from time T_1 to time T_2, then:

$$T = T_2 - T_1 \quad (17)$$

(c) FD Volume (V)

The FD Volume is the sum of the cumulative flood diversion volume of SR Polder and KS Detention, that is:

$$V = V_{1sum} + V_{2sum} \quad (18)$$

3. Results

3.1. Flood Diversion Simulation of Flood Diversion and Storage Measures Under Different Schemes

3.1.1. Analysis of SR Polders Flood Diversion Simulation

Based on the hydraulic model of SR Polders established in Section 2.3.1, 185 Polders were placed in the model using the observed water levels at various stations in 1998 as boundary conditions. The diversion conditions of each polder facility in the model are set to be controlled according to the water level, and the water level is determined based on the OWL in each scheme shown in Table 2 and the correlation between the water level of the reference station and the representative station. The results of changes in the flood diversion discharge (Q_1—T) and cumulative flood diversion volume (V_1—T) of schemes A, B, and C from July 19th to August 8th are shown in Figures 9 and 10, respectively.

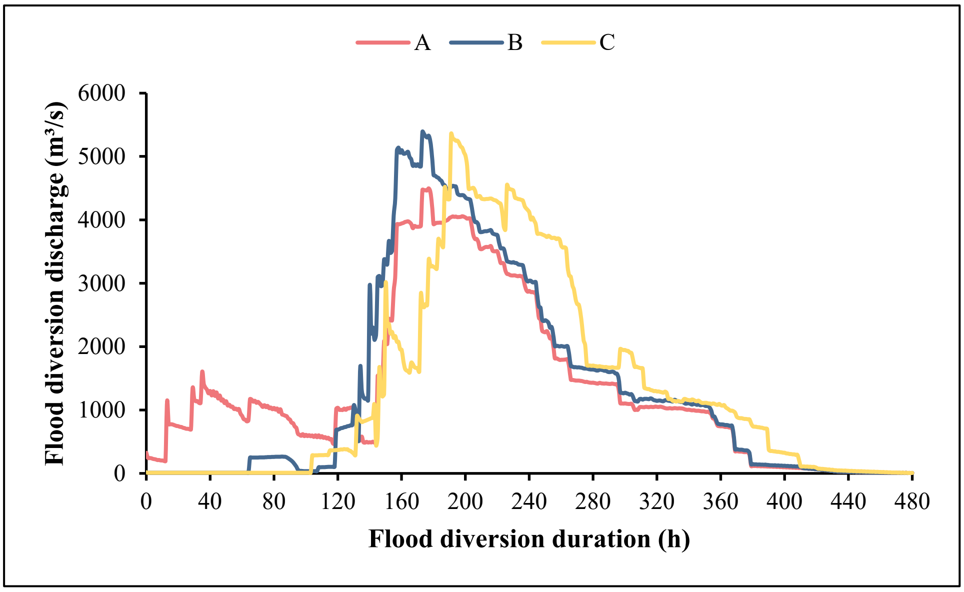

Figure 9. The changes in flood diversion discharge of SR Polders in different schemes.

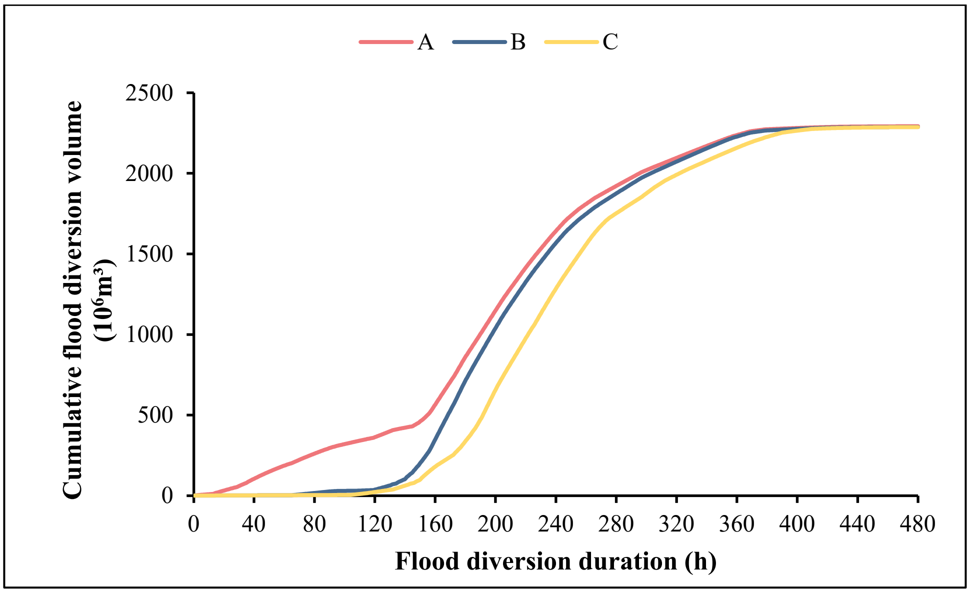

Figure 10. The changes in cumulative flood diversion volume of SR Polders in different schemes.

Analysis of Figures 9 and 10 reveals that:

(1) The rise in the OWL of the SR Polders has caused some Polders to fail to meet the flood diversion conditions during the flood diversion period, resulting in a decrease in the total flood volume. The total duration of the 1998 flood in the Poyang Lake area was 480 h (20 days), and the maximum diversion discharge for schemes A, B, and C were 4498 m^3/s, 5392 m^3/s, and 5358 m^3/s, respectively. The total flood diversion volume was 2292.55 million m^3, 2287.76 million m^3, and 2287.13 million m^3, respectively.

(2) Raising the OWL of SR Polders-I has led to an increase in the maximum flood diversion discharge, but the main flood diversion period remains basically unchanged. Compared with scheme B, scheme A has increased the OWL of SR Polders-I by 1.0 m, while the OWL of SR Polders-II remains unchanged. The maximum diversion discharge of scheme B exceeds that of scheme A by 894 m^3/s. Meanwhile, the main flood diversion periods for both are from 26 July to 29 July, during which the diversion volume accounts for 46.19% and 47.26% of the total flood volume, respectively. Raise the OWL of SR Polders-II, and the maximum flood diversion discharge remains basically unchanged, but the main flood diversion period is relatively lagging. Compared with scheme C, the OWL of SR Polders-I remains basically unchanged, with a difference of 0.15 m, while the OWL of SR Polders-II increases by 0.37 m. However, the maximum diversion discharge of the two only differs by 34 m^3/s. At the same time, the main diversion period is from 27 July to 30 July, during which the diversion volume accounts for 48.53% of the total diversion volume.

3.1.2. Analysis of KS Detention Flood Diversion Simulation

According to the operation conditions of schemes I, II, and III, the observed water levels at Kangshan Station from 14:00 on 29 July to 14:00 on 31 July, 1:00 on 25 July to 1:00 on 27 July, and 0:00 on 19 July to 0:00 on 21 July were selected as the boundary conditions for the hydrodynamic model. Based on the model of the KS Detention established in Section 2.3.2, the flood diversion of three schemes was simulated, and the changes in flood diversion discharge (Q_2-T) and cumulative flood diversion volume (V_2-T) of schemes I, II, and III were obtained. The results are shown in Figures 11 and 12.

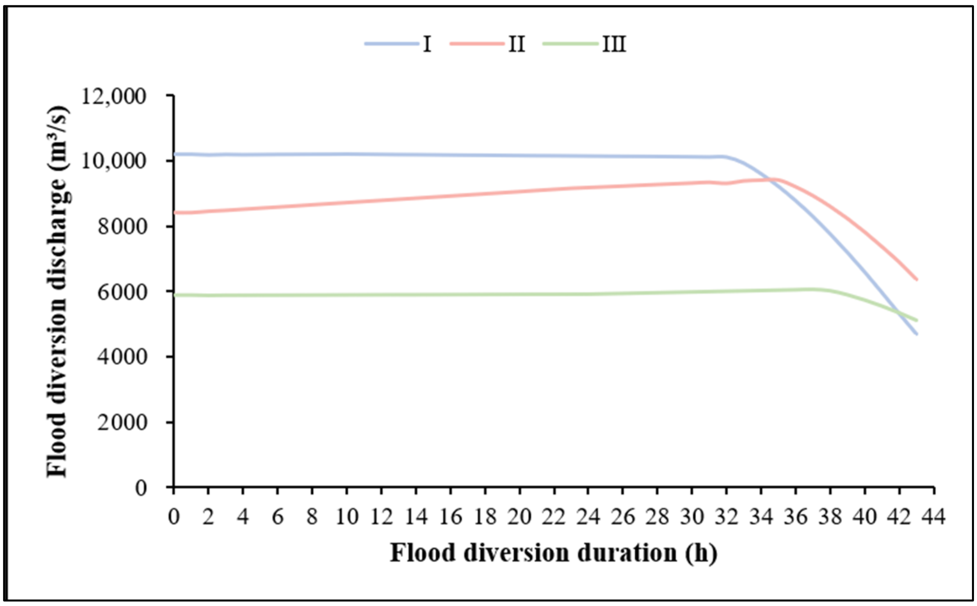

Figure 11. The changes in flood diversion discharge of KS Detention in different schemes.

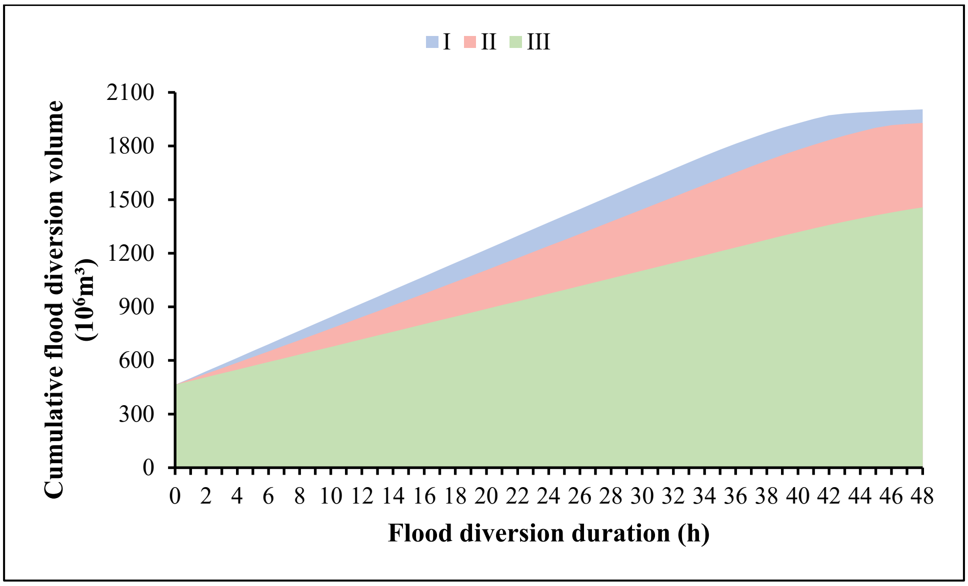

Figure 12. The changes in cumulative flood diversion volume of KS Detention in different schemes.

Analysis of Figures 11 and 12 shows that:

(1) In the early stage of flood diversion, due to the small change in water level at Kangshan Station during the diversion periods of scheme I and scheme III, with a variation of less than 0.04 m, the flood diversion discharge remained basically unchanged. During the flood diversion period of scheme II, the water level at Kangshan Station rose from 19.74 m to 20.19 m, an increase of 0.45 m, and its flood diversion discharge showed a gradual upward trend. In the later stage of flood diversion, due to the rise in downstream water level, the flow pattern gradually varies from free flow to submerged flow under the three schemes, and its discharge capacity gradually decreases.

(2) Higher flood diversion levels correspond to greater discharge capacities. Comparing schemes I, II, and III, when the flood diversion levels are 20.52 m, 20.19 m, and 18.64 m, the corresponding diversion discharges are 10,193 m^3/s, 9411 m^3/s, and 6062 m^3/s, respectively. In the early stage of flood diversion, the duration of flood diversion under each scheme is approximately linearly increasing with the cumulative flood diversion volume, and the higher the flood diversion water level, the more flood diversion volume will be in the same period; In the later stage of flood diversion, as the downstream water level gradually rises, the upward trend of flood volume gradually slows down. After about 43 h of flood diversion in scheme I, the flood storage capacity of the KS Detention approaches its limit which is to store 2.07 billion m^3 of floods.

3.2. Fuzzy Optimization for Joint Flood Diversion Operation Scheme of Flood Diversion and Storage Measures

3.2.1. Calculation of the RSDM of Quantitative Targets

According to Table 4, the simulated results in Section 3.1, and the method described in Section 2.3.4 was used to obtain the water level of Xingzi Station before the implementation of the Polders and Detention for different schemes, as shown in Figure 13. The eigenvalues of quantitative targets for different schemes are shown in Table 5.

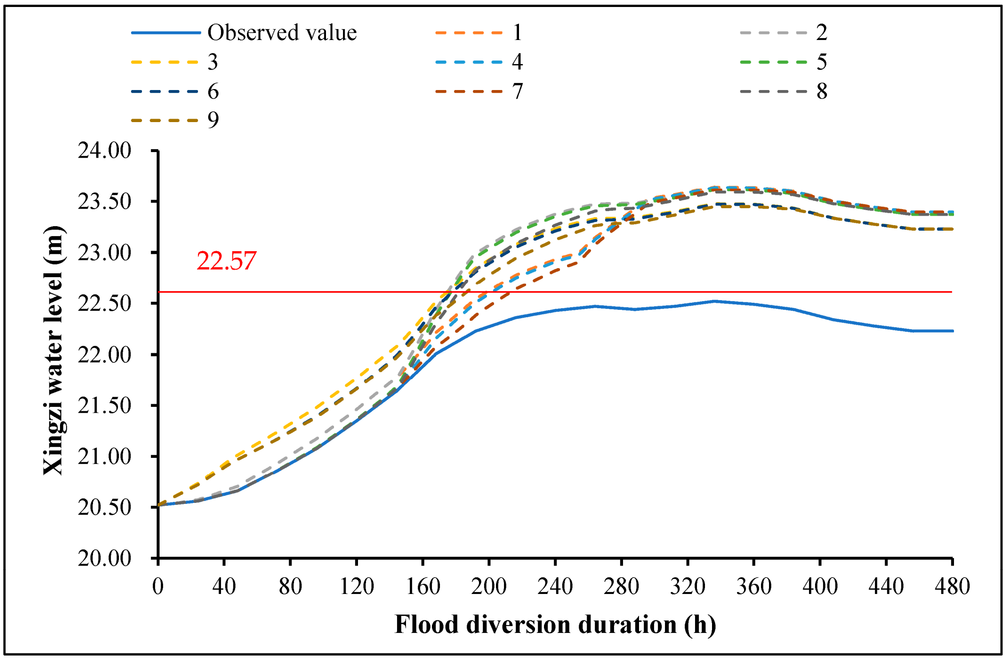

Figure 13. The water level of Xingzi Station before the implementation of the SR Polders and KS Detention for different schemes.

Table 5. The eigenvalues of quantitative targets for different schemes.

Scheme Name	WL Reduction (m)	EL Duration (h)	FD Volume (10^4 m³)
1	1.128	285	393,367
2	1.105	306	375,755
3	0.963	308	328,546
4	1.134	282	382,888
5	1.110	304	375,276
6	0.971	304	328,067
7	1.118	270	382,825
8	1.094	300	375,213
9	0.956	296	328,004

By analyzing and comparing the results of each scheme in Figure 13 and Table 5, it can be concluded that:

(1) Raising the OWL of SR Polders, due to the observed water level outside the Polder being lower than OWL, some Polders have not been used, resulting in a smaller FD Volume. The total flood volume of scheme 1 exceeds that of scheme 4 and scheme 7 by 10,479 and 105.42 million m^3, respectively. Compared with scheme 4, scheme 7 has a similar total flood volume, with a reduction of 630,000 m^3. After comparative analysis, the main reason is the insufficient flood diversion of Lixin Polder and Longtan Polder belonging to SR Polders-II and Zhangshan Polder belonging to SR Polders-I.

(2) Raising the OWL of SR Polders will reduce EL Duration. Among them, scheme 4 and scheme 7 reduced the time by 3 h and 15 h, respectively, compared to scheme 1; scheme 5 and scheme 8 reduced the time by 2 h and 6 h, respectively, compared to scheme 2; and scheme 6 and scheme 9 reduced the time by 4 h and 12 h, respectively, compared to scheme 3.

(3) When the OWL of the KS Detention is the same, the WL reduction in different schemes are relatively close, and scheme 4 has the best flood diversion effect. Comparing the different schemes, such as scheme 1 and scheme 4 or scheme 2 and scheme 5, it can be seen that the OWL of SR Polders-I is relatively low.

According to the results in Table 5, convert it into a quantitative target eigenvalue matrix ($\boldsymbol{X}$) as follows:

$$\boldsymbol{X} = \begin{bmatrix} 1.128 & 1.105 & 0.963 & 1.134 & 1.110 & 0.971 & 1.118 & 1.094 & 0.956 \\ 285 & 306 & 308 & 282 & 304 & 304 & 270 & 300 & 296 \\ 393,367 & 375,755 & 328,546 & 382,888 & 375,276 & 328,067 & 382,825 & 375,213 & 328,004 \end{bmatrix}$$

Convert the quantitative target eigenvalue matrix ($\boldsymbol{X}$) into the RSDM ($\boldsymbol{R}$) as follows:

$$\boldsymbol{R} = \begin{bmatrix} 0.966 & 0.837 & 0.039 & 1.000 & 0.865 & 0.084 & 0.910 & 0.775 & 0.000 \\ 0.605 & 0.053 & 0.000 & 0.684 & 0.105 & 0.105 & 1.000 & 0.211 & 0.316 \\ 0.150 & 0.648 & 0.015 & 0.446 & 0.662 & 0.002 & 0.448 & 0.664 & 0.000 \end{bmatrix}$$

3.2.2. Determination of the Weight of Quantitative Targets

Qualitative analysis has led to the ranking of the importance of each quantitative target in descending order: WL Reduction, EL Duration, and FD Volume. After the calculation by adopting the method in Section 2.3.3, the final weight of each target is shown in Table 6.

Table 6. The final weight of each quantitative target.

Quantitative Target	RMD	Final Weight
WL Reduction	1	0.402
EL Duration	0.818	0.329
FD Volume	0.667	0.269

3.2.3. Solution of the ORMDM

To improve the accuracy of the optimal selection decision, the membership degree is set to level 5, that is, c = 5. Therefore, according to Equation (8), the standard value vector of the RSD ($\boldsymbol{s}$) is:

$$\boldsymbol{s} = \begin{pmatrix} 1, & 0.75, & 0.50, & 0.25, & 0 \end{pmatrix}$$

According to $\boldsymbol{R}$, $\boldsymbol{s}$, and Equation (9), the values of a_j and b_j for each scheme can be obtained. Meanwhile, by using Table 6 and applying Equation (13), the u_{hj} is obtained, and finally transformed into the $\boldsymbol{U}$ as shown below:

$$\boldsymbol{U} = \begin{bmatrix} 0.181 & 0.125 & 0 & 0.253 & 0.135 & 0 & 0.341 & 0.108 & 0 \\ 0.349 & 0.253 & 0 & 0.485 & 0.277 & 0 & 0.454 & 0.280 & 0 \\ 0.277 & 0.332 & 0 & 0.189 & 0.328 & 0 & 0.146 & 0.387 & 0.092 \\ 0.129 & 0.194 & 0.015 & 0.073 & 0.175 & 0.174 & 0.059 & 0.158 & 0.379 \\ 0.064 & 0.096 & 0.985 & 0 & 0.085 & 0.826 & 0 & 0.067 & 0.529 \end{bmatrix}$$

3.2.4. Optimal Selection of Flood Control Schemes

Apply Equation (15) to solve the $\boldsymbol{H}$, and the result is as follows:

$$\begin{aligned} \boldsymbol{H} &= \begin{pmatrix} 1, 2, 3, 4, 5 \end{pmatrix} \begin{pmatrix} u_{hj} \end{pmatrix} \\ &= \begin{pmatrix} 2.549, 2.882, 4.985, 2.082, 2.799, 4.826, 1.924, 2.797, 4.438 \end{pmatrix} \end{aligned}$$

According to Table 7, comparing the H_j under different schemes, it can be concluded that:

Table 7. The H_j and optimal sequence of each scheme.

Scheme Name	1	2	3	4	5	6	7	8	9
H_j	2.459	2.882	4.985	2.082	2.799	4.826	1.924	2.797	4.438
Optimal sequence	3	6	9	2	5	8	1	4	7

(1) The higher the OWL of KS detention, the better the scheme. Comparing schemes 1, 2, and 3, it can be seen that the OWL of the KS detention is scheme 1 > scheme 2 > scheme 3. The superiority of schemes is scheme 1 > scheme 2 > scheme 3.
(2) The higher the OWL of SR Polders-I, the better the scheme. Comparing scheme 1 and scheme 4, it can be seen that the OWL of SR Polders-I is scheme 4 > scheme 1, and the superiority of schemes is scheme 4 > scheme 1.
(3) When the OWL of KS detention exceeds 21.68 m, raising the OWL of SR Polders-II has a limited effect on optimizing the scheme. The H_j of scheme 8 is only 0.002 smaller than scheme 5. When the OWL is below 21.68 m, increasing the OWL significantly enhances the superiority of the scheme. Comparing scheme 6 with scheme 9, it can be seen that the H_j of scheme 9 is 0.388 smaller than that of scheme 6.
(4) According to the principle of the $H_{\min}$, representing the optimal scheme, the optimal joint flood diversion strategy for Poyang Lake involves operating SR Polders-I at a Hukou water level of 21.65 m, operating SR Polders-I at a Hukou water level of 22.05 m, and operating the KS Detention at a Hukou water level of 22.50 m.

4. Discussion

(1) A comprehensive approach to flood control through the strategic deployment of FDSM, coupled with the meticulous timing of flood diversion, is imperative to safeguard the flood control security of lakeside areas. The current water levels for operating the SR Polders in Poyang Lake are deemed lower. Building upon the work of Fu Chun [17] and Wen Tianfu [18], who employed fuzzy optimization theory to identify the optimal operation strategy for SR Polders, a consensus emerges that an appropriate raising of the OWL for Polders is justified. Our research corroborates this finding. As delineated in Table 7, a comparative analysis of schemes 1, 4, and 7 reveals that, under identical conditions, an appropriate raising of the OWL for SR Polders-I correlates positively with the superiority of the scheme. Notably, basing our investigation into the optimized flood control operation of SR Polders, we conducted a nuanced analysis of the OWL for joint flood diversion involving SR Polders and the KS Detention. The results underscore a direct correlation; as the OWL for the KS Detention incrementally decreases across schemes 1, 2, and 3, the superiority of the respective schemes progressively diminishes, highlighting a positive correlation between the OWL of the KS Detention and the superiority of schemes.
(2) As an integral component of flood control engineering systems, FDSM such as SR Polders and FS Detentions play a vital role in alleviating the flood control pressures on rivers and lakes, as well as safeguarding people's lives and property. It is of paramount importance to enhance the construction of flood control engineering systems and implement effective management and operational mechanisms. Since Jiangxi Province initiated the embankment area project of "leveling embankments for flood diversion and returning farmland to lakes" in 2003, many flood diversion facilities have, over the years of operation, suffered from aging, disrepair, or partial damage. The absence of a routine operation and management mechanism for Polders has prevented timely maintenance, leading to a diminished actual flood diversion

capacity. In recent years, to effectively bolster the overall flood control capabilities of lakeside areas, Jiangxi Province issued the "Overall Plan for the Safety of Poyang Lake and the Well-being of Its People" in 2021, which mandates the coordinated implementation of embankment reinforcement to eliminate hazards and upgrade quality, strengthening the capacity for flood diversion and storage, and forming a scientific and rational spatial layout of flood storage and detention areas to achieve modernization in water governance systems and capabilities. In May 2023, the Jiangxi Provincial Water Resources Department progressively advanced construction projects and the reinforcement and improvement of flood inlet facilities for the Kangshan, Zhuhu, Huanghu, and Fangzhouxietang FS Detentions. The research findings presented in this paper provide technical methodologies and support for the optimization and scheduling of joint flood diversion operations across multiple FDSM, offering promising application prospects.

(3) Poyang Lake in China is a large plain lake, and there are many lakes in the world that also belong to this type, such as Amazon floodplain lakes [30], Tonle Sap Lake in Southeast Asia [31], and Winnipeg Lake in North America [32]. Due to their unique geographical features, these lakes are unable to construct water conservancy hubs to effectively regulate floods, resulting in relatively limited flood control measures. Therefore, the construction of flood diversion and storage areas, including polders and flood storage and detention areas, has become an important measure to make up for this deficiency. The research on flood diversion of polders and flood storage and detention areas conducted in this paper not only has important guiding significance for flood control management of lakes with similar characteristics, but also provides useful references for the joint operation of flood diversion and storage areas in other regions around the world.

(4) The limitations of this paper and potential research directions in the future are as follows. (a) This study investigated the joint operation of flood diversion with the KS Detention at operation water levels of 22.50 m, 21.68 m, and 20.50 m, alongside SR Polders, through the establishment of nine distinct schemes. Schemes involving water levels higher than 22.50 m were not considered. (b) With the gradual escalation of environmental protection awareness, it has become imperative to incorporate ecological benefits as a flood control target in the optimization of flood management. (c) Based on the constructed hydraulic model for SR Polders and hydrodynamic model for KS Detention, an innovative joint flood diversion simulation system for the SR Polders and FS Detentions of Poyang Lake, integrating big data analysis and artificial intelligence technology, is expected to be developed. The system will utilize the hydrological variables provided by the flood forecasting system as the model boundary conditions and formulate multiple schemes to simulate the actual application of flood diversion measures. Subsequently, through the powerful analytical capabilities of artificial intelligence technology, the simulation results of each scheme will be deeply mined and compared using big data, providing solid data support and intelligent assistance for scientific decision-making and optimization scheduling.

5. Conclusions

Addressing the issue of optimal strategies for joint flood diversion of FDSM, this study focuses on the SR Polders and the KS Detention of Poyang Lake. A hydraulic model for the SR Polders and a hydrodynamic model for the KS Detention were established to carry out flood simulation. Using the 1998 flood as a typical case, flood diversion simulations of it were conducted under various operational schemes. Furthermore, based on fuzzy optimization theory, the joint flood diversion operational schemes for the SR Polders and the KS Detention were optimized. Lastly, the timing of flood diversion for the FDSM, as well as management and operational issues, were discussed alongside the limitations of this study. The primary conclusions are as follows:

(1) Altering the operation criteria for FDSM influences both the maximum diversion discharge and the timing of the main diversion period. For the SR Polders, under the current flood control scheme, raising the OWL of SR Polders-I by 1.0 m increases the maximum diversion discharge by 894 m^3/s, but the main flood diversion period remains basically unchanged, from 26 July to 29 July. Additionally, raising the OWL of SR Polders-II by 0.37 m delays the main diversion period by one day, shifting it from 27 July to 30 July, but the maximum diversion discharge remains basically unchanged. For the KS Detention, higher flood diversion levels correspond to greater discharge capacities. Specifically, when the flood diversion levels are 20.52 m, 20.19 m, and 18.64 m, the corresponding diversion discharges are 10,193 m^3/s, 9411 m^3/s, and 6062 m^3/s, respectively.
(2) Establishing scientifically reasonable operation criteria is a crucial aspect of optimal flood control operation for FDSM. A set of operation criteria that not only meet the requirements of flood control safety but also take into account economic and social development is of great significance for maximizing the benefits of flood control and disaster reduction. Building on the prior research on SR Polders conducted by other scholars, this study further analyzed using fuzzy optimization theory and determined that the optimal joint flood diversion operational scheme for the SR Polders and the KS Detention of Poyang Lake is as follows: operating SR Polders-I at a Hukou water level of 21.65 m, operating SR Polders-II at a Hukou water level of 22.05 m, and operating the KS Detention at a Hukou water level of 22.50 m.
(3) Strengthening the construction of flood control engineering systems and implementing efficient management and operational mechanisms are essential steps. Typical FDSM, such as Polders and FS Detentions, play a crucial role in alleviating the flood control pressure on rivers and lakes and protecting people's lives and property. Through scientific planning and coordinated arrangement of FDSM to regulate and store floods, supplemented by rigorous monitoring, early warning, and emergency scheduling mechanisms, the overall effectiveness of the flood control system can be significantly enhanced. This ensures rapid response and effective management in the face of flood challenges, minimizing disaster losses to the greatest extent possible.

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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.

Abbreviations

The following abbreviations are used in this manuscript:

FDSM	Flood diversion and storage measures
SR Polders	Semi-restoration polder areas
SR Polders-I	SR Polders with less than 6.67 km^2 of crop cultivation
SR Polders-II	SR Polders with more than 6.67 km^2 of crop cultivation
FS Detentions	Flood storage and detention areas
KS Detention	Kangshan flood storage and detention area
OWL	Operation water level
WWL	Warning water level
WL Reduction	Reduction in maximum water level at the Xingzi Station
EL Duration	Duration of exceeding KS Detention OWL
FD Volume	Total flood diversion volume
RSD	Relative superiority degree
RSDM	Relative superiority degree matrix
RMD	Relative membership degree
ORMD	Optimal relative membership degree
ORMDM	Optimal relative membership degree matrix

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