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Integrated Analysis of Flooding and Waterlogging Risks in New Urban Development: A Case Study of Jinan Start-up District, China

Benyou Jia[1,2], Yixin Jing[1], Haochuan Hong[1], Jingxiu Wu[1], Shujuan Cai[1], Ziwu Fan[1]
Hydraulic Engineering Department, Nanjing Hydraulic Research Institute, Nanjing, 210029, China[1]
E-mail: byjia@nhri.cn
National Key Laboratory of Water Disaster Prevention, Nanjing, 210029, China[2]
E-mail: zwfan@nhri.cn

ABSTRACT

The development of new urban areas involves complex subsurface modifications through concurrent construction of critical infrastructure systems. These include flood control structures, drainage networks, transportation corridors, utility pipelines, and urban facilities spanning governmental, residential, educational, and industrial functions. Effective flood risk management in such developments requires comprehensive assessment of both external flood inundation and internal waterlogging hazards to inform resilient urban planning. This study presents a multi-model integration framework combining: 1) rainfall-runoff generation modeling, 2) 1D hydrodynamic simulations for river networks and drainage systems, 3) 2D surface inundation modeling, and 4) hydraulic structure operation protocols for sluice gates and pumping stations. The coupled modeling system enables holistic simulation of complete flood processes from precipitation through runoff generation, surface flow propagation, and water recession.Using Jinan Start-up District as a demonstration case, we developed a flood integration model evaluating 17 computational schemes across two rainfall scenarios. Spatial risk patterns were analyzed through flood depth and duration parameters, with hazard levels classified into four tiers (very high, high, medium, low). The assessment incorporates critical urban assets including completed infrastructure and population centers. Our findings reveal key vulnerabilities and support proposed mitigation strategies: 1) Upgrading drainage channels and pipe networks, 2) Developing park-integrated detention basins, 3) Implementing risk-adaptive measures (population evacuation protocols, temporary flood barriers), and 4) Coordinated watershed-level flood management. The methodology provides a technical foundation for resilient urban planning, emphasizing integrated structural and non-structural flood prevention measures.

KEYWORDS: Resilient Cities; Urban Flood Modeling; Multi-risk Assessment; Extreme Rainfall; Urban Flood Management Strategies

1 INTRODUCTION

In recent years, influenced by climate change, China has experienced increasingly frequent and severe hazardous weather events, with urban rainstorm-induced flooding being particularly prominent in northern regions. The extreme rainfall event that occurred in Zhengzhou, Henan Province, on July 20, 2021, triggered catastrophic urban flooding, leading to cascading disasters such as subway inundation, damage to roads and bridges, and widespread disruption of daily life and economic activities. This event resulted in more than 300 fatalities and direct economic losses amounting to 53.2 billion CNY, causing extraordinarily severe human and property losses and offering profound lessons. Urban flood disasters induced by extreme rainfall are typically characterized by sudden onset, concealed risk points, wide impact ranges, compound flooding processes, diverse secondary hazards, and substantial losses. These features pose complex and formidable challenges to urban flood prevention and mitigation in China (Zhang et al., 2025; Ahmad & Simonovic, 2013). Consequently, promoting the development of sponge cities and resilient cities has become an inevitable choice. On the one hand, such initiatives help enhance the capacity of built-up urban areas to prevent and respond to rainstorm-induced flooding. On the other hand, in the construction of new urban districts, it is necessary to coordinate the relationship between flood control infrastructure and rapid urban spatial development, so as to achieve an organic integration of disaster prevention and urban construction (Ma et al., 2021; Yang et al., 2025).

Over the years, numerous scholars both domestically and internationally have conducted extensive research on urban flood risk assessment and management, forming a comprehensive research chain from risk identification and process simulation to decision-making and response, and yielding abundant (Hou et al., 2025). In terms of risk assessment, early studies predominantly adopted indicator-based approaches, such as the hazard-exposure-vulnerability framework, to perform static evaluations. With technological advancement, scenario-based simulation has become the mainstream approach, in which rainfall – flood modeling is coupled with loss assessment models to quantify risks under multiple climate and land-use scenarios. This approach has progressively evolved from regional-scale analyses toward refined assessments at the street and community levels, and has begun to address the risk characteristics and evaluation models of cascading rainstorm events, such as subway inundation and building damage (Ming et al., 2020; Lin et al., 2023; Chen et al., 2012). In terms of simulation and scenario deduction, which constitute the core technologies for risk assessment and early warning, traditional hydrological and hydraulic models, such as SWMM, HEC-RAS, and MIKE, have been widely applied in urban flood modeling. The current trend is to couple physical-process-based models with data-driven models in order to balance accuracy and computational efficiency (Lu et al., 2024; Dazzi et al., 2024; Romana et al., 2015). In emergency management, the focus has shifted from an emphasis on engineering defenses toward comprehensive process-oriented management and the coordination of socio-technical systems. Complex network theory has been employed to analyze disaster-chain propagation and emergency resource allocation. Meanwhile, emerging information technologies, including media data mining, artificial neural networks, and unmanned aerial vehicle remote sensing, have demonstrated increasing effectiveness in emergency response (Yang & Yeh, 2014; Li et al., 2023; Konapala et al., 2020). In summary, risk assessment provides risk scenarios and vulnerability parameters of exposed elements for simulation, while simulation generates dynamic inundation extents, depths, velocities, and early-warning information for risk assessment. Emergency management, in turn, utilizes the warning outputs from simulations and the vulnerability analyses from risk assessment to optimize resource allocation and implement targeted interventions. These three components are mutually reinforcing and form a closed-loop framework, constituting a core technical pathway for urban flood risk governance.

This study selects the Jinan Start-up District, a rapidly developing urban new area, as the research object. Based on the construction tasks defined in the flood control and drainage master plan, the dimensions and anticipated parameters of engineering infrastructure are preset. A coupled hydrological-hydrodynamic model is then constructed. Multiple rainfall scenarios are assumed to analyze river water level processes and the spatial distribution of surface inundation risk. The impacts of inundation risk factors on planned urban spatial elements are systematically evaluated. On this basis, recommendations are proposed for the optimization and adjustment of planned infrastructure as well as for the prevention and response of key urban protection targets under extreme rainfall conditions. The study aims to provide effective technical support for the development and construction of urban new districts.

2 METHEDOLOGY

2.1 Jinan Start-up District Overview

Jinan is one of China’s key flood-prone cities. It is located with Mount Tai to the south and the Yellow River to the north, situated at the transitional zone between the central-southern Shandong mountainous region and the northwestern Shandong alluvial plain. The terrain is characterized by higher elevations in the south and lower elevations in the north, with pronounced intra-annual and inter-annual variability in precipitation. The long-term mean annual rainfall is approximately 670 mm, with most precipitation concentrated during the flood season from June to September. Under extreme weather conditions, the city is highly susceptible to flood disasters. The Jinan New and Old Kinetic Energy Conversion Start-up District (hereinafter referred to as the Start-up District) is a national-level strategic new area. Its directly administered area includes four subdistricts: Daqiao, Cuizhai, Sungeng, and Taiping. The total area is approximately 450 km^2. According to statistics in 2020, the district contained 308 villages and nearly 400,000 mu of cultivated land, and is currently undergoing a rapid process of urbanization. According to the flood control and drainage special plan for the Start-up District, by 2035, a “safe and resilient” flood control and drainage disaster reduction system will be established through a combination of engineering and non-engineering measures. This system is intended to safeguard the sustainable socio-economic development of the Start-up District. The 2020 satellite imagery of the Start-up District and the planned river system and concentrated urban areas for 2035 are shown in Figure 1.

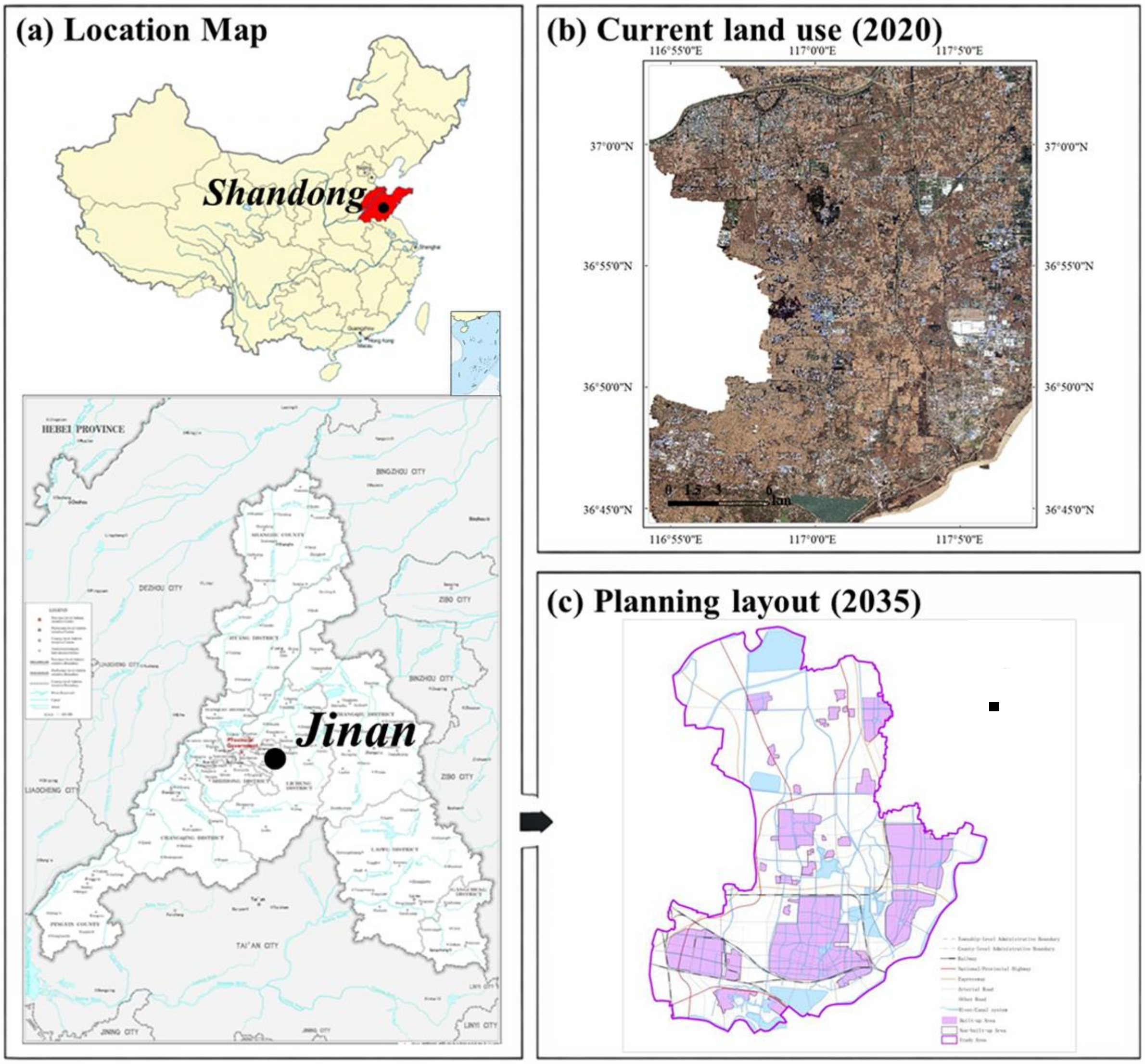

Figure 1. Location and planning layout of the study area (a) Geographic location of the study area within Jinan City, Shandong Province, China. (b) Curent land useconditions in 2020. (c) Planned urban layout in 2035. Major rivers, urban areas, and planning boundaries are ill.

2.2 Integrated Analysis Process

Based on the fundamental parameters of flood control and drainage infrastructure at the planning stage, and incorporating key geographical attributes such as the construction targets in urban areas and their parcel elevations, this study constructs an integrated flood simulation model. The model is employed to evaluate inundation risk factors under both design rainfall and extreme rainfall scenarios. Flood impact assessment criteria are established accordingly. Using GIS-based spatial overlay analysis, the flooding risk levels of urban construction targets are identified. Targeted long-term flood risk prevention and response strategies for urban new district development are then proposed. The results provide technical support for improving the flood control and drainage master plan of the Start-up District, enhancing flood resilience, and informing safety-oriented decision-making.

2.3 Hydrology and Hydrodynamic Model

The integrated flood simulation model which is conducted by Infoworks ICM for the Start-up District mainly incorporates hydrological and hydrodynamic processes, including rainfall generation, surface runoff formation, drainage network convergence, and river network routing. A basin-scale integrated urban flood modeling software is employed to construct the model framework and support flood inundation simulations under multiple analytical scenarios. The flood inundation simulation adopts a coupled one-dimensional and two-dimensional hydraulic computation approach. The one-dimensional unsteady flow simulation in rivers is based on the Saint-Venant equations. Model construction primarily involves establishing river cross-sections, hydraulic structures, and their operational rules. The two-dimensional overland flow simulation is based on the shallow water assumption. Under this assumption, the fundamental conservation equations are simplified and solved using grid-based numerical computation. The key components of model construction are illustrated in Figure 2.

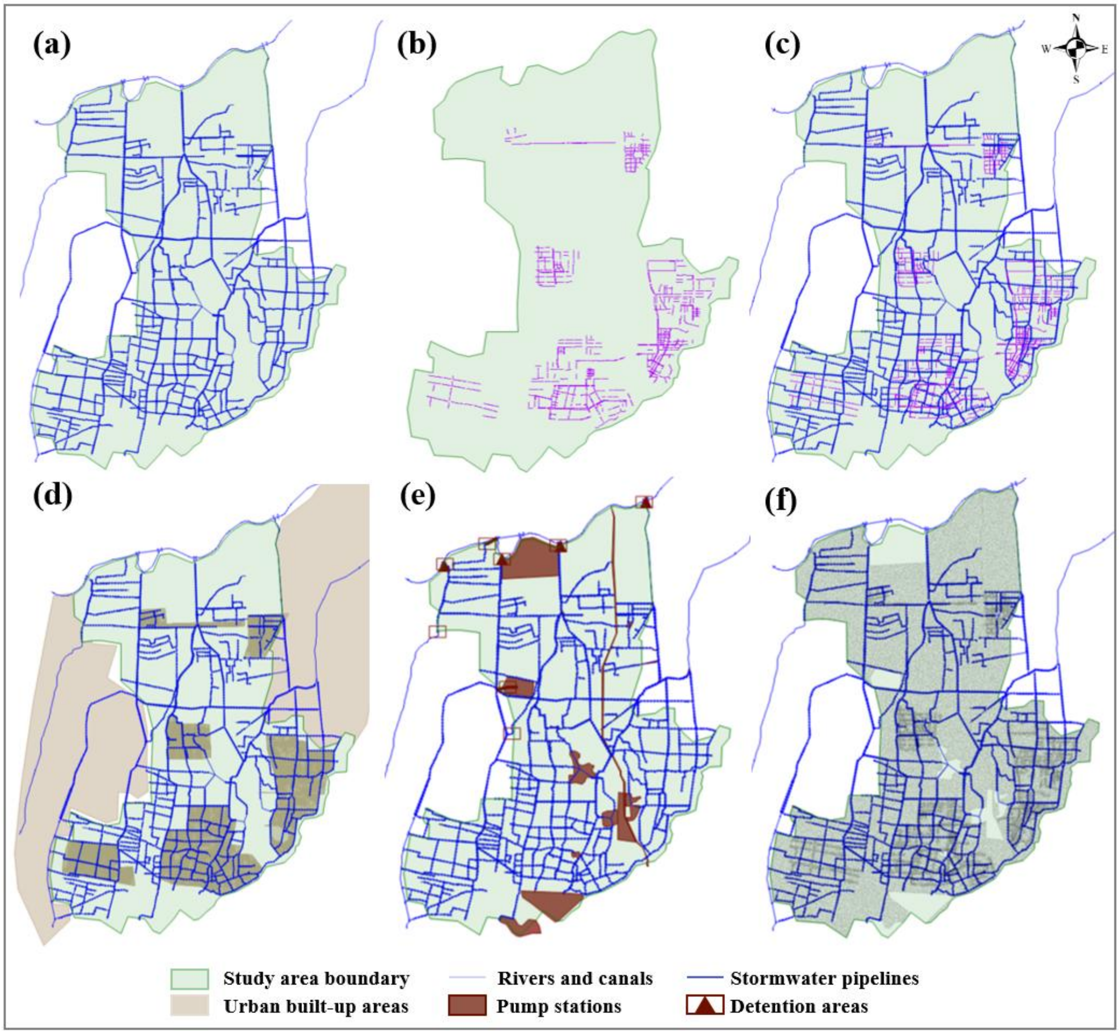

Figure 2. Schematic diagram of key components of hydrology & hydrodynamic model construction ((a) River and canal network, (b) Stormwater pipelines network, (c) Integrated rivers and pipelines, (d) Urban built-up areas, (e) Pump stations & Flooding detention areas, (f) Computational grid)

2.4 Integrated Analysis Scheme

Flood risk is often the result of the superposition of multiple adverse factors, and it is therefore necessary to first clarify the composition of floodwater sources responsible for inundation. This step is essential for identifying the flood-generating mechanisms considered in the risk analysis. According to the actual conditions of the Start-up District, under regional heavy rainfall events, the main flood sources considered in this study include three types: (1) inundation caused by the overtopping of internal trunk drainage rivers due to backwater effects from high water levels in external rivers, representing flood-induced waterlogging; (2) waterlogging caused by insufficient drainage capacity of urban stormwater pipelines due to backwater effects from high water levels in internal trunk rivers, representing capacity-limited waterlogging; (3) waterlogging caused by rainfall accumulation in locally low-lying areas. The computational schemes for different scenario combinations are presented in Table 1.

Table 1. Computational schemes under different scenarios

Scenario Design	Scheme Combination	No.	Rainfall (mm)	Rainfall Return Period (a)	Initial Water Depth (m)
Design Rainfall	Short-duration (3h) combined with high / low inner river water depth	1	85.7	3	0.1, 1.2
		2	98.0	5	0.1, 1.2
		3	114.6	10	0.1, 1.2
		4	131.3	20	0.1, 1.2
	Long-duration (24h) combined with outer river flood control / drainage water depth	5	199.0	20	3.0, 5.0
		6	219.8	30	3.0, 5.0
		7	246.0	50	3.0, 5.0
		8	281.3	100	3.0, 5.0
Extreme Rainfall	Short-duration (1h) combined with low inner river water depth	9	100	50	0.1
	Short-duration (6h) combined with low inner river water depth	10	200	/	0.1
	Long-duration (24h) combined with outer river drainage water depth	11	250	50	3.0
		12	280	100	3.0
		13	350	/	3.0
		14	450	/	3.0
		15	550	/	3.0
		16	650	/	3.0
	Zhengzhou 7·20 Rainstorm (72h)	17	201.9 645.6 789.1	1000	3.0

2.5 Flooding Risk Classification Criteria

Studies by Xu Zongxue and colleagues on human and vehicle vulnerability indicate that the risk of human sliding and falling instability is determined by water depth. When the overturning moment generated by the drag force of flowing water equals the resisting moment produced by the effective body weight, a person will topple. The Guidelines for Flood Risk Mapping provide explicit indicators and standards for flood risk classification. By synthesizing existing academic findings and industry standards, this study classifies flood disaster risk levels based on the maximum inundation depth. Five risk levels are defined, as presented in Table 2.

Table 2 Flooding Risk Level Classification Criteria

Risk Level	Inundation Depth (m)	Impact Severity	Distinguishing Color
No Risk	≤0.15	Minimal impact on production and daily life	White
Low Risk	0.15~0.30	Significant impact on travel	Green

Medium Risk	0.30~0.60	Travel safety for children is threatened	Yellow
High Risk	0.60~1.00	Life safety of minors cannot be guaranteed	Orange
Extremely High Risk	≥1.00	Movement is threatened for everyone	Red

3 RESULT AND DISCUSSION

3.1 Design Rainfall Scenario

(1) Short-duration rainfall

Comparisons between high and low initial inner-river water levels indicate that the differences in the total inundation extent across the Start-up District are negligible. The differences in the total inundated area within the concentrated urban zones are 0 km^2, 0.01 km^2, 0 km^2, and 0.02 km^2, respectively. This demonstrates that, during short-duration rainfall events, the drainage performance of the concentrated urban areas is only weakly influenced by the initial river water level. For short-duration design rainfall events at different return periods, most of the concentrated urban areas fall within the no-risk category, with a small proportion classified as low risk. The proportion of areas with high risk or above (inundation depth $\geqslant$ 0.6 m) is 0.24%, 0.35%, 0.40%, and 0.54%, respectively. These inundated locations are primarily distributed in locally low-lying zones. The results indicate that, by 2035, the planned stormwater drainage network will significantly enhance the drainage capacity of urban areas.

(2) Long-duration rainfall

Different combinations of the initial drainage and flood-control water levels of external rivers are employed to comprehensively evaluate the potential inundation-prone areas, inundation severity, and the accumulation and recession processes of floodwater under various design frequencies. Under low external river water levels, when the concentrated urban areas encounter 20-, 30-, 50-, and 100-year return period design rainstorms, the total inundated areas (water depth > 0.15 m) are 5.33 km^2, 5.97 km^2, 6.80 km^2, and 8.15 km^2, accounting for 4.38%, 4.91%, 5.59%, and 6.70% of their respective areas. In the non-concentrated urban areas, the corresponding inundated areas are 77.84 km^2, 83.53 km^2, 90.73 km^2, and 98.92 km^2, representing 20.69%, 22.28%, 24.42%, and 26.92% of their total extents. Under high external river water levels, when the concentrated urban areas experience 20-, 30-, 50-, and 100-year return period design rainstorms, the total inundated areas are 5.34 km^2, 6.02 km^2, 6.91 km^2, and 8.31 km^2, accounting for 4.38%, 4.91%, 5.59%, and 6.70% of their areas. In the non-concentrated urban areas, the corresponding inundated areas are 81.57 km^2, 87.86 km^2, 96.30 km^2, and 106.17 km^2, representing 19.74%, 21.18%, 23.01%, and 25.08% of their extents. These results indicate that, by 2035, owing to the planned river widening, dredging, and water system connectivity projects, the river water level hydrographs under long-duration rainfall events exhibit limited variation. The trunk rivers are capable of maintaining effective drainage performance. However, downstream areas remain affected by backwater effects from the Tuhai River.

3.2 Extreme Rainfall Scenario

(1) 24-hours Extreme Rainstorm

Taking the 250 mm rainfall event as an example, the total inundated area reaches 99.99 km^2, accounting for 19.38% of the district. The inundated area within the concentrated urban zones is 7.01 km^2, representing 5.76% of their total area. Compared with the 6-hour 200 mm rainfall scenario, the inundation extent in the concentrated urban zones is slightly reduced. Only a very small number of medium- to high-risk areas (inundation depth > 0.3 m) are observed. This indicates that, although the total rainfall amount increases, its temporal concentration decreases. Meanwhile, the planned drainage network operates over a longer discharge duration, resulting in a reduced inundation extent.

(2) Zhengzhou 7 • 20 Rainstorm

The total inundated area reaches 243.4 km², accounting for 47.2% of the Start-up District. Within the concentrated urban zones, the inundated area accounts for 25.45% of their total extent. Areas classified as high risk or above constitute 9.08% of the concentrated urban zones. Regarding urban waterlogging, the peak rainfall of the Zhengzhou “7 • 20” event occurred at 17:00 on July 20, with a maximum single-station intensity of 201.9 mm/h. After the peak, rainfall persisted until 12:00 on July 21. When this event is transposed to the Start-up District for simulation, the peak inundation depths in the concentrated urban zones mostly occur between 21:00 on July 20 and 06:00 on July 21, corresponding to 2-11 hours after the rainfall peak. Urban waterlogging is primarily caused by overtopping of secondary rivers and surcharging of stormwater pipelines. In terms of river drainage, the water level hydrographs at representative cross-sections exhibit a pattern of rapid rising and slow recession. By 2035, although the river drainage capacity will be enhanced, overtopping still occurs, indicating that the Zhengzhou “7 • 20” rainstorm exceeds the planned design standards.

3.3 Flooding Risk Impact Assessment

Based on the attribute information of planned urban spatial elements in the Start-up District, this study focuses on two categories of objects: urban lifeline infrastructures and key flood-protection targets. A total of 150 urban lifeline infrastructure objects and 665 key flood-protection objects are involved. By integrating the model-derived inundation risk results, flood risk hotspots for different urban objects under various rainfall scenarios are identified. The flooding impacts on representative objects, including power infrastructure and primary and secondary schools, are illustrated in Figure 3.

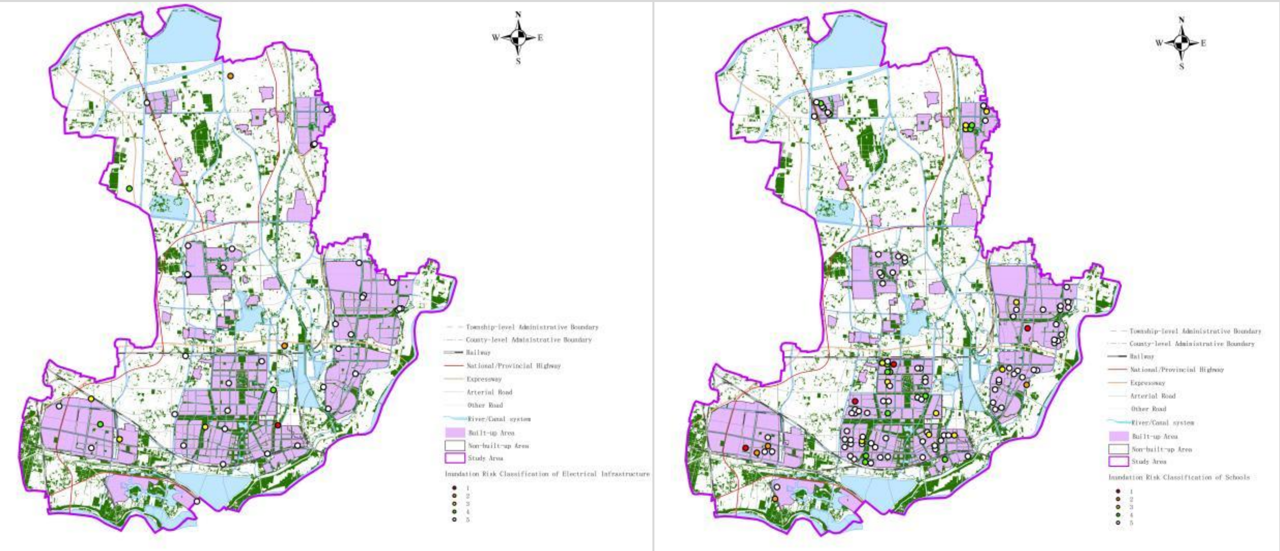

Figure 3. Illustration of flood impacts on planned power infrastructure and primary & secondary schools

4 CONCLUSION

Based on the 2035 urban development layout and the flood control and drainage construction tasks of the Jinan Start-up District, this study proposes a planning-level coupled flood simulation framework. The framework is applied to analyze flood inundation risks under both design rainfall and extreme rainfall scenarios, and refined assessments of inundation risk impacts are conducted. The main conclusions are summarized as follows.1) Under short-duration design rainstorms, the inundation extent within concentrated urban zones shows negligible differences under different initial river water levels, and urban waterlogging is primarily controlled by the intake capacity of the stormwater drainage network. 2) Under long-duration design rainstorms, the overall drainage performance generally meets the 50-year return period design standard. The inundation extent within concentrated urban zones increases with rainfall magnitude, while being only weakly affected by the backwater effects of external rivers. 3) Under the Zhengzhou “7 • 20” extreme rainstorm scenario, the inundation extent in the Start-up District becomes extensive. The rainfall amount is approximately 2.6 times that of the 50-year design rainfall, far exceeding the response capacity of the planned 2035 flood control and drainage system of the Start-up District. Future research should prioritize optimizing the spatial layout of planned engineering measures, exploring the potential of coordinated flood control operations at both watershed and regional scales, and strengthening flood emergency management measures.

5 ACKNOWLEDGEMENTS

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