Digital Twin for Urban Flood Resilience: Integrating Four-Pre Modules into Digital Infrastructure

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ABSTRACT

Climate change and rapid urbanization have significantly amplified flood risks from extreme rainfall events, exposing critical limitations in conventional flood management systems. Traditional approaches often fail to address systemic challenges such as fragmented data integration, computationally heavy forecast models, and static emergency protocols lacking dynamic adaptability. This study proposes an innovative digital twin framework that integrates "Four-Pre" modules (Forecasting, Warning, Rehearsal, Planning) into urban flood resilience infrastructure. The framework employs a unified digital baseboard to aggregate multi-source spatial-temporal data, extending beyond traditional IoT sensors to include urban crowdsourced monitoring. A novel hybrid dual-engine architecture, utilizing multi-layer grid overlay analysis and decoupled interpolation, is established to overcome computational bottlenecks. This hybrid approach accelerates 72-hour flood simulations to merely 1/12 of the time required by traditional models, while maintaining sub-5cm inundation depth accuracy. Furthermore, enhanced by advanced Knowledge Graph technologies and a multi-scenario rainstorm waterlogging scheme library, the platform shifts from direct physical interventions to an intelligent decision-support ecosystem, enabling dynamic map visualization and rapid one-click scheme invocations. The Nanjing case study demonstrates the framework's effectiveness in upgrading urban flood standards through cyber-physical convergence, aligning with national strategies for digital twin basin development.

KEYWORDS: Digital Twin; Urban Flood Resilience; “Four-Pre” Modules; Hydro-hydraulic Coupled Modelling; Computational Acceleration

1 INTRODUCTION

The confluence of shifting climate patterns and rapid urban expansion has led to a marked rise in extreme rainfall, placing immense strain on urban public safety and infrastructure (Fan et al., 2025, Zhang et al., 2025). High-density urban environments, characterized by vast impervious surfaces and shrunken natural retention areas, have become highly sensitive to flash floods that frequently overwhelm traditional drainage systems (Bakhtiari et al., 2023, Zeng et al., 2025). The transition from natural landscapes to built environments has fundamentally altered the urban water cycle, resulting in higher runoff coefficients and shortened concentration times (Song et al., 2024).

Despite continuous engineering advancements, conventional flood management often hits technical and operational ceilings. A primary obstacle is the existence of fragmented data silos across meteorological, hydrological, and municipal planning departments (Ge et al., 2025). Critical information remains isolated within disparate administrative units, complicating unified response efforts during a crisis (Liu et al., 2024). Furthermore, older forecasting models frequently struggle to reflect the complex, non-linear water flow changes seen during intense cloudbursts (Zeng et al., 2025). While broad-scale models offer discharge estimates, they often lack the granularity required to simulate dynamic inundation at the street or building level (Zhang et al., 2025, Qi et al., 2021). Perhaps most importantly, current emergency protocols rely heavily on static plans that lack the flexibility to adapt to rapidly evolving flood conditions in real time (Liu et al., 2024).

To address these vulnerabilities, Digital Twin technology provides a way to bridge these disconnected elements. Defined as a virtual mirror of physical entities that undergoes continuous updates via real-time data, a Digital Twin facilitates the visualization, analysis, and simulation of complex system behaviour (Kaynak et al. 2025, Chen et al., 2024). In the context of urban flooding, DT technology allows for the fusion of multi-source data—including satellite imagery, Internet of Things (IoT) sensors, and 3D city models (BIM/GIS)—into a cohesive digital baseboard (Li Q, 2022, Ge et al., 2025). Recent strategic initiatives, such as the "Digital Twin Basin" development framework, have underscored the necessity of moving toward proactive, intelligence-driven management (Zhang et al. 2024, Cai Y. 2022, Zhu et al., 2025).

The operational heart of this framework is the "Four-Pre" logic: Forecasting, Warning, Rehearsal, and Planning (Li, et al., 2022). In this cycle, Forecasting establishes the empirical basis through rolling data updates; Warning serves as a sentinel, identifying risk thresholds before a disaster manifests; Rehearsal acts as an essential tool for "what-if" testing, enabling managers to evaluate the efficacy of various interventions in a virtual environment; and Planning represents the final objective, translating simulation-derived insights into actionable, optimized emergency responses (Mao, et al., 2024).

Realizing a functional urban flooding digital twin, however, requires overcoming substantial modelling and computational hurdles. High-resolution simulations that couple one-dimensional pipe networks with two-dimensional surface flow are notoriously resource-intensive (Yang, et al., 2024, Wang, et al., 2025). To provide results within the "minute-level" windows needed for emergency decision-making, advanced acceleration techniques—such as GPU-based parallel computing and Local Time Step (LTS) algorithms—are essential to minimize calculation overhead without compromising precision (Fan et al., 2025, Wang, et al., 2023). Moreover, the integration of advanced Knowledge Graph technologies transforms the platform from a passive monitoring tool into an intelligent decision-support ecosystem, enabling rapid multi-scenario visualization and actionable emergency planning.

The following sections provide a systematic exploration of the framework, beginning with Methods and System Architecture and the protocols for Data Fusion and Digital Baseboard Construction. Subsequent chapters focus on Coupled Hydro-Hydraulic Modelling and Computational Acceleration, followed by an analysis of forecasting precision in Results and Case Studies. Finally, Discussion and Conclusions reflect on the framework's contribution to urban resilience.

2 METHODS AND SYSTEM ARCHITECTURE

The proposed framework implements a hierarchical configuration to maintain a direct correspondence between physical watershed processes and their virtual representations. This methodological approach ensures that the digital twin functions not merely as a visualization tool, but as an active management infrastructure capable of autonomous response and predictive analysis.

2.1 Hierarchical Framework and Layered Architecture

The proposed framework implements a decoupled five-layer architecture to establish a high-fidelity mapping between the physical watershed and its digital twin.

The Physical Layer represents the baseline urban topography and hydraulic infrastructure such as pipe networks, pump stations, and sluice gates. Overlying this, the Perception Layer utilizes IoT sensors and rain radars to capture real-time dynamic boundary conditions, such as rainfall intensity and water levels. These streams are integrated into the Data Layer, which fuses static 3D city models via LiDAR and oblique photography with real-time sensor data into a unified spatiotemporal database.

The Model Layer serves as the simulation core. Unlike conventional digital twins that rely either on computationally heavy traditional models which lack timeliness or pure-AI algorithms which often yield unstable and low-precision results, this framework distinguishes itself through a novel hybrid dual-engine architecture. It tightly couples physically-based 1D-2D hydro-hydraulic solvers with a rapid forecasting module utilizing multi-layer grid overlay analysis and static-dynamic variable decoupled interpolation. This hybrid innovation resolves the inherent conflict between simulation speed and physical accuracy, reducing computational time to 1/12 of classic models while maintaining an absolute inundation depth error of less than 5 cm. Finally, the Application Layer acts as the executive interface for urban flood management.

Crucially, this hierarchical design establishes a Data-Model-Decision Closed-loop. Rather than acting solely as a passive observation tool, the digital twin empowers operators with a domain-specific Knowledge Graph and a scheme library. This ensures that simulation insights are rapidly translated into optimized, actionable emergency scheduling strategies.

2.2 The "Four-Pre" Operational Cycle

The operational efficacy of the proposed framework is governed by the "Four-Pre" operational cycle, which systematizes the dynamic transition from environmental data to proactive risk mitigation through Forecasting, Warning, Rehearsal, and Planning (Figure 1). Forecasting serves as the empirical foundation, utilizing rolling data ingestion to generate high-resolution hydrological projections across a 72-hour horizon. When simulated water stages breach safety thresholds, the Warning module automatically triggers multi-level risk alerts, ensuring critical information is rapidly disseminated to administrative authorities.

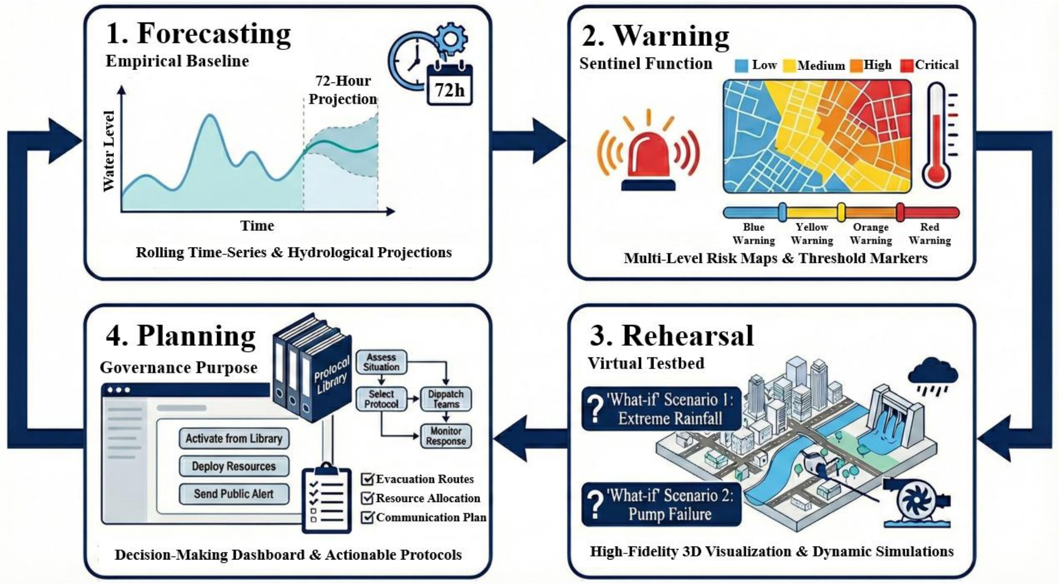

Figure 1: the “Four-Pre” Operational Logic

Building on these predictions, the Rehearsal component functions as a virtual testbed. It utilizes optimization algorithms to evaluate diverse scheduling schemes—such as varying sluice gate openings or pump station configurations—under extreme rainfall scenarios prior to physical deployment. Finally, the Planning phase translates these simulation-derived insights into optimized, actionable emergency protocols. This continuous cycle shifts urban flood management from a reactive, experience-based crisis response to a proactive, evidence-based governance paradigm.

3 DATA FUSION AND DIGITAL BASEBOARD CONSTRUCTION

The framework establishes a unified digital baseboard that is deeply integrated with the broader Smart City framework, dismantling traditional data silos across municipal departments. It fuses multi-source spatiotemporal data into comprehensive dimensions: hydrological sensing, engineering facility status, space-air-ground integrated perception, and urban crowdsourced monitoring (Figure 2).

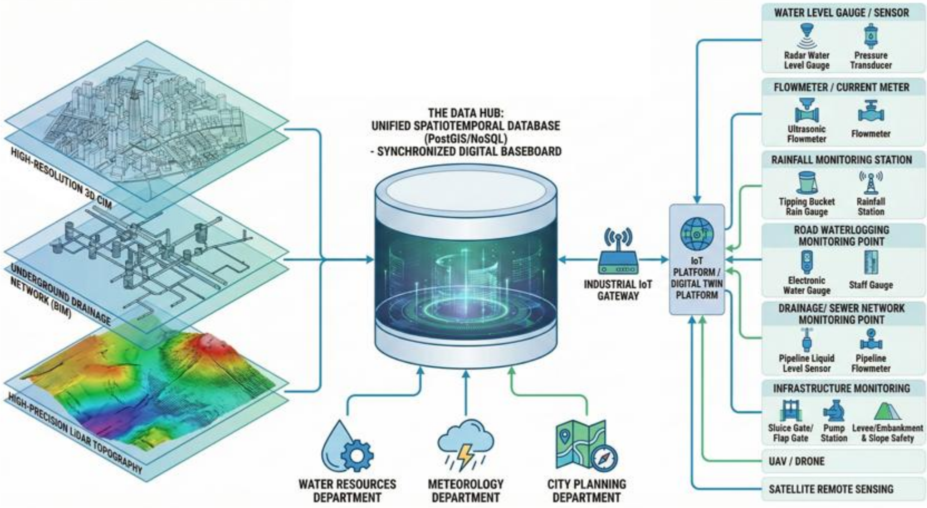

Figure 2: Multi-source Data Fusion

At the ground and subterranean levels, an extensive IoT network captures dynamic boundary conditions via radar water gauges, pipeline sensors, and geotechnical monitors. Crucially, moving beyond conventional water-centric data, the system ingests cross-departmental and public data streams. This includes real-time traffic information and crowdsourced data from social media platforms (e.g., Weibo, WeChat, and Douyin). These non-traditional data sources serve as vital auxiliary indicators, enabling the system to rapidly detect, verify, and assess the severity of urban waterlogging on streets and underpasses in real time.

To achieve space-air-ground integration, the system fuses high-resolution 3D city models with X-band rain radar data. Synchronized via robust industrial IoT gateways and protocols (e.g., 5G, NB-IoT, SCADA), these multimodal streams are continuously ingested into a distributed spatiotemporal database. This comprehensive data fusion provides the high-fidelity empirical foundation necessary to drive the "Four-Pre" operational cycle.

4 COUPLED HYDRO-HYDRAULIC MODELLING AND COMPUTATIONAL ACCELERATION

The simulation core of the framework is built upon a dual-engine modelling architecture that integrates a high-fidelity hydrodynamic solver with a novel rapid forecasting system based on multi-layer grid overlay analysis. The mechanistic component employs a refined 1D-2D coupled model to simulate flood propagation across urban surfaces, river networks, and subsurface drainage systems. Flow dynamics in channels and conduits are governed by the Saint-Venant equations. To represent intricate surface inundation processes typical of dense urban settings, the 1D drainage network is bidirectionally coupled with a 2D shallow-water solver. The model employs dynamic mesh refinement and local time-stepping methods to handle complex micro-topography, enabling the pre-simulation of historic and synthetic 72-hour flood events to populate a comprehensive model scenario library.

While this study is conceptualized under the macro-framework of China's 'Digital Twin Basin' strategic initiative, the specific hybrid dual-engine methodology and the Nanjing demonstrative case study presented herein represent our original, previously unpublished adaptations and technical enhancements.

Complementing the physics-based engine, a data-driven rapid forecasting module provides near-immediate projections. Unlike conventional approaches, this module executes a multi-layer grid overlay analysis across three distinct spatial scales: meteorological grids, catchment grids, and hydrodynamic model grids. Through GIS-based geometric intersection, the system dynamically calculates the rainfall allocated to each catchment unit using the intersection area between meteorological grid points and catchment zones as the distribution weight.

To achieve massive computational acceleration, the system leverages a distributed spatiotemporal database (e.g., PostgreSQL with Postgres-BDR) and employs a static-dynamic variable decoupled interpolation method. The dynamically calculated catchment rainfall is rapidly queried via database indexes against the pre-computed scenario library to identify the matching historical rainfall intervals. Subsequently, utilizing barycentric coordinate linear interpolation within a parallel computing environment, the maximum inundation depth for each hydrodynamic grid cell is rapidly calculated.

Within the platform, the two engines operate cooperatively: the mechanistic solver ensures physical consistency, while the multi-layer grid matching module supplies low-latency forecasts. Quantitative evaluations demonstrate that this hybrid innovation effectively resolves the inherent conflict between simulation speed and physical accuracy. It reduces computational time to merely 1/12 of classic hydro-dynamic models, while maintaining an absolute inundation depth error of less than 5 cm. This coupled mechanism transforms the digital twin into an active operational infrastructure capable of driving minute-level emergency decision-making.

5 RESULTS AND CASE STUDIES

The practical efficacy of the proposed framework is demonstrated by the Nanjing Extreme Rainstorm Flood Prevention and Drainage Platform, which integrates multi-source spatiotemporal data to maintain a high-fidelity digital representation of the urban watershed. A central technical achievement of the Nanjing project is the realization of synchronous operation between mechanistic hydro-hydraulic solvers and data-driven predictive models, augmented by advanced knowledge graph technologies.

5.1 Performance of the Dual-Engine Architecture

By coupling physically-based 1D-2D solvers with the multi-layer grid overlay algorithm, the system bypasses the computational bottlenecks inherent in traditional numerical schemes while preserving physical consistency. Supported by distributed databases and parallel computing, this dual-engine architecture facilitates rolling forecast-update mechanisms. Quantitative evaluations in the Nanjing platform demonstrate that this hybrid approach reduces the computational time required for simulating a 72-hour flood process to merely 1/12 of classic hydro-dynamic models. Furthermore, the framework maintains an absolute inundation depth error of less than 5 cm, with over 97.7% of hydrodynamic grid cells exhibiting absolute errors below 0.25 cm, ensuring granular and highly reliable situational awareness.

5.2 Multi-Scenario Visualization and Optimization

The Rehearsal component serves as a high-fidelity virtual testbed utilizing a comprehensive multi-scenario rainstorm waterlogging scheme library. To demonstrate its practicality, an extreme rainfall event in Nanjing was utilized as a case study. The platform simulated diverse precipitation scenarios and their corresponding inundation evolution across the urban terrain. Through intelligent data analysis and map visualization, administrators could visually assess the dynamic distribution of waterlogging risks. Within minutes, the platform retrieved the most appropriate scheduling schemes—such as optimal pump operation sequences—allowing decision-makers to execute one-click scheme invocations. This visual demonstration of effects ensures that the generated emergency protocols are both scientifically rigorous and practically actionable.

5.3 Knowledge Graph-Driven Intelligent Decision Support

Rather than relying on direct physical interventions, the platform emphasizes holistic, system-level decision-making supported by a domain-specific Knowledge Graph. Specifically, the system established the "Nanjing City Main Urban Area River and Hydraulic Engineering Topological Relationship Knowledge Graph". This semantic network extracts and integrates multi-dimensional entities—including spatial relationships, historical flood scenarios, and operational rules.

By fusing this Knowledge Graph with an expert experience library and a business rule library, the digital twin transforms massive, unstructured historical disaster records into structured, reusable reasoning paths. During extreme events, the reasoning engine automatically correlates real-time hydrodynamic predictions with the Knowledge Graph to recommend optimized, scenario-specific scheduling strategies. This intelligent visualization of entities, rules, and predicted outcomes equips urban managers with a comprehensive and practical decision-support ecosystem, fundamentally upgrading the city's proactive flood resilience.

6 DISCUSSION AND CONCLUSIONS

The successful implementation of the Nanjing Extreme Rainstorm Flood Prevention and Drainage Platform confirms that the integration of the "Four-Pre" operational logic transforms urban flood management into a proactive, evidence-based governance paradigm. By utilizing a high-fidelity digital baseboard, the platform effectively dismantles fragmented data silos across meteorological, hydrological, municipal departments, and crowdsourced social platforms, achieving a comprehensive spatiotemporal representation of the urban watershed.

A pivotal milestone of this framework is the development of a hybrid dual-engine modelling architecture that couples mechanistic 1D-2D solvers with a rapid forecasting module based on multi-layer grid overlay analysis. This hybrid innovation dramatically accelerates computational speeds—reducing simulation time to merely 1/12 of classic hydro-dynamic models—while maintaining an absolute inundation depth error of less than 5 cm. Furthermore, by establishing a domain-specific Knowledge Graph and a multi-scenario scheme library, the digital twin has upgraded its cyber-physical integration. Instead of relying solely on manual physical infrastructure adjustments, the system provides an intelligent decision-support ecosystem capable of multi-scenario visualization and one-click scheme invocations. This transition from reactive intervention to an automated, model-driven strategy is critical for high-density urban environments where the lead time for effective crisis mitigation is exceptionally narrow.

To further advance this capability, future iterations will integrate Graph Neural Networks to better capture the complex spatial dependencies inherent in interconnected river and pipe networks. By incorporating Physics-Informed Neural Networks, the system can ensure that data-driven outputs strictly adhere to fundamental hydraulic laws. Furthermore, the emergence of Generative AI offers the potential for on-the-fly scenario synthesis to overcome the limitations of sparse historical datasets.

Ultimately, this study establishes a scalable blueprint for urban resilience in direct alignment with China’s “Digital Twin Basin” strategic initiative. Future research will prioritize Federated Learning to facilitate secure, multi-agency data collaboration, alongside Large Language Models to provide semantic reasoning for emergency responders. By converging high-performance computing clusters with these frontier AI technologies, the urban flood digital twin framework will serve as a robust foundation for the next generation of smart water management.

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