"Four-pre" application for Flood Control under Matrix Management in Modern Reservoir–A Case Study in Hengshan Reservoir

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ABSTRACT

Floods rank among the most severe natural disasters. The development of the "Four Pre" module within the reservoir operation and management matrix provides critical support for flood response operations. Using the flood models embedded in the "Four Pre" module, the research validates reservoir inflow forecasting and simulates reservoir flood routing scenarios. Results show that the distributed hydrological forecasting and regulation model accurately replicates historical flood events, with flood volume relative errors of -8.1% for the representative floods, offering a reliable scientific basis for flood control operations at Hengshan Reservoir. Additionally, the two-dimensional surface water dynamics model enables rapid and precise extraction of key flood parameters—including inundation extent, water depth, flow velocity, and time of arrival—under various scenarios. This study analyzed flood propagation and inundation risks downstream of a reservoir under three dam breach scenarios: design flood level, check flood level, and overtopping flood level The model effectively captures dynamic flood evolution and provides substantial support for flood prevention and mitigation strategies.

KEYWORDS: Reservoir Matrix Management; "Four-pre" for Flood Control; Integration of Hydrological Forecast and Dispatch; Hydrodynamic Model

1 INTRODUCTION

Floods rank among the world's most devastating natural disasters, frequently leading to substantial casualties, economic losses, infrastructure damage, and ecological degradation（UNDRR, 2020）. In response, China has in recent years actively pursued innovation in water conservancy management models to enhance flood control and disaster mitigation capacities and safeguard water resource security. A key initiative in this effort has been the vigorous advancement by China's water resources authorities of a modern reservoir operation and management matrix（MWR, 2023）.

This matrix is structured around four core dimensions: First, realizing "Four Comprehensives" in management—ensuring comprehensive coverage, all-element control, round-the-clock monitoring, and full-cycle supervision. Second, improving the "Four Systems"—namely the institutional, mechanistic, legal, and accountability frameworks. Third, strengthening the "Four Preemptive Measures"—forecasting, early warning, simulation, and contingency planning. Fourth, enhancing the "Four Management Tasks"—risk elimination, inspection, maintenance, and safety oversight. Collectively, these components constitute a multi-level, systematic management matrix designed to standardize, intellectualize, and coordinate the entire reservoir management process. This matrix has now been implemented in several regions. For instance, Jiangsu Province has preliminarily established matrix management platforms for seven reservoirs, including Hengshan, Laoyaba, and Xiangshan (Cheng, 2024). By integrating functions such as data monitoring, simulation forecasting, and dispatch decision-making, these platforms have significantly improved the precision, informatization, and modernization of reservoir operations, providing crucial support for flood safety and efficient water resource utilization.

As one of Jiangsu's pilot projects in reservoir matrix management, Hengshan Reservoir—supported by digital twin technology—has fully integrated various sensing devices to build a matrix platform that encompasses the four comprehensive aspects, four systems (governance mechanisms), four preemptive measures, and four management dimensions (Lin et al., 2024). In terms of operationalizing the "four preemptive measures," the platform has established a three-tier monitoring and forecasting system for rainfall and water conditions. It incorporates 0–72 hour rainfall forecasts, real-time precipitation data from seven upstream rainfall stations, and flow data from three gauge stations. Using an integrated forecasting and dispatch model, the platform dynamically updates flood forecasts, improving accuracy. It also integrates defenses against rainfall, flood conditions, risks, and disasters, providing real-time warnings for downstream river conditions to enable earlier alerts. Based on a two-dimensional hydrodynamic model, the platform enables dynamic simulation of flood propagation across the entire river basin. It supports forward simulation of forecasted floods and design floods with different return periods (e.g., 10-year, 50-year, 100-year, and 2000-year events) to optimize dispatch strategies, as well as reverse simulation to verify the safety of the dam and downstream protected areas. By incorporating these simulation results, the platform iteratively refines emergency plans, ensuring alignment between online simulations and offline preparedness, thereby enhancing the scientific rigor of contingency planning.

Based on the integrated forecasting and operation model and the two-dimensional hydrodynamic model embedded in the "Four Preemptive Measures" module of the Hengshan Reservoir, this study conducts a backward simulation of historical flood events and performs scenario analyses of dam-break flood propagation downstream of the reservoir. The outcomes provide a reference for enhancing the "Four Preemptive Measures" framework within the reservoir management matrix, thereby effectively supporting flood defense efforts.

2 DATA AND METHOD

Hengshan Reservoir (119.443~119.7°E, 31.1~31.275°N) is located in the mountainous southwest of Yixing City, Jiangsu Province. It is a water retention project in the Zhixi River system, with a catchment area of 154.8 km² and a total storage capacity of 112 million m³. The main dam of Hengshan Reservoir is an earth-rock dam with a length of 4090 m (Cui et al., 2020). The reservoir provides flood protection for an area of approximately 20,000 hectares and a population of 300,000 people.

The upstream basin of Hengshan Reservoir has a multi-year average rainfall of approximately 1225 mm, with water surface evaporation of about 950 mm. The mean annual temperature is around 15 °C, characteristic of a humid subtropical monsoon climate. Between 50% and 60% of the annual precipitation occurs during the flood season from June to September. The period from June to July is prone to continuous rainy plum-weather (Meiyu), while from July to September the area is often affected by typhoons and tropical storms, which can cause intense and rapid-onset heavy rainfall events.

2.1 Data

This study collected geospatial data, rainfall data, and reservoir operation data for the Zhixi River Basin and the downstream area of Hengshan Reservoir. The geospatial data primarily consist of Digital Elevation Model (DEM) data covering the basin and the downstream influence area of the reservoir, with a spatial resolution of 1.8 m × 1.8 m. The rainfall data mainly comprise hourly records from seven rainfall stations—during the flood events of "20240630". The reservoir operation data include hourly records of inflow, outflow, and water level variations throughout these two flood events.

2.2 Method

1. Forecasting and dispatching model

This study employs a watershed forecasting and operation integration model independently developed by the China Institute of Water Resources and Hydropower Research (IWHR) (Lin et al., 2024) to establish a distributed hydrological model of the Zhixi River Basin and to analyze the storm flood processes entering the Hengshan reservoirs. The model enables basin-wide, full-river-segment, and whole-project-system operation pre-simulation and supports parallel computing. The models are managed in a model library format, allowing appropriate processors to be selected based on different computational requirements to enable CPU-GPU heterogeneous parallel acceleration. The supporting model data primarily include watershed topology data, model parameters, reservoir parameters, reservoir operation settings, as well as information such as rainfall and initial reservoir water levels. These data are managed via standardized interfaces and stored in Json files. Based on historical flood event data, parameter tuning for the distributed hydrological model is performed by coupling the SCE-UA algorithm, resulting in a separate set of model parameters for each sub-basin.

2. Hydrodynamic model

This study employs FASFLOOD (Fast Analysis System for Flood) (CDPR., 2021), a domestically developed, general-purpose, high-performance flood analysis software independently created by the China Institute of Water Resources and Hydropower Research. The model engine adopts the shock-capturing Godunov scheme, supports heterogeneous parallel acceleration via GPU, and is capable of rapidly simulating various typical flood scenarios, including dam-break wave propagation, mountainous floods, and urban stormwater inundation.

3. Breaching model

Earth dams typically undergo gradual breaching. The breach dimensions (final breach width and breach development duration) are calculated using the empirical Lu Jikang formula (Lu et al., 2001). To simulate the breach widening process incorporating sediment effects, this study employs the widely applicable and mathematically straightforward de Vries sediment transport rate formula implemented in FASFLOOD to compute sediment transport at the breach.

4. Evaluation index

This study evaluates the hydrological forecast results using the Pearson correlation coefficient (Pearson, 1900), Nash-Sutcliffe efficiency coefficient (Nash, 1950), relative errors in flood volume and peak discharge, peak time error, and runoff depth forecast error.

3 FORECAST FOR THE FLOOD EVENT

During this flood event, rainfall was mainly concentrated from 23:00 on June 29 to 17:00 on June 30. The maximum average hourly rainfall in the basin reached 23.1 mm at 02:00 on the 30th, with the maximum 6-hour cumulative rainfall measuring 75.9 mm and the maximum 24-hour cumulative rainfall reaching 143.6 mm (Lin et al., 2024). The Hengshan Reservoir recorded its peak inflow of 408.2 m^3/s at 15:00 on the 30th. The forecasted flood hydrograph at the cross-section is shown in Figure 1 Verification results indicate a correlation coefficient of 0.97 between the predicted and observed flood hydrographs, with an NSE of 0.92. The relative deviation in flood volume was -8.1%, the forecast error in runoff depth was -8.1%, and the relative deviation in peak flow was -9.5%. No timing error in peak occurrence was observed, and the simulation results were within acceptable error limits.

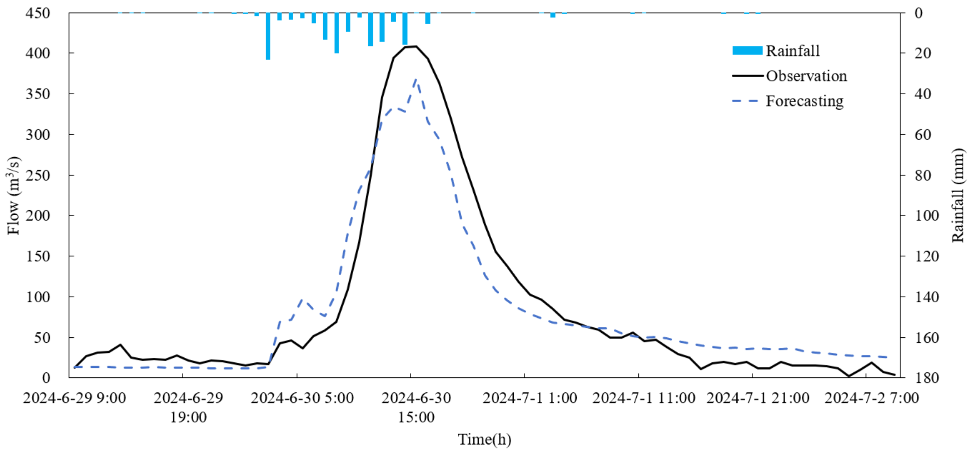

Figure 1: The process of simulated (using observed rainfall) vs. observed flood hydrograph in the Hengshan River Basin (Lin et al., 2024)

4 SCENARIO ANALYSIS OF FLOOD PROPAGATION DOWNSTREAM OF THE RESERVOIR

This study analyzed flood propagation and inundation risks downstream of the reservoir under three dam breach scenarios: the design flood level, the check flood level, and the overtopping flood level.

4.1 The process of outflow from a breach

Based on the calculation results of dam breach parameters under different water level scenarios, the key findings are presented in Table 1 and summarized as follows:

Table 1. Calculated Dam Breach Parameters under Different Water Level Scenarios

Parameter	Design Scenario	Check Scenario	Over-dam Scenario
Initial Invert Elevation (m)	38.75	40.36	42.10
Initial Water Level (m)	38.75	40.36	42.20
Initial Breach Width (m)	10.00	10.00	10.00
Minimum Controlled Water Level (m)	18.00	18.00	18.00
Maximum Breach Width (m)	113.21	122.35	128.31
Breach Development Duration (hr)	2.75	2.85	2.81

The analysis reveals a clear correlation between the initial hydraulic head (represented by the initial water level) and the resulting breach dimensions. As the initial water level increases from the Design (38.75 m) to the Check (40.36 m) and finally to the Over-dam (42.20 m) scenario, the calculated maximum breach width shows a consistent increasing trend, expanding from 113.21 m to 122.35 m and 128.31 m, respectively. This indicates that a higher initial reservoir level leads to the formation of a wider final breach, which is consistent with the expected greater erosive force and energy release during the breach event.

In contrast, the breach development duration remains relatively stable across the three scenarios, with values of 2.75 hours, 2.85 hours, and 2.81 hours. The minor variation suggests that the time required for the breach to develop to its maximum width is less sensitive to the initial water level within this range, potentially reaching a limiting erosion rate governed by the dam material properties or the simplified model assumptions.

The peak discharge exhibits a significant and progressive increase across the escalating scenarios. Compared to the Design scenario (10,931 m³/s), the peak discharge in the Check scenario rises by approximately 22%, reaching 13,349 m³/s (Figure 2). Under the most severe Over-dam condition, the peak discharge escalates to 16,438 m³/s, marking an increase of about 50% relative to the Design scenario baseline.

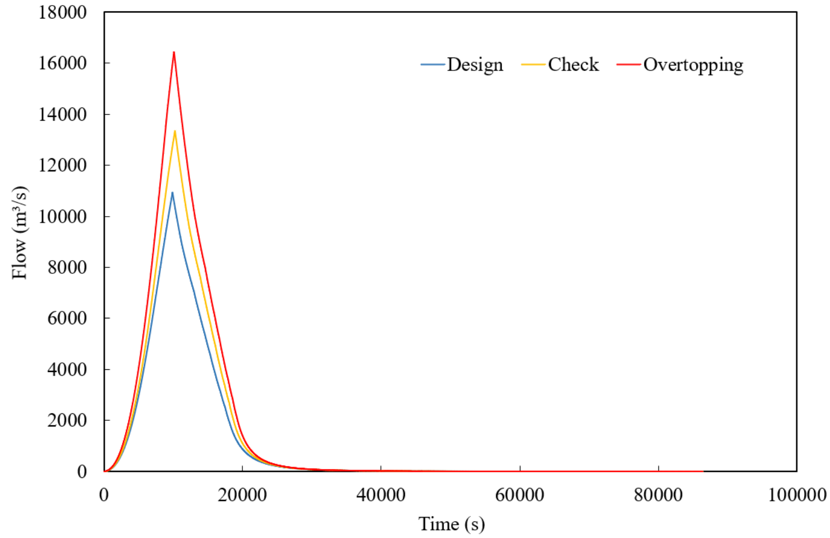

Figure 2: The process of outflow from a breach

4.2 Flood evolution analysis

The upstream boundary was defined as a flow boundary set at the gate of Hengshan Reservoir, while the downstream boundary was set as a free outflow boundary near Xijiu downstream of the reservoir. The simulation assumed dam failure occurring at time T, with the dam-break flood process concluding at T+24 hours, capturing the maximum flood inundation over the 24-hour period. The study area was discretized using an unstructured triangular mesh. To accurately represent the river channels, the channel network was extracted as a control line, with a mesh edge length of 30 meters, resulting in a total of 1,174,938 elements and 588,938 nodes.

The flood routing results indicate a consistent escalation in all key inundation parameters with increasing initial reservoir water levels. For the Design water level breach scenario, the maximum inundation depth, affected area, and flow velocity are 15.6 m, 120.8 km², and 14.3 m/s, respectively (Figure 3). These values increase to 17.0 m, 143.1 km², and 15.9 m/s under the Check water level scenario. The most severe Over-dam water level scenario produces the most extreme conditions, with the maximum inundation depth reaching 18.3 m, the inundated area expanding to 170.1 km², and the flow velocity rising to 17.3 m/s.

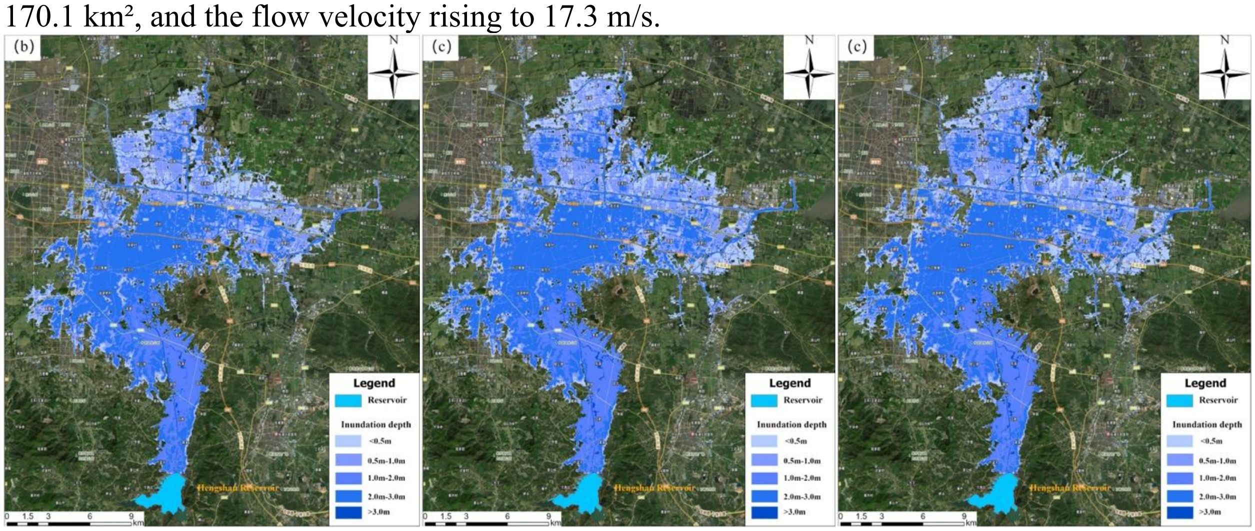

Figure 3: The inundation depth of the downstream flood propagation scenario of Hengshan Reservoir The inundation depth of the downstream flood propagation scenario of Hengshan Reservoir for (a) Design level, (b) Check level and (d) Overtopping level

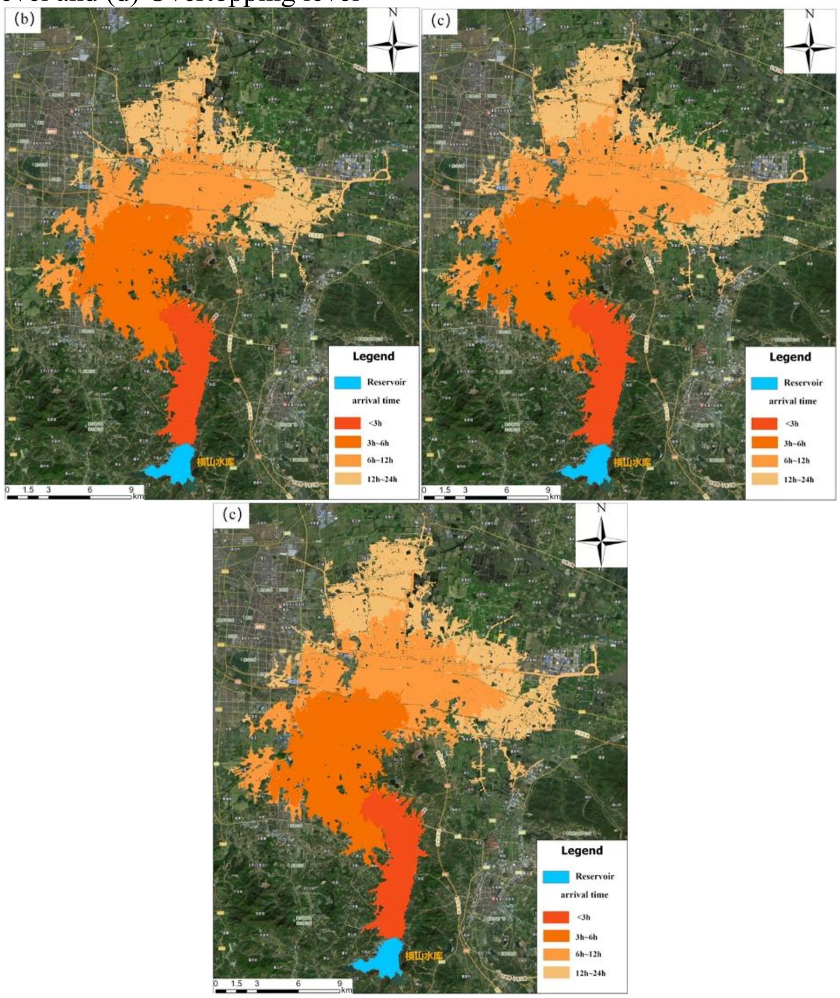

Figure 4: The arrival time of the downstream flood propagation scenario of Hengshan Reservoir The inundation depth of the downstream flood propagation scenario of Hengshan Reservoir for (a) Design level, (b) Check level and (d) Overtopping level

In summary, the "Four Previsions" (forecast, early warning, simulation, and contingency planning) module of the Hengshan Reservoir's comprehensive flood control system can achieve rapid simulation of flood processes under various scenarios based on forecast-based operation results. It provides flood inundation characteristic data for downstream affected areas, thereby offering effective support for flood defense decision-making.

5 CONCLUSION

Based on the developed hydrological and hydraulic models, this study conducted validation of reservoir inflow flood forecasting and scenario-based analysis of reservoir flood routing.

The main findings are as follows:

(1) The integrated watershed forecasting and regulation model demonstrated good performance in simulating the flood hydrograph of the "20240630 flood event." The flood forecasting results were highly accurate, with deviations in peak discharge and flood volume falling within acceptable limits, thus providing a scientific basis for flood control operations at Hengshan Reservoir.

(2) The hydrodynamic model developed in this study can rapidly provide key data—such as flood extent, water depth, flow velocity, and time of arrival downstream of the reservoir under dam breach scenarios—and can accurately and dynamically reflect real-time flood evolution.

6 ACKNOWLEDGEMENTS

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