Flood defense technology of "July 23" catastrophic floods in the Haihe River based on hydrodynamic model and remote sensing data

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ABSTRACT

In 2023, the Haihe River Basin experienced catastrophic flooding triggered by the heavy rainfall of Typhoon Doksuri. To support real-time forecasting and the strategic operation of flood control infrastructure, the China Institute of Water Resources and Hydropower Research (IWHR) independently developed a 1D-2D coupled hydrodynamic model leveraging the high-performance IFMS/Urban platform, alongside an emergency monitoring system integrated with remote sensing. Taking the Dongdian Flood Storage and Detention Area (FSDA) as a case study, this paper evaluates the entire spatio-temporal evolution of inundation through numerical simulation and satellite observations. Furthermore, a comprehensive technical framework for basin-wide flood defense is proposed. The findings provided critical scientific support for the regulation of detention areas and governmental decision-making during the flood, offering a reproducible framework for modern flood management strategies.

KEYWORDS: flood evolution; hydrodynamic model; remote sensing ; flood storage and detention areas; the Haihe River Basin

1 INTRODUCTION

Flood storage and detention areas (FSDAs), which serve as crucial zones for diverting and detaining floodwater during major river floods, are an essential component of flood control engineering systems. The coordinated operation of FSDAs, river channels, and reservoirs effectively attenuates flood peaks, stores excess volume, and enhances the overall flood defense capability of a river basin (Wang, 1998; Hou and Shen, 2010). Chinese researchers have conducted extensive studies on the rational operation of these areas. In particular, two-dimensional (2D) hydrodynamic numerical models, as well as coupled 1D-2D models, are widely utilized to simulate flood propagation within FSDAs.

Two-dimensional (2D) hydrodynamic models are well-suited for simulating flows in wide and shallow water bodies. However, when a significant scale disparity exists between river channels and detention areas, relying solely on 2D models becomes computationally prohibitive and inefficient (Li et al., 2017; Li et al., 2018). To address this, coupled 1D-2D hydrodynamic models have been developed to represent the complex flow interactions and water exchange between rivers and FSDAs. This coupled approach effectively balances computational efficiency with simulation accuracy (Liu et al., 2020; Chen et al., 2017). Previous studies have demonstrated the robust performance of 1D-2D models in simulating flood propagation across various regions, including the Daming Floodplain (Wu et al., 2019), the five FSDAs in the Daqinghe River (Li et al., 2009–2016), and the Guduiwei area (Fu et al., 2013). Furthermore, satellite remote sensing has increasingly been integrated into flood monitoring due to its broad spatial coverage and near-real-time data acquisition capabilities.

Remote sensing imagery enables rapid, large-scale monitoring of flood disasters. It facilitates the delineation of inundated areas and associated hydrological features, which is critical for effective emergency response and damage assessment(Liu et al., 2023; Sui et al., 2021).

As climate change drives the northward shift of rain belts, Northern China is experiencing more frequent flooding and an increased frequency of FSDAs utilization. Consequently, high-fidelity flood propagation modeling and remote sensing are paramount for informed decision-making in flood dispatching (Feng et al., 2002; Song et al., 2022).

2 OVERVIEW OF THE "JULY 23" CATASTROPHIC FLOODS IN THE HAIHE RIVER BASIN

Driven by the interaction between the northward-moving Typhoon Doksuri and cold air masses, the Haihe River Basin experienced extreme rainfall from July 28 to August 1, yielding a basin-wide average precipitation of 155.3 mm.

This triggered floods surpassing warning levels in 22 rivers, with the Daqing and Yongding Rivers experiencing catastrophic inundation. Formally designated by the Ministry of Water Resources as the "23·7" Haihe River Basin Flood, it represents the region's most severe hydrological event since 1963.

2.1 Natural Overview of the Haihe River Basin

The Haihe River Basin comprises three primary water systems: the Haihe, Luanhe, and Tuhai-Majia Rivers. Within the Haihe system itself, the network is further divided into several key tributaries, including the Jiyun, Chaobai, Beiyun, Yongding, Daqing, Ziya, and Zhangwei Rivers, as well as the drainage systems of the Heilonggang and Yundong regions. The basin boasts a dense hydrological network, with 59 rivers each possessing a drainage area exceeding 1,000 km^2.

Covering a vast expanse of 320,600 km^2, the basin encompasses Beijing, Tianjin, and parts of six provinces, including Hebei and Shanxi. It supports a population of approximately 150 million (11% of the national total) and generates roughly 13% of China's GDP. With 9.33 million hectares of arable land, the region functions as the center of nation's political and cultural, a powerhouse of economic development, and a strategic hub for grain and energy production.

2.2 Characteristics of Rainfall

The rainfall event exhibited pronounced spatial extensiveness, substantial volumetric magnitude, spatiotemporal concentration, and elevated intensity. Spatial analysis indicated that precipitation exceeding 50 mm and 100 mm enveloped approximately 77.4 % and 52.8 %, respectively, of the entire catchment area. The preliminary estimation of total rainfall volume amounted to 49.4 billion m^3 . Notably, accumulated areal precipitation attained 155.3 mm, equivalent to roughly 30.5 % of the multi-year mean annual precipitation for the region.

The heavy rainfall was primarily concentrated in the following regions: the Juma River within the Daqing River basin; the Hutuo and Fuyang Rivers of the Ziya River basin; and the Guanting Gorge section of the Yongding River basin. Within a 83-hour window (from 20:00 on July 29 to 07:00 on August 2), Beijing recorded precipitation equivalent to 60% of its long-term annual average. The maximum hourly intensity reached 111.8 mm at the Qianlingshan station in Fengtai District, surpassing the peak intensity recorded during the "7·21" extraordinary rainstorm of 2012. Comparative rainfall data for historical flood events are summarized in Table 1.

Table 1: Rainfall Comparison in the Haihe River of historical flood events

Rainfall Event	Duration	Storm Center	Cumulative Area Precipitation (mm)	Total Rainfall Volume（ 10^8m^3）

"23·7" Rainfall	July 28 – Aug 1	Juma River, Fuyang River, Guanting Canyon (Yongding River)	155.3	494
"63·8" Rainfall	Aug 1 – Aug 11	Zhangmo Station (Ziya River)	139.9	624
"96·8" Rainfall	Aug 2 – Aug 7	Windward slopes of the Taihang Mountains	97.6	310
"21·7" Rainfall	July 17 – July 22	Xinxiang, Jiaozuo, Hebi (Henan) and Handan (Hebei)	79.9	253

2.3 Hydrological Characteristics

The catastrophic flooding in the Haihe River basin was characterized by synchronous flooding across both mainstreams and tributaries, marked by extreme magnitudes and massive runoff volumes. The event triggered water levels exceeding warning stages in 22 rivers, eight of which experienced unprecedented floods since records began. Notably, the Yongding and Daqing Rivers experienced catastrophic floods (highest classification), while the Ziya River experienced a major flood. Figure 2 illustrates the flood hydrographs at key hydrological stations. The total runoff is preliminarily estimated at 20 billion m^3, significantly surpassing the scale of the "96·8" major basin-wide flood.

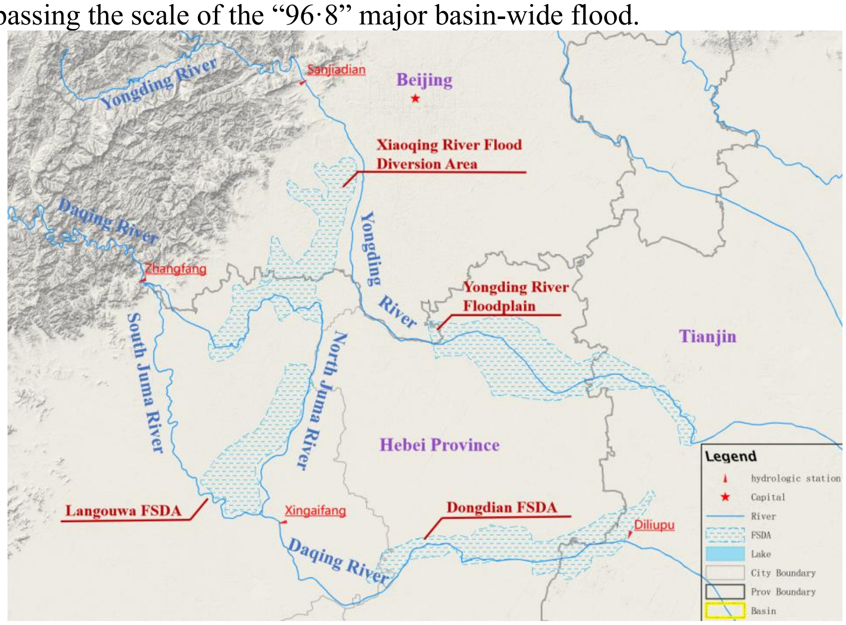
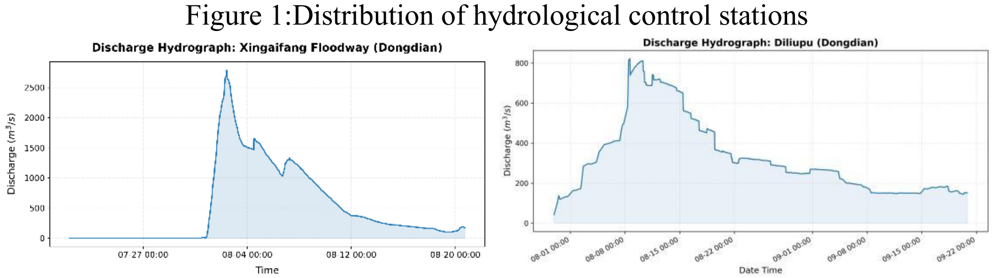


Figure 1:Distribution of hydrological control stations



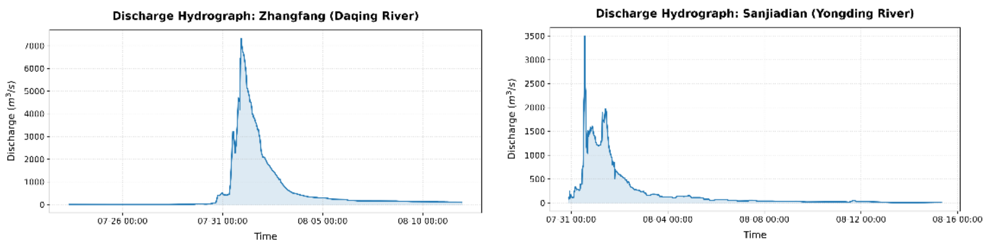


Figure 2:Flood hydrographs at key hydrological control sections

1.1 3 UTILIZATION AND TECHNICAL SUPPORT OF FLOOD STORAGE AND DETENTION AREAS IN THE HAIHE RIVER BASIN

3.1 Utilization of Flood Storage and Detention Areas

In response to heavy rainfall and flood warnings, eight Flood Storage and Detention Areas (FSDAs) within the Haihe River Basin were promptly activated. These included the Gongquxi FSDA; the Daluze and Ningjinbo FSDA, and Xianxian flood plain zoning; the Xiaoqing River FSDA , Langouwa FSDA, and Dongdian FSDA ; and the Yongding River flood plain zoning. The cumulative peak storage volume reached 2.53 billion m³. The spatial distribution of these FSDAs is illustrated in Figure 3.

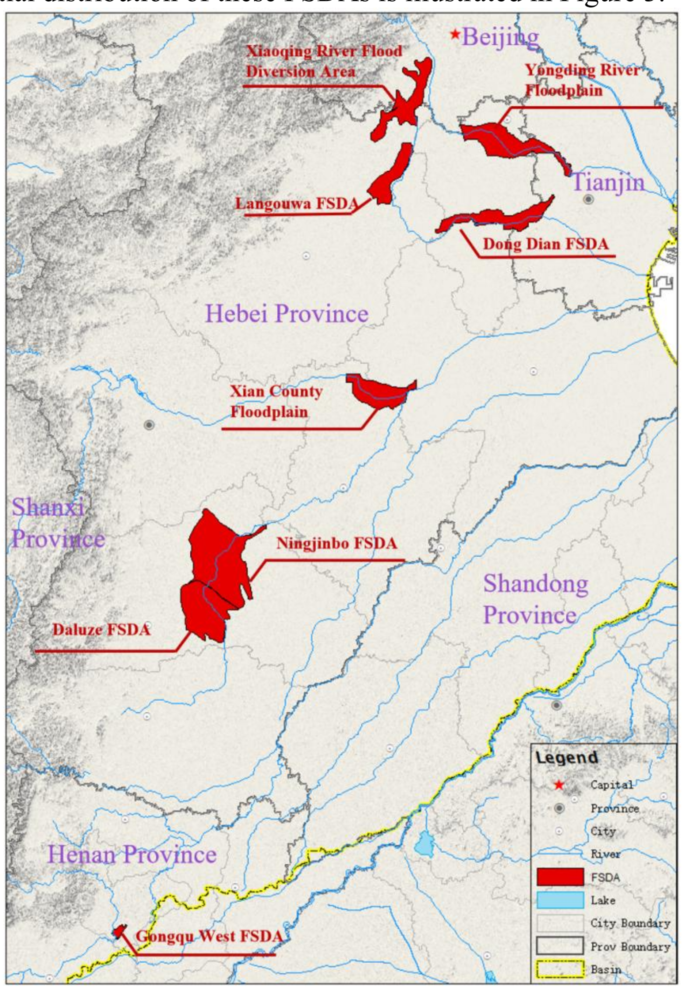


Figure 3: Utilization of FSDAs in the “July 23” catastrophic floods in the Haihe River Basin

3.2 Hydrodynamic flood models

In the course of the flood defense, 1D and 2D coupled hydrodynamic flood models were constructed for the eight FSDAs(Wang et al., 2023). Analysis was conducted based on the outputs of the flood risk maps and the "Four-Pre" flood defense system (forecast, early warning, simulation, and emergency planning). By integrating on-site surveys, satellite remote sensing, and UAV imagery, the hydrodynamic parameters were dynamically calibrated in real-time. This approach significantly refined the accuracy of flood simulations, providing essential technical support for the scientific operation of FSDAs, levee patrolling, and the strategic management of post-flood recession and resident repatriation.

(1) Model Principles

A 1D and 2D coupled hydrodynamic model was employed to simulate flood routing within the FSDAs. The model implements a Godunov-type scheme discretized via the Finite Volume Method (FVM).. Specifically, the Riemann problem is addressed using Roe's approximate Riemann solver, while the bottom slope source terms are treated using characteristic decomposition. The river channels and FSDAs are linked via hydraulic structures—including weirs, sluice gates, inlets, and levee breaches. The exchange of flow at the 1D-2D coupling interfaces is quantified using the weir flow formulation.

(2) Model Construction

In the development of the 1D riverine model, the modeling extent was defined to encapsulate the dynamic interaction between flood detention basin storage and mainstem water levels, while also incorporating the spatial distribution of hydrological stations. Correspondingly, the 2D model domain was delineated to match the geographical boundaries of the flood storage and detention areas (FSDAs). Within the 2D grid discretization, linear features such as highways, railways, internal embankments, and minor drainage channels were treated as internal constraint boundaries. Grid refinement was implemented at critical locations, such as flood diversion gates, with cell elevations interpolated from either preliminary risk map datasets or high-resolution field survey data.

The model's upstream and downstream boundary conditions were prescribed based on observed and forecasted discharge and water levels from hydrological stations. Roughness coefficients were initially assigned according to standard ranges provided in the Hydraulic Calculation Manual and further informed by regional planning reports and historical studies within the basin.

(3) Activation and Evolution Simulation of Flood Storage and Detention Areas

Based on hydrological forecasts, flood routing simulations are conducted for main channels prior to the deployment of Flood Storage and Detention Areas (FSDAs). Activation timing is determined in strict accordance with the basin's flood control scheduling protocols. Through multi-scenario simulations, optimized schemes are developed for gate operations and zonal flooding sequences.

Upon FSDA activation, multi-source remote sensing data are integrated with water distribution forecasts to predict critical hydrodynamic metrics, including flood-front progression (water head locations), inundation depths, and flow velocities. These results are used to assess the vulnerability of key infrastructure, such as village foundations and safety zones.

Following peak regulation, a coordinated water release plan is formulated based on forecasted river levels and simulated hydrographs. This plan defines the optimal timing, aperture (degree of gate opening), and duration of discharge to ensure a safe and efficient recession process.

3.3 Remote sensing monitoring

As a rapidly evolving geospatial technology, remote sensing offers unparalleled capabilities for wide-area, high-frequency, and all-weather surface observation. Following decades of specialized research and practical application, our center has established a comprehensive remote sensing framework for flood disaster monitoring, providing end-to-end analysis across the entire pre-disaster, during-disaster, and post-disaster spectrum.

In response to the Haihe River "23· 7" basin-wide catastrophic floods, wwe quickly formed an air-space-ground integrated remote sensing monitoring and analysis team, coordinating more than 20 domestic and international optical and radar remote sensing satellite resources.

By integrating emergency response with routine operations and leveraging our self-developed Water Conservancy Remote Sensing Emergency Monitoring System Platform, we designed a multi-satellite synergistic observation strategy. This approach combined optical and synthetic aperture radar (SAR) assets to achieve 1 to 3 daily remote sensing observations of the eight FSDAs in the Haihe River Basin. It effectively mitigated the limitations of optical sensors in acquiring reliable data under persistent cloud cover and rainfall—common during flood seasons, thereby significantly enhancing the satellite-based emergency monitoring capabilities for flood disasters.

Based on the platform, we automated the end-to-end workflow for multi-source satellite imagery, encompassing querying, downloading, ingestion, radiometric calibration, geometric correction, and noise filtering. By integrating expert knowledge, the system achieved precise identification of the extent of inundated water bodies. Furthermore, it dynamically extracted critical flood parameters—including inundated area and duration—for the eight detention basins. This continuous monitoring spanned the entire flood lifecycle from July 31, 2023, covering the phases of “flood warning activated - flood invasion - peak flow occurrence - floodwaters began to recede - floodwaters fully receded”.

Aerial remote sensing proved indispensable for this emergency monitoring mission. Low-altitude UAVs, characterized by sub-cloud operation, high maneuverability, and rapid deployment cycles, effectively mitigated the limitations of satellite imagery—namely cloud interference, latency, and high tasking costs. By integrating both platforms through data fusion and cross-verification, we achieved comprehensive multi-source information acquisition. Specifically, we deployed the Kodiak 100 aircraft equipped with the Optech Galaxy T2000 LiDAR to conduct high-precision surveys over activated flood detention zones. This yielded critical LiDAR point clouds and orthophotos, providing essential “ground truth” for flood analysis. Additionally, portable UAVs, powered by our self-developed YC-mapper rapid processing system, were utilized for real-time monitoring of breach sites along the dike of Langgouwa FSDA and Baigou Rivers, enabling the swift measurement of key metrics such as breach dimensions.

Remote sensing monitoring technology provides robust scientific support for the safe operation of flood storage and detention areas. It provides a comprehensive perspective on current flood dynamics within the FSDAs, offering critical datasets for hydrodynamic simulation, flood forecasting, and disaster impact assessment.

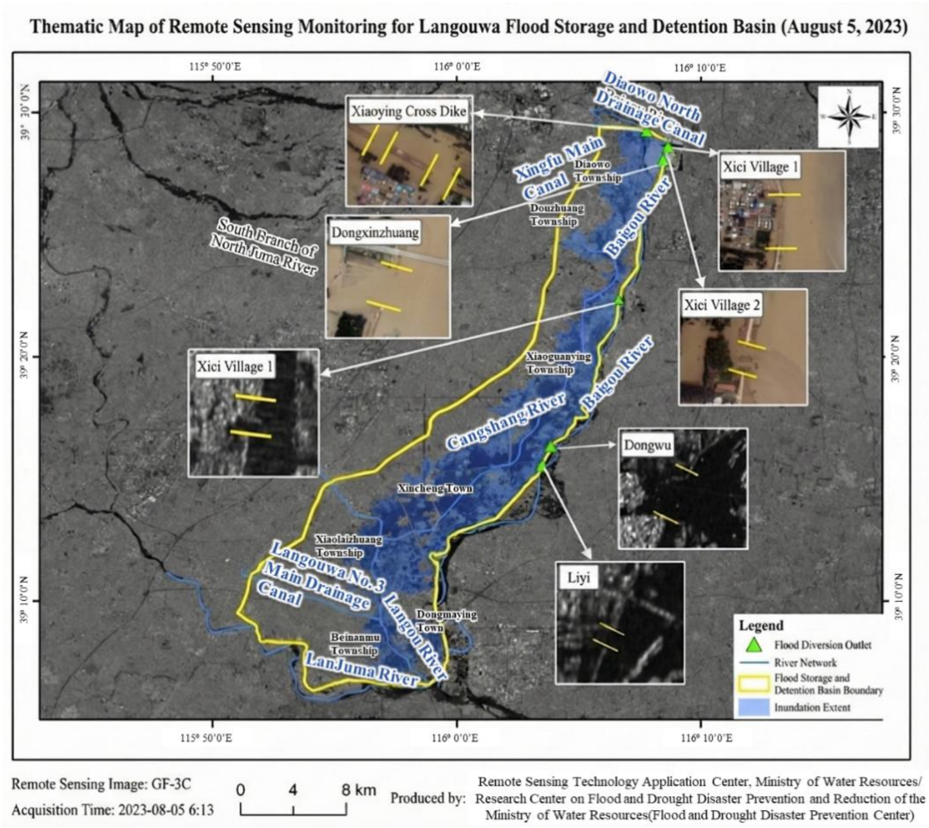


Figure 4: Satellite and Aerial Remote Sensing Map of Flood Inundation in Langgouwa FSDA

3.4 Supporting case — Flood evolution analysis of the dongdian FSDA

The Dongdian FSDA is located in the downstream reaches of the Daqing River basin. Covering a total area of 377 km^2, the Dongdian FSDA acts as the ultimate convergence point for floodwaters from the northern and southern branches of the Daqing River basin, as well as the regional runoff from the Qingnan and Qingbei areas.. A 1D-2D coupled hydrodynamic model, integrated within the IFMS (Integrated Flood Management System) software developed by the China Institute of Water Resources and Hydropower Research (IWHR), was employed to simulate flood propagation across the primary river networks-including the Daqing, Zhaowangxin, and Ziya Rivers-as well as the Dongdian FSDA. The model architecture comprises 359 river cross-sections with an average spacing of 400 m, integrated with 114,000 2D grid cells at a spatial resolution of approximately 60 m. Leveraging the full GPU heterogeneous parallel acceleration of IFMS v4.0, the system significantly enhances computational efficiency. A 30-day flood inundation simulation for the Dongdian FSDA (from August 1 to August 31) can now be completed within 20 minutes. This high-performance capability ensures the platform meets the rigorous demands of real-time operational forecasting.

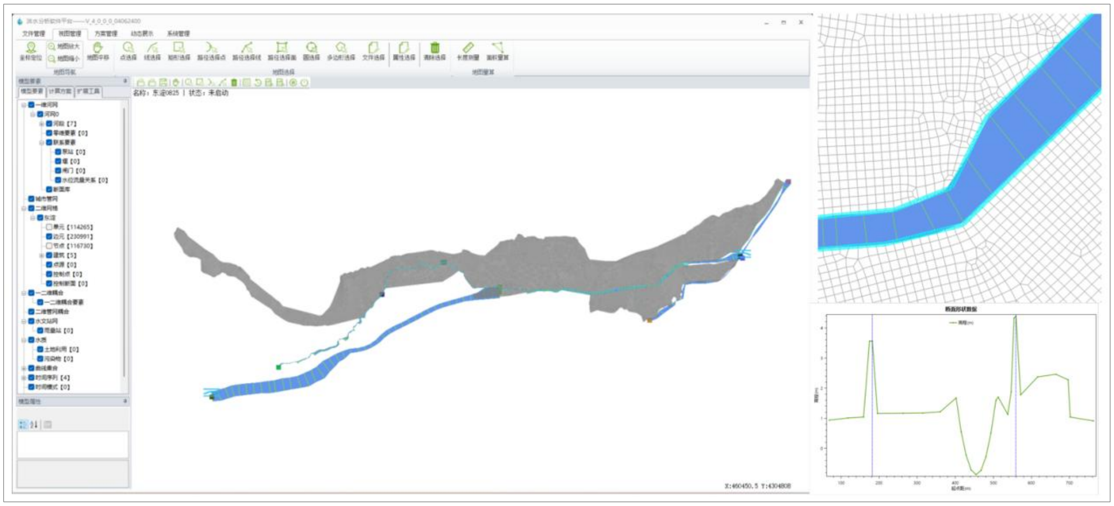
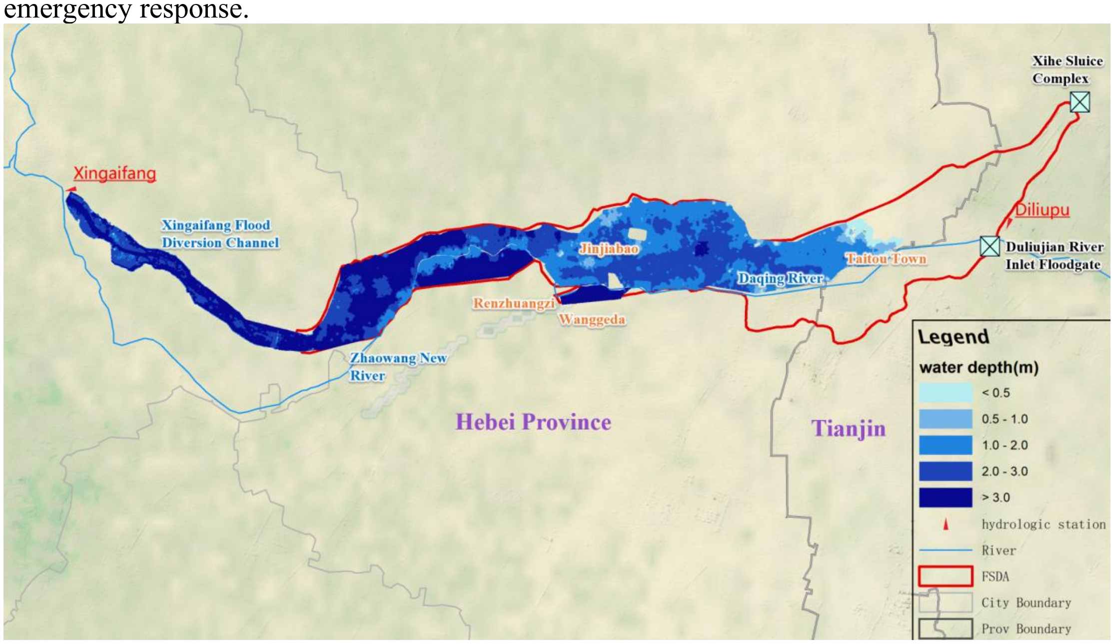


Figure 5: Construction diagram of the 1D-2D coupled model of Dongdian FSDA

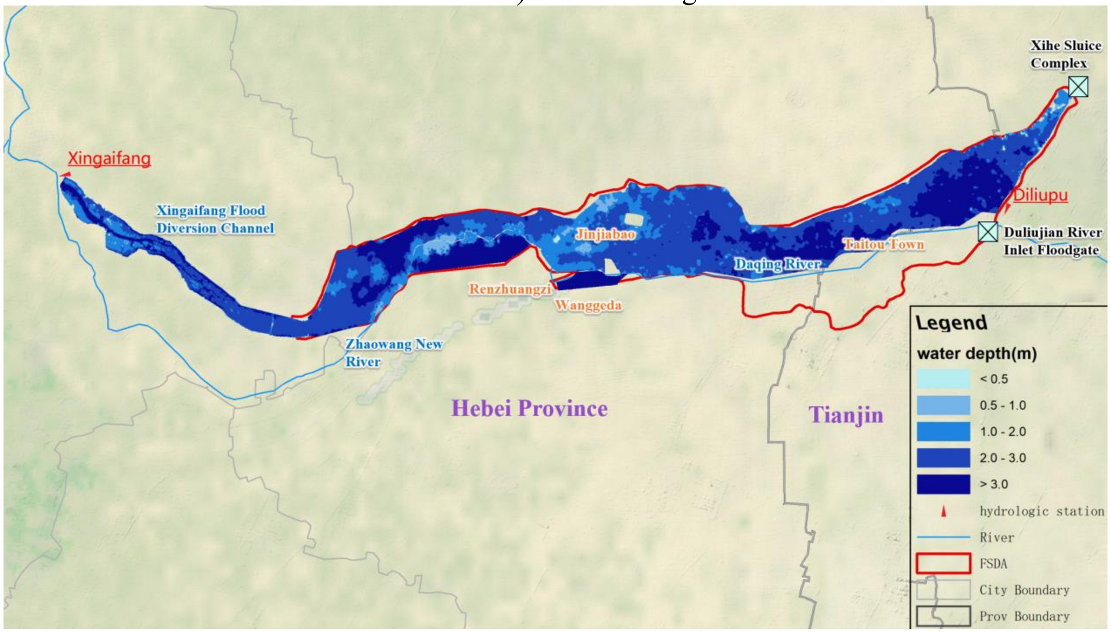
The model's upstream boundary conditions are driven by real-time monitoring and forecast discharge data from the Xingaifang Diversion Hub and the Baiyangdian outflow. For the downstream boundary, a stage-discharge rating curve at the Duliu Jianhe Floodgate is applied to ensure hydraulic consistency.

This framework enables the simulation and predictive analysis of flood propagation within the Dongdian FSDA. The model undergoes daily calibration and validation using inundation extents derived from remote sensing imagery and field surveys. For over a month, continuous rolling forecasts have been maintained, with results demonstrating a high degree of consistency between the simulated inundation patterns and the actual satellite-observed data.

Based on monitoring and forecast data as of 12:00 on August 4, the peak flood originating from the Xingaifang Diversion was projected to reach Tianjin by 08:00 on August 5. Field validation confirmed the actual peak arrived at Taitou Town between 09:00 and 10:00 on August 5. These results demonstrate the high precision of the Dongdian flood evolution model developed in this study, which successfully achieved a 20-hour lead time with a temporal error of less than one hour. These forecasts were promptly submitted to the Ministry of Water Resources, the Haihe River Water Conservancy Commission, and the Hebei Provincial Department of Water Resources, providing critical lead time for strategic flood diversion and emergency response.



a) 08:00 on August 5



b) 11:10 on August 9

Figure 6: Model predicted flood water in the FSDA

1.2 4 SUMMARY AND RECOMMENDATIONS

4.1 Conclusion

The "July 23" catastrophic floods in the Haihe River Basin, the FSDAs played an irreplaceable and important role. To address critical challenges-including optimized activation timing for FSDAs, embankment integrity, flood propagation dynamics, and precise water diversion schedulin-the Flood and Drought Disaster Prevention and Reduction Engineering Technology Research Center(CDPR) provided strategic technical support in the following areas:

(1) Space-Ground Integration: Leveraging a multi-source remote sensing network, the CDPR achieved high-precision, real-time observation of flood storage and detention areas. During the flood periods, inundation analyses were performed 1 to 3 times daily to track flood-front progression (water head), assess the status of safe zones, and monitor village-level flooding with high frequency.

(2) Hydraulic Modeling and Forecast Operations. Leveraging coupled 1D-2D hydrodynamic models, flood evolution simulations were developed for eight FSDAs. The model's reliability was cross-validated against remote sensing data, ensuring high fidelity. Integrating these with hydrological forecasts, the CDPR formulated optimized dispatching strategies and delivered daily rolling evolution forecasts, providing critical early warnings for key downstream regions.

(3) Drawing on defense experience from the "23· 7" catastrophic flood in the Haihe River Basin, this paper proposes an integrated technical support framework for flood storage and detention areas. This system leverages the synergy between remote sensing (RS) monitoring and hydrodynamic modeling: while 1D-2D coupled models enable rapid forecasting and early warning, RS-derived data provides critical empirical calibration, ensuring the high fidelity of simulation outcomes.

4.2 Limitations of the Current Defense System

(1) Engineering System

The flood defense infrastructure in the Haihe River Basin remains relatively fragmented, with critical river sections lacking essential control reservoirs. Much like the "63· 8" catastrophic flood event, the "23·

7” extreme rainfall was concentrated downstream of existing reservoirs-specifically along the windward slopes and piedmont plains of the Taihang Mountains-rendering upstream reservoir regulation largely ineffective. This hydrological pattern bypassed primary defenses and struck the system’s most vulnerable points. Consequently, The flood storage and detention areas, the final line of defense, were forced into operation to compensate for key dikes and channels that significantly underperform their design standards.

Besides, the construction of flood storage and detention areas lags behind-the control facilities are inadequate. Among the 28 flood storage and detention areas in the Haihe River Basin, only three have completed construction to design standards. Critically, none of the eight activated flood storage areas had fully completed their safety-standardized construction.

(2) Non-Engineering System

The digital twin watershed construction and the "four-prevention" system are not well-developed. In terms of forecasting, factors such as special complex terrain and typhoon impacts causing uncertainties, along with the damage to some hydrological stations, have led to large adjustments in heavy rainfall and flood forecasting; in terms of early warning, the limitations of hydrological forecast accuracy and changes in the underlying surface leading to variations in flood risk distribution have affected precise early warning capability, which needs improvement; in terms of simulation exercises, the conditions of the underlying surfaces of flood storage areas are unclear, and the data foundation cannot be quickly obtained, making real-time dynamic simulation based on gate conditions impossible; in terms of emergency plans, the dynamic adjustment of dispatching plans still needs improvement; emergency monitoring capabilities are greatly affected by floods and traffic conditions.

(3) Technical Support Enhancement

Several flood dispatching schemes require urgent revision. Significant shifts in land surface characteristics, driven by crustal subsidence and rapid socio-economic development, have altered local hydraulic responses. Currently, when independent discharge-reduction rivers reach their design flow, actual water levels remain below the benchmarks set in existing flood control plans. Furthermore, the “Four Preventions” digital system for flood storage and detention areas remains incomplete, limiting the capacity for precision decision-making. Given the substantial changes in the physical and socio-economic landscape of these areas, a comprehensive update of flood risk mapping is now imperative.

4.3 Proposed Countermeasures and Recommendations

(1) Optimization of Watershed Flood Control Infrastructure

Future efforts should align with the upcoming round of watershed flood control planning revisions to further optimize the spatial layout of flood control projects. This includes a systematic enhancement of the regional defense system and the rigorous demonstration and advancement of pre-feasibility studies for key projects, such as the Zhangfang Reservoir in the Daqing River Basin. Priority must also be given to the standardized construction of river embankments and the strengthened management of flood storage and detention areas (FSDAs).

(2) Digital Twin Integration and Intelligent Decision Support

Based on current hydraulic conditions and recent flood events, the revision of flood dispatching protocols should be expedited. Leveraging the “Four Preventions” framework alongside Digital Twin Watershed initiatives, it is essential to develop intelligent monitoring and rapid fusion technologies for underlying surface data. Furthermore, research should focus on high-fidelity flood modeling, dynamic simulation, and real-time risk assessment to generate dynamic flood risk maps. These advancements will facilitate iterative plan updates and enable the integrated forecasting and scheduling of reservoirs, rivers, embankments, and FSDAs, ultimately providing robust decision support for scientific flood defense.

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