Flood Control in the Song-Li Region Based on a 1D-2D Coupled Hydrodynamic Model

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Abstract. The Song-Li region is located in the region where the downstream of the Lishui River converges with the Songzi River, the diversion channel for floodwaters from the Yangtze River to Dongting Lake. It is one of the areas most severely affected by flood disasters in the Dongting Lake region. Since the completion of the Three Gorges and its upstream basin reservoirs, its flood situation has changed with the evolving river-lake relationships. Constructing a 1D-2D coupled hydrodynamic model of the Yichang - Hankou area (including Dongting Lake and the downstream of Sishui River), we analyzed the flood levels and excess flood volumes in the Song-Li region under different typical flood conditions after the construction of flood control reservoirs in the Three Gorges and upstream basin. Besides, the existing flood control engineering system in the Song-Li region was also evaluated under current river-lake relationships and channel conditions. The results show that the existing flood control engineering system and reservoir operation have greatly improved the flood control situation in the Song-Li region. However, they have not fundamentally improved the tense flood control situation. The results of the study can also provide a reference for flood control and management in the Song-Li region.

Keywords: Flood control; Song-Li region; Hydrodynamic model; Flood modelling; Flood volume; Flood level.

1 Introduction

Song-Li region refers to the area protected by the embankments along the downstream of the Lishui River and the Songzi River system. Extending from the Xin'an and Xinhe embankments of Linli in the west to the Anzao and Anbao embankments of Anxiang in the east, it is demarcated by the Hudu River. This region includes areas from the Censhang, Cenxia, and Jingxiang embankments in the north to the Minzhuyangcheng embankment in the Yuan River and Li River round areas in the south. Comprising 41 embankments of various sizes with a total length of 531.3 km, the Song-Li region is where the Lishui River and the Songzi River, the diversion channel of Yangtze River, converge, historically one of the most severely affected areas by flood disasters in the Dongting Lake region. For instance, in the 1954 Flood, most embarkments in the Song-

F. Ding et al. (eds.), *Proceedings of the 2024 International Conference on Civil Engineering Structures and Concrete Materials (CESCM 2024)*, Advances in Engineering Research 247,
https://doi.org/10.2991/978-94-6463-564-5_3

Li region collapsed, resulting in heavy losses. Moreover, flood disasters also occurred in 1935, 1980, 1983, 1991, 1998, 2003, and other years [1-3].

The Songzi River and the Lishui River flood channels are connected and serve as water level jacking for each other during floods. Thus, during high water periods in the Yangtze River, the Songzi River diverts water to the Lishui River, which raises the upstream water level in Jin, Li County. Conversely, during high water periods in the Lishui River, encountering floodwaters from the Songzi River, the Lishui River will jack the outflow of the Songzi River, and even reverse flow through the western branch of the Songzi River to Anxiang, raising the water level of the Songzi River, forming a mutual water level jacking situation [4]. According to the relevant research [5,6], floods in the Song-Li region mainly come from the Lishui River and the Songzi River, with additional contributions from inflows such as those from the Hudu River through the Zhonghekou diversion and from mountain streams like the Weishui River. When peak floods from the Lishui River coincide with those from the Songzi River, it results in high water levels in the Song-Li region. However, encounters between peak floods from the Songzi River and inflows from the Lishui River are generally less significant.

After years of management, the flood control construction in Song-Li region has made great achievements. Jiangya, Zaoshi and Jiangpinghe reservoirs have been completed in 1999,2008 and 2013 respectively. The embankment has been reinforced according to the highest water level before 1991, and the flood control capacity has been greatly improved. However, with the evolution of the relationship between rivers and lakes, sediment deposition and other factors, the flood control situation in Songli area is still severe. After the construction of the reservoirs in the Three Gorges and upstream basin, there have been significant changes in the erosion and sedimentation of the Songli channel and Dongting Lake area [7]. Consequently, it is necessary to use relatively new terrain data to reproduce historical floods for investigation of the flood control situation in the Song-Li region in the latest erosion and sedimentation conditions.

In this study, under current river-lake relationships and channel conditions, a 1D-2D coupled hydrodynamic mathematical model was constructed. Subsequently, this model was utilized to analyze the flood levels and excess flood volumes in the Songli area under different typical flood conditions after the construction of flood control reservoirs in the Three Gorges and upstream basin, as well as to evaluate the flood control situation in the Song-Li region under the current flood control engineering system.

2 Research Methodology

In order to study the hydrological process and hydrodynamic process mechanism of river floods, under current river-lake relationships and channel conditions, a 1D-2D coupled hydrodynamic model of the Yichang-Hankou area (including Dongting Lake and the downstream of Sishui River) was constructed to investigate and analyze the flood levels and excess flood volumes in the Song-Li region under typical flood conditions after the construction of flood control reservoirs in the Three Gorges and upstream basin. Especially, the 1D mathematical model was applied to simulate the situation the downstream of Sishui River, the main stem of the Yangtze River from Yichang to

Hankou, and the three tributaries of the Jinjiang River system. Meanwhile, the 2D mathematical model was employed to simulate the conditions in the Dongting Lake area. Subsequently, a real-time coupling between the 1D and 2D models was implemented.

2.1 1D-2D Coupled Hydrodynamic Model

2.1.1 Research Scope and Topography of the Model. The research scope of this model mainly includes three parts: the main stem of the Yangtze River from Yichang to Hankou, including tributaries such as Qingjiang River, Juzhang River, Dongjing River, and Hanjiang River; the river network in the Dongting Lake area, including the three tributaries of Jinjiang River system and Xiang-Zi-Yuan-Li downstream river channels; and Dongting Lake, including Muping Lake, East Dongting Lake, and South Dongting Lake. These three parts are coupled in real time and mutually related, forming a unified section. The schematic diagram of the model generalization is shown in Fig. 1. Fixed cross-sectional data measured from 2019 to 2020 were used for the main stem of the Yangtze River, and the three tributaries of Jinjiang River, while terrain data measured from 2011 to 2012 were used for the Dongting Lake area.

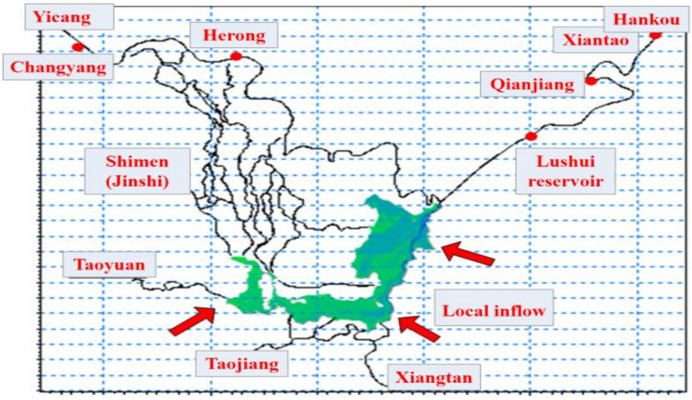

Fig. 1. The schematic diagram of the model generalization

2.1.2 Model Boundary Conditions. The model's boundary conditions were divided into inflow boundary, lateral point source inflow boundary, water level boundary, and rainfall and runoff boundary. The inflow boundary concerns flow processes, including inflows from the Sishui Control Stations (Xiangtan, Taojiang, Taoyuan, and Shimen), Yichang Station, and Han River. Lateral point source inflow concerns daily average flow processes as a point source, including inflows from the Qingjiang River, Juzhang River, Lushui, and Dongjing Rivers. The water level boundary concerns the water level-flow relationship at the Hankou hydrological station determined by the flood control planning for the Yangtze River Basin. Rainfall and runoff boundary include runoff production flow at the rainfall and runoff intervals and tributary runoff production flow. Tributary runoff follows the tributary flow, while interval production flow enters as overland flow. It mainly simulates rainfall runoff in uncontrolled sections below control stations such as the Sishui Control Stations in the Dongting Lake area, Xinqiang River, and the Weishui River.

2.1.3 Model Calibration and Validation. The roughness parameters for the model are determined via calibration and validation. The roughness parameters of the 1D model for river channels are determined based on changes in water level and flow volume. For the 2D model of lake areas, roughness coefficients are assigned based on the actual characteristics of the lake basin boundaries, distinguishing between river channels and marshlands. Given the large computational scope, complex interconnections of river networks, and intricate connectivity in the study area, a calibration process involving initial sectional calibration followed by overall fine-tuning is adopted.

The model calibration and validation are conducted using the data from years 2016 and 2020 as representative samples. Water level and flow volume data from six stations, namely Zhicheng, Shashi, Xinchang (water level station), Shishou (water level station), Jianli, and Luoshan, are selected as representative stations for calibration on the main stem of the Yangtze River. Five stations, including Nanzui, Xiahezui, Yangliutan (water level station), Lujiao (water level station), and Qilishan, are chosen as representative stations for calibration in the lake area. Fourteen stations, including Xinjiangkou, Shadaoguan, Mituo Temple, Kangjiagang, Guanjiapu, Guanyuan, Zizhiju, Dahukou, Anxiang, Shigui Mountain Xiaojiawan (water level station), Maocaojie (water level station), Sancha River, and Nan County, are selected as representative stations for calibration in the three tributaries of Jinjiang River. The calibration results are shown in Fig. 2.

The calibration results indicate that the hydrodynamic model constructed adequately captures the flow characteristics and water surface gradients of the Yangtze River main stem during different periods. The computed water levels and flow rates generally agree with the measured values at various stations, exhibiting consistent peaks and fluctuations. In other words, peak-valley correspondence, consistent rise and fall of the water level, and agreement of peak water level (flow) are observed. The flow distribution and convergence/divergence relationships in the three tributaries of the Jinjiang River system also correspond well with observations. This suggests that the water level and flow calculation results at 25 stations, including those on the Yangtze River main stem, Dongting Lake area, and the three tributaries of Jinjiang River system, are generally consistent with the measured values and can be used for regional flood reenactment and computation.

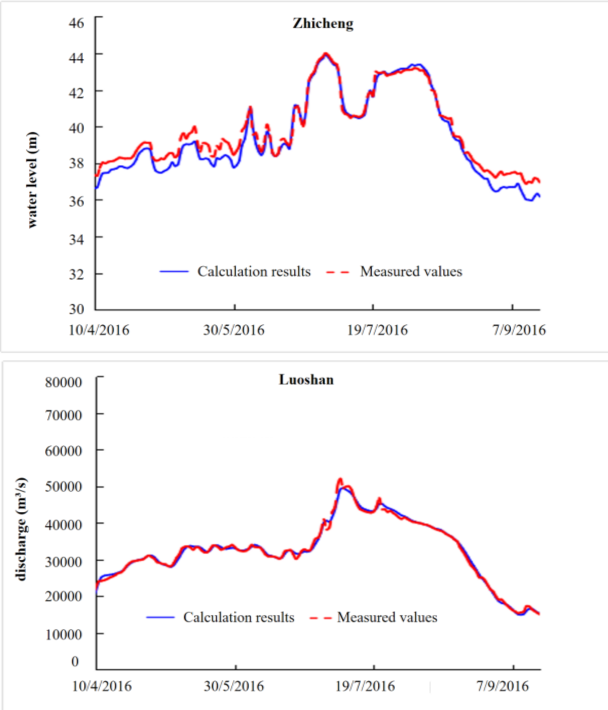

Fig. 2. The calibration results of the representative stations

2.2 Selection of Representative Years

Based on the analysis of flood events in different representative years, it is found that in years such as 1935, 2003, 1998, 1996, 1983, 1954, and 1991, the flood levels at the main control stations in the Song-Li region, such as Anxiang and Shigui Mountain exceed the safety water levels, and the peak flow rates at the Shimen hydrological station exceed the safe discharge of 12,000 m^3/s. Therefore, these seven years are selected as representative years for investigating the flood levels and excess flood volumes in the Song-Li region after the construction of the Three Gorges and its upstream basin reservoirs and the Lishui River basin reservoirs.

3 Results

3.1 Evaluation of the Flood Control Situation in the Song-Li Region Considering the Flood Control Effects of the Three Gorges and Lishui River Basin Reservoirs

3.1.1 Current Flood Control Situation. According to the arrangements of *the Comprehensive Plan for the Lishui River Basin*, three reservoirs have been built: Jiangpinghe Reservoir and Jiangya Reservoir on the tributary Loushui River with a capacity of 200 million m^3 and 740 million m^3 respectively, as well as the Zaoshi Reservoir with a capacity of 780 million m^3 on the tributary Xieshui. Moreover, the Yichongqiao Reservoir on the main stem (yet to be built) has a capacity of 240 million m^3. Therefore, the evaluation of the current flood control situation in this research is based on the operation calculations of the three completed reservoirs.

The Three Gorges Reservoir is located at the end of the upper reaches of the Yangtze River, governing a basin area of 1 million km^2 with a flood control capacity of 22.15 billion m^3. According to the *Joint Operation Plan for Water Resources Projects in the Yangtze River Basin in 2023* approved by the Ministry of Water Resources, in the case of floods below a once-in-a-century level in the Jingjiang River section, the flow at the Zhicheng station can be controlled below 56,700 m^3/s under current river-lake conditions, ensuring that the water level at Shashi is under 44.50 m; in case of a flood disaster occurring once in a millennium, akin to the flood occurrence in 1870, the flow at the Zhicheng station can be controlled below 80,000 m^3/s. With the flood storage areas in the Jingjiang region, the water level at Shashi can be kept below 45.0 m. We selected the operation of 25 reservoirs, which play a major role in flood control, in the upper reaches of the Three Gorges for operation calculation.

The flood control tasks undertaken by the reservoirs investigated in this research are mainly determined by comprehensive basin planning and flood control planning. The reservoir operation methods and joint flood control operation schemes for reservoir groups are mainly based on the *Flood Control Plan for the Yangtze River* (approved by Letter No. 124 [2015] of the State Council) and the *Joint Operation Plan for Water Resources Projects in the Yangtze River Basin in 2023* (approved by No. 210 [2023] of the Ministry of Water Resources). Based on this, the construction of the Shuangjiangkou Reservoir is underway, and according to the principle of "stage-by-stage reservation and gradual impoundment," it will gradually impound the base flow to reduce the inflow flood volume of the Three Gorges Reservoir.

Jiangping River Reservoir flood control operation is set as follows:

- When the reservoir level is lower than the flood control high water level of 470 m, and the incoming flow is less than or equal to the 5-year flood flow of 3,470 m^3/s, a balance control is conducted according to incoming and outgoing flow volume; if the incoming flow is greater than the 5-year flood flow of 3,470 m^3/s, and the reservoir begins to stop the flood, then the discharge of flow will be conducted according to the flood control of 1,400 m^3/s until full flood control reservoir capacity is achieved;
- When the reservoir water level reaches the flood control high water level of 470 m, a flood control operation is conducted to ensure the safety of the hub project.

Jiangya Reservoir flood control operation is set as follows:

- When the forecasted peak flow at Sanjiangkou exceeds 12,000 m^3/s, the reservoir is controlled to discharge at 1,700m^3/s;
- After the reservoir water level reaches 236 m, the operation is carried out according to the safety requirements of the hub project.

Zaoshi Reservoir flood control operation is set as follows:

- When the reservoir water level exceeds the flood season limit water level of 125 m and the inflow does not exceed the downstream safe discharge, the discharge is controlled based on the inflow. When the inflow exceeds the downstream safe discharge, the discharge is controlled at the safe discharge of 1,300 m^3/s until the reservoir water level reaches the flood control high water level of 143.5 m.
- After the reservoir water level reaches the flood control high water of 143.5 meters, the reservoir discharges according to the inflow.

3.1.2 Maximum Flood Levels at Major Control Stations in Different Representative Years. We constructed a hydrodynamic mathematical model to calculate the excess flood volume at major control stations in the Song-Li region, including Anxiang, Shigui Mountain, and Nanju. These calculations were conducted across seven different flood scenarios, with the findings for the years 1935, 1998, and 2003 detailed in Table 1.

Table 1. Calculation of the maximum flood level in the Song-Li region after the operation of the reservoirs in the Three Gorges and the Lishui River basin

	Station	Design flood level (m)	Maximum flood level (m) Representative year 1935	1998	2003
Lishui River floodway	Jinshi	41.92	43.15	43.19	43.11
	Shigui Mountain	38.72	39.85	39.81	39.67
	Nanju	34.17	34.81	34.57	34.45
	Station	Design flood level (m)	Maximum flood level (m) Representative year 1935	1998	2003
Songzi River	Wayao River	39.61	39.63	39.37	39.48
	Zizhiju	38.89	39.29	38.97	38.92
	Huikou	38.81	38.26	38.10	38.01
	Anxiang	37.11	36.98	36.81	37.57
	Nanju	34.17	34.81	34.57	34.45

The calculation results show that the maximum flood level was in 1935, with all sections along the Lishui River exceeding the design levels, where Jinshi exceeded the design level by 1.33 m, Shigui Mountain by 1.13 m, and Nanju by 0.64 m. For the Songzi River, parts of the area, including Wayao River, Zizhiju, Hui Kou, Anxiang, and Nanju, exceeded the design levels by 0.02 m, 0.40 m, and 0.64 m respectively.

3.1.3 Excess Flood Volume in Song-Li Region in Different Representative Years. The excess flood volume in the Song-Li region was calculated using a hydrodynamic mathematical model under the seven flood conditions mentioned above. The results are presented in Table 2. After the operation of the Three Gorges and Lishui River Basin reservoirs, the Song-Li region still requires allocation of 87 to 337 million m^3 of excess flood volume for representative years such as 1954, 1998, and 2003, with the excess flood volume in 1935 reaching 851 million m^3.

Table 2. Calculation of excess flood volume in Song-Li region after reservoir operation in the Three Gorges and the Lishui River Basin

Rank	Year	Excess flood volume before operation in the Three Gorges and the upstream reservoir group, the Lishui River, Jiangping River, Jiangya, Zaoshi Reservoir (10^8 m^3)	Excess flood volume after operation in the Three Gorges and the upstream reservoir group, the Lishui River, Jiangping River, Jiangya, Zaoshi Reservoir(10^8 m^3)	Maximum Water Level of Three Gorges (m)
1	1935	42.5	8.51	158.0
2	1954	8.73	0.87	159.6
3	2003	6	2.74	148.4
4	1998	10.13	3.37	155.0
5	1983	3.3	0	148.2
6	1991	3.1	0	145.8
7	1996	0.66	0	147.9

4 Conclusion

In this study, we developed a 1D-2D coupled dimensional hydrodynamic model for the Yichang-Hankou area, including Dongting Lake and the downstream of Sishui River. Subsequently, we employed it to analyze the flood levels and excess flood volumes in the Song-Li region under seven typical flood conditions after the construction of flood control reservoirs in the Three Gorges and the Lishui River basin. Based on this, the existing flood control system in the Song-Li region was evaluated. The following are the research findings obtained:

Following the implementation of the Three Gorges upstream reservoir group and the Lishui River basin reservoirs, the highest flood level was found in 1935, when the entire Song-Li region along the Lishui River from Jinshi to Nanzhu exceeded design levels. Despite the flood control measures, there remains an excess flood volume of 87 million to 337 million m^3 in the Song-Li region during representative flood years such as 1954, 1998, and 2003, with the 1935 flood having an excess flood volume of 851 million m^3. In conclusion, while the existing flood control engineering system and reservoir operation methods have greatly improved the flood control situation in the Song-Li region, they have not fundamentally alleviated the tense flood control situation in the area.The follow-up study should be carried out to consider the Three Gorges Reservoir taking into account the peak shifting scheduling method for the Songli area.

Acknowledgments

This work was financially supported by the National Key R&D Program of China (Grant No. 2022YFC3002703) and Research Project of China Three Gorges Corporation(Grant No. 0799249).

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