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Simulation Study on Rain-Flood Regulation in Urban "Gray-Green-Blue" Spaces Based on System Dynamics: A Case Study of the Guitang River Basin in Changsha

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Abstract: Urban rainstorms and flood disasters are the most common and severe environmental problems worldwide. Many factors influence rain-flood control simulation, forming a complex network system of interconnected and mutually constraining elements. In terms of spatial scale selection, existing research on rain-flood disaster risk largely relies on a single-scale infrastructure index system and has not yet focused on urban "gray-green-blue" spatial scale simulations for rain-flood storage. Regarding research methodology, applying system dynamics methods to the simulation of rain-flood storage and disaster prevention planning in watershed cities is still in its initial stages. System dynamics models can simulate the feedback interactions among various sub-elements in the coupled mega-system, fully addressing complex issues within the system structure that involve multiple variables, non-linear relationships, and numerous feedback loops, thereby compensating for the inadequacies of traditional linear models in the collaborative management of rain-flood risks. Taking the Changsha Guitang River Basin as an example, this paper constructs a system dynamics model covering four dimensions: natural environment, socio-economics, internal structure, and policy development. It aims to derive the optimal planning scheme for gray-green-blue spatial coordination in rain-flood storage by weighing four different development scenarios. The simulation results show: (1) Simply changing the surface substrates without considering rainwater discharge and the plan that emphasizes the construction of municipal drainage facilities will see the capacity gap for rain-flood storage-space construction continue to widen by 2035. This indicates that the plans mentioned above will struggle to bear the socio-economic losses cities face during rain-flood disasters. (2) The plan of combining gray and green infrastructures sees the rain-flood storage construction capacity turn from negative to positive from 2024, rising to 52.259 billion yuan by 2035. This reflects that the plan can significantly reduce the rainwater volume in the later stages of low-impact development infrastructure construction, mitigate rain-flood disaster risks, and reduce government investment in rain-flood disaster risk management, making it a relatively excellent long-term rain-flood storage space planning option. (3) The rain-flood regulation space planning scheme, under the combined effect of the urban "gray-green-blue" network system, sees the capacity for rain-flood storage construction turn positive a year earlier than the previous plan, reaching 54.232 billion yuan by 2035. This indicates that the scheme can not only effectively respond to extreme flood and rainstorm disasters but also maintain ecological environment benefits and mitigate the socio-economic losses caused by disasters, making it the optimal choice for future government disaster management planning. The research results provide a theoretical framework and practical insights for territorial spatial planning, rain-flood control management, and resilient city construction in watershed areas.

Keywords: rain-flood regulation; "gray-green-blue" spaces; system dynamics; Guitang River Basin

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1. Introduction

Urban rainstorms and flood disasters rank among the most prevalent and severe environmental challenges globally [1,2]. The *Global Natural Disaster Statistics Report* highlights that, owing to their frequent occurrence and associated risks, flood disasters have emerged as the foremost type of natural calamity, critically impacting ecological safety patterns and the stability of societal operations [3–5]. Notably, China, with its extensive basin areas, stands as one of the nation's most susceptible areas to rainstorm and flood disasters. This is particularly true in its densely populated and economically vibrant southern plains and hilly regions [6]. Cities situated in watershed areas, due to their distinct lacustrine network geography and complex water–land interrelations, are inherently more prone to rainstorms and flood disasters compared to other urban settings [7]. Exacerbated by the abrupt shifts in monsoon climates and the rapid expansion of human societal activities, the risk and frequency of rain-flood disasters in these Chinese watershed cities have intensified. Consequently, when prolonged heavy rainfall overwhelms the regional drainage systems, it precipitates a cascade of urban disasters. These include rain-induced urban waterlogging, river overflows, levee breaches, infrastructural damages, and subsequent failures in cross-ditch road bases, thereby posing secondary hazards to agriculture, transportation, urban development, and human health [8]. Hence, in the context of low-impact development, devising strategies to mitigate the adverse effects of rain-flood disasters on urban areas and to augment the flood resilience and recovery capabilities of urban infrastructures has become a critical concern for governments worldwide [9,10].

The evolution of rain-flood disasters constitutes a complex systemic process that encompasses the intricate interactions and mutual influences of various domains, including the natural environment, social environment, land resource management, water resource management, and urban planning. Primarily, elements within the natural environment act as direct catalysts for rain-flood disasters. Factors such as precipitation, topography, and geological conditions collectively delineate the dynamics of these disasters, with intense rainfall potentially leading to flooding and the terrain and geological features influencing flood spread and depth. Secondly, the social environment plays a pivotal role in the context of rain-flood disasters. Escalating population density and urbanization render cities increasingly susceptible to flooding. Concurrently, societal environmental consciousness and the focus on climate change directly shape society's perception, response, and management of such disasters. In terms of land resource management, judicious land use planning can mitigate the risk of construction and infrastructure development in flood-prone zones. Conversely, imprudent land management might contribute to the expansion of flood hazard areas. Water resource management is equally critical; mismanagement in this sector can result in the siltation of water bodies and obstruction of flood discharge channels, thereby intensifying flood-related damage. Lastly, urban planning is integral to the prevention and control of rain-flood disasters. Thoughtfully designed drainage systems, green spaces, and rain gardens can significantly decelerate rainwater runoff and diminish flood risks. Thus, to efficaciously manage and alleviate the impacts of rain-flood disasters, it is imperative to consider multifaceted factors spanning the natural and social environments, land and water resource management, and urban planning. Developing cross-disciplinary, comprehensive strategies is essential for ensuring the sustainable development of communities and cities and for mitigating potential disaster risks.

In practical scenarios, the frequent onset of rain-flood disasters in regions characterized by dense water networks poses a significant challenge, disrupting the stable functioning of socio-economic systems and threatening the healthy progression of ecological environments. Addressing urban rain-flood and waterlogging predicaments, scholars both domestically and internationally have historically relied on a variety of hydrological coupling models in their research [11]. These studies involve simulations and control analyses of the rain-flood storage capabilities of infrastructures at different scales: small-scale low-impact development facilities [12,13], medium-scale municipal infrastructure [14–16], and large-scale river wetlands [17–19]. These investigations also take into account the impact of environmental factors that contribute to rain-flood disaster risks [20]. One notable example is Kyle's development of a coupled optimization simulation model, which integrates the United States Environmental Protection Agency's Storm Water Management model (SWMM) with the Borg multi-objective evolutionary algorithm (Borg MOEA). This hybrid model is capable of performing multi-objective optimizations, utilizing SWMM simulations to assess potential solutions for optimization challenges [21]. In a similar vein, Zhang, based on observational data and the Hydrus-1D hydrological model, conducted simulations to evaluate the rainwater retention and delay efficacy of various rooftop greening modules with differing types and substrate depths in Beijing, China [22]. Na employed field measurement data, digital elevation model (DEM), radar imagery, as well as climate, meteorological, and land use/land cover data to develop the MIKE21 hydrodynamic model. This model facilitated fine-scale simulation of the eco-hydrological storage processes in semi-enclosed floodplain wetlands [23]. Furthermore, Wang devised a comprehensive river flood risk model, enabling the derivation of exceedance probability loss (EPL) curves and expected annual damage (EAD) assessments under prevailing climate conditions [24].

Reflecting upon historical evaluations and model-based forecasts of rain-flood disaster risks, urban centers globally, particularly those endowed with extensive water networks, are actively devising targeted disaster prevention strategies. These strategies are focused on reducing the threats posed by rain-flood disasters to both socio-economic and ecological environments [25]. Shao has championed proactive adaptation and active mitigation approaches to combat increasingly severe urban waterlogging resulting from extreme weather phenomena, such as storm surges and heavy rainfalls. These strategies are geared towards reconstructing and optimizing urban water systems to bolster their disaster resilience and enhance adaptability and responsiveness to climate change [26]. Zhou introduced an innovative framework for pinpointing areas that should be prioritized in green stormwater infrastructure (GSI) planning. This framework integrates an assessment of flood regulation services (FRS) supply and demand, considering not just flood mitigation advantages but also the socio-economic benefits [27]. Sun has proposed an optimization method that employs predicted peak inflow to determine the necessary storage capacity, further facilitating the management of flood discharge during heavy rainfall. This method explores the synergy between forecast analysis during heavy rains and real-time control to improve the peak outflow reduction capabilities of relatively small storage reservoirs [28]. Mathilde highlighted the governance challenges that emerge from conflicts between spatial planning policies, typically directed by local authorities, and risk prevention policies led by national authorities. This was illuminated through a comparative study of flood prevention planning tools in three European nations: the United Kingdom, France, and the Netherlands [29]. Furthermore, Alhassan suggested a comprehensive green governance framework, taking into account the comprehensive nature of identified barriers and advocating for active participation and collaboration among various stakeholders. This includes watershed management agencies, community groups, local governments, and national institutions functioning collaboratively to address these challenges [30].

The scholarly landscape surrounding urban rain-flood storage simulations has witnessed a marked proliferation in research outputs, with methodologies progressively transitioning from subjective assessments to more quantifiable approaches, including mathematical statistics, 3S (GIS, GPS, and RS) technology analysis, and sophisticated model extrapolations [31–35]. Nevertheless, at the spatial scale level, watershed cities encompass the integral "gray-green-blue" spaces for rain-flood storage. Here, "gray" encapsulates the built environment, such as roads, buildings, and other urban infrastructural elements; "green" embodies natural urban landscapes like parks, forests, gardens, and additional green spaces; while "blue" pertains to water components, such as rivers, lakes, ponds, and related aquatic infrastructures [36]. A notable limitation in existing studies is their reliance on singular-scale infrastructure index systems, often neglecting the comprehensive research on urban "gray-green-blue" spatial scales for rain-flood storage simulations [37]. Moreover, while model simulations have ascended as predominant research methodologies for addressing urban rain-flood disaster risks, there remains a substantial gap in the systematic simulation of feedback interactions among various sub-components within the "natural-social-internal-policy"-coupled mega-system. This oversight highlights a critical area for future research, underscoring the need for more holistic and integrated simulation approaches that encompass the complex interplay of these diverse elements.

System dynamics, a methodology pioneered by Forrester in 1956, employs computer simulation to dissect and address multifaceted multi-system challenges. It notably emphasizes simulating feedback loops within system structures, offering a comprehensive perspective [38,39]. This approach has proven to be an invaluable asset in the realm of water resource management, enabling the study of dynamic behaviors inherent in complex systems [40]. Over the past two decades, system dynamics have seen substantial application and progress in China, particularly in research geared towards the sustainable development of watersheds. A notable contribution in this field is from Wang, who developed a coupled coordination evaluation model for the water resource economic–environment system of the Yellow River. Utilizing system dynamics, Wang simulated and forecasted the levels of coupling coordination under various sub-scenarios, thereby providing a theoretical framework for ecological preservation and high-quality development in the Yellow River Basin [41]. Similarly, Dai established a comprehensive evaluation model for the water environment carrying capacity of the Yongding River Basin in North China. This model serves as a technical aid for balancing economic growth with water security in the water-deficient northern regions of China [42]. Moreover, Jiang constructed a flood management simulation model based on system dynamics, employing scenario simulations to analyze the interplay between flood control, fish production, sediment flushing, and potential landslide risks during different flood season events [43]. However, despite the prevalent use of system dynamics in water-related domains, such as water environments, water resources, and aquatic ecology, its application in the process of rain-flood disaster prevention and management remains nascent. Particularly, a systematic simulation that evaluates the rain-flood storage efficacy of the "gray-green-blue" spatial scales in a coordinated manner has yet to be conducted, signifying a promising area for future research endeavors.

Addressing the abovementioned bottleneck, this paper takes the Guitang River Basin, a water-abundant area in Changsha City, as a research case. Innovatively, it links watershed city rain-flood disasters with natural environments, social environments, land management, and urban planning, fully leveraging the infiltration and storage functions of blue-green spaces such as urban forests, river-lake systems, wetlands, river floodplains, and natural depressions for rainwater. A system dynamics model for rain-flood storage in the city's three core spaces of "gray-green-blue" has been constructed. In practice, the findings of this paper have profound implications for urban planning and disaster management. By integrating the "gray-green-blue" network system into the urban fabric of Changsha City, specifically in the Guitang River Basin, city planners and policymakers can more effectively mitigate the impact of rain-flood disasters. The practical application of this model involves reimagining urban landscapes to incorporate more blue-green spaces, like urban forests and wetlands, which are aesthetically pleasing and serve a critical role in rainwater infiltration and storage. This approach marks a shift from traditional gray infrastructure to a more holistic method that includes green and blue infrastructure, offering a more sustainable and resilient urban environment. Subsequently, based on the analysis of the interaction mechanisms among urban natural environment, economic development, watershed structure, and policy development in four dimensions, we established four disaster-bearing scenarios: the "Status Quo Continuation Scheme", "Gray Infrastructure Planning Scheme", "Gray Infrastructure Combined with the Green Infrastructure Planning Scheme", and "Gray-Green-Blue Infrastructure Space Planning Scheme". Simulations were conducted on the rain-flood storage efficacy of the Guitang River Basin from 2018 to 2035, comparing the optimal planning scheme for rain-flood storage under the joint action of the urban "gray-green-blue" network system of the Guitang River Basin. Furthermore, the disaster-bearing scenarios outlined in this paper provide a roadmap for cities facing similar challenges. Implementing the "Gray-Green-Blue Infrastructure Space Planning Scheme", for instance, would mean redesigning urban areas to create a balance between built environments and natural spaces, enhancing the city's capacity to cope with extreme weather events. This could involve the development of green roofs, permeable pavements, and expanded river floodplains, which not only reduce flood risk but also contribute to biodiversity and improve the quality of life for residents. Urban planners and policymakers can use the system dynamics model developed in this research as a decision-making tool. It allows them to simulate various scenarios and understand the potential impacts of different urban planning strategies on flood mitigation and disaster resilience. This model can be adapted to other urban settings, enabling cities worldwide to benefit from the insights of the Guitang River Basin case study. In summary, this paper's approach to integrating natural and built environments through the "gray-green-blue" network system offers a solution to mitigate rain-flood disasters. It sets a new standard for sustainable urban development. It provides a comprehensive framework that other cities can emulate, ensuring that urban development is in harmony with nature, thereby enhancing the resilience of cities to withstand and recover from environmental challenges.

2. Overview of the Study Area and Research Methods

2.1. Research Area Overview

The Guitang River, situated in the southeastern segment of Changsha City, holds a prominent position as a primary tributary of the Liuyang River. Unique for its course entirely within the urban confines of Changsha, the river stretches approximately 28 km, encompassing a basin area of about 108.6 square kilometers. This area is divided into urban regions spanning 91.06 square kilometers and rural sectors covering roughly 17.11 square kilometers (Figure 1). In recent times, Yuhua District, the location of the Guitang River Basin within Changsha City, has emerged as a pivotal zone for urban construction land expansion. Concurrently, this rapid urbanization has escalated challenges pertaining to water resources, the water environment, and water ecology to the extent of posing significant hindrances to the city's socio-economic development. Per the Hunan Province Disaster Statistics Yearbook, since the inception of the People's Republic of China in 2023, Changsha has endured flood disasters in 59 of the past 75 years, with only 15 years remaining relatively disaster-free; the year 2017 marked the most severe flood disaster in recorded history. These extreme rain-flood disasters have led to a substantial reduction in the Guitang River's network density, water surface ratio, and river meandering coefficient by 18.83%, 65.84%, and 20.25%, respectively. The river now has virtually no remaining tributaries. Given these conditions, this paper selects the Guitang River Basin as the focal point for a system dynamics simulation study of urban "gray-green-blue" space rain-flood storage. This choice is predicated on the basin's typicality and demonstrative significance, providing a valuable case study for understanding and addressing the complexities of rain-flood storage in urban watershed environments.

2.2. Overview of Research Methodology

Addressing the intricate challenges of managing rain-flood disaster risks in the Guiyang River Basin, this study introduces notable innovations in the realms of research subjects, content, and methodology, building upon the foundations of previous scholarly work. In terms of the research subject, the focus is placed on the sustainable regulation of rain-floods within specific basin areas. This entails considering the spatial heterogeneity of the basin, including aspects such as resource allocation, industrial structure, economic development, and policy-making. To this end, pertinent indicators from four subsystems—natural factors, socio-economic factors, internal factors, and policy factors—have been selected. Substantial efforts in data collection, digitization, and entry were undertaken to establish a comprehensive primary database for the system dynamics model of the Guiyang River Basin.

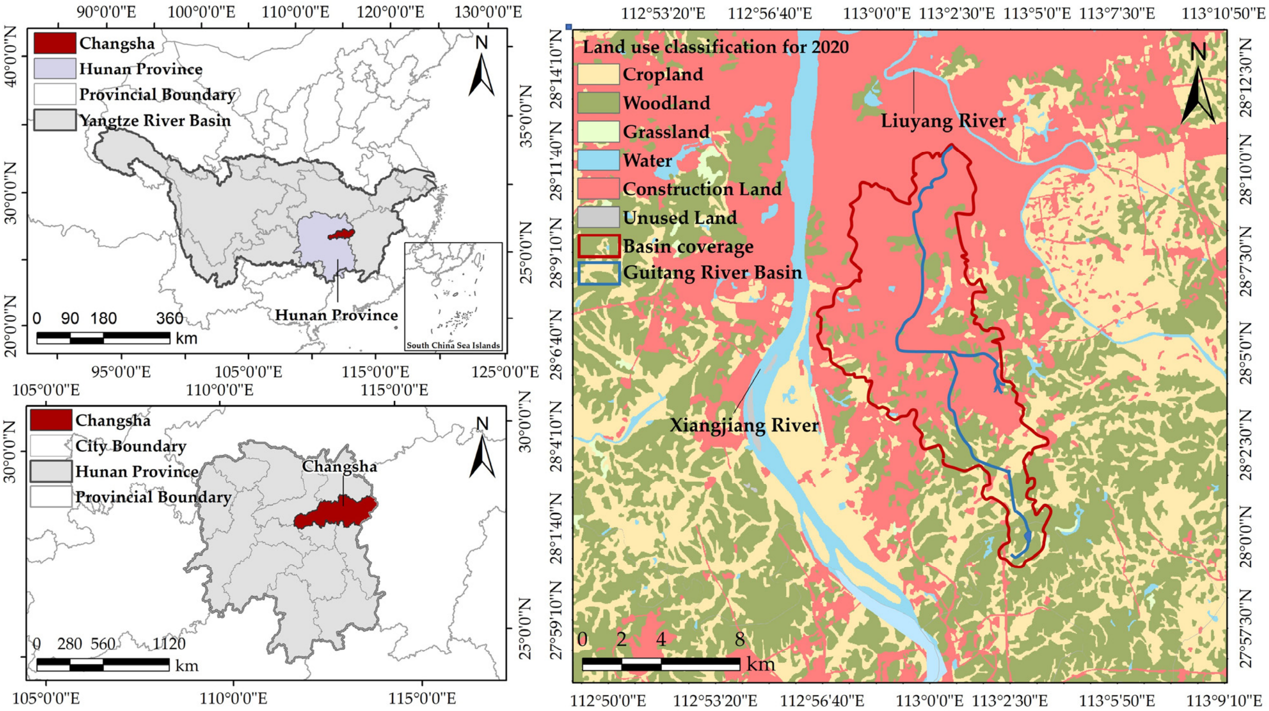


Figure 1. Geographical location, administrative division, and current land use in 2020 of the Guitang River Basin.

Regarding the research content and methodology, the simulation of rain-flood regulation is characterized by its dynamic, hierarchical, and holistic nature, aligning well with the requirements of system dynamics research. This paper aims to deduce an optimal rain-flood regulation plan for the Guiyang River Basin, employing a system dynamics model to construct a simulation framework for rain-flood regulation and comprehensive disaster prevention and management in urban basins. This framework integrates "gray-green-blue" spatial planning, striving to develop a complex urban river system that harmoniously intertwines social, economic, and natural elements. The ultimate goal is to reconcile the demands of high-quality urbanization with the enhancement of ecosystem disaster resilience, thereby offering a fresh perspective for optimizing sustainable rain-flood management models in basin territories.

Figure 2 in the paper delineates the research methodology system and technical roadmap, which encompasses the following four key aspects:

Conducting a causative analysis of the origins of urban basin rain-flood disaster risks and the complexities in rain-flood regulation, this phase involves examining the interplay between rain-flood disaster threats and regulatory measures. Utilizing domestic and international literature, natural environmental coverage imagery, and socio-economic development index data concerning rain-flood disasters, a foundational database for "gray-green-blue" spatial rain-flood regulation is constructed.

The second phase involves defining system boundaries and analyzing cause-and-effect relationships to construct a system dynamics model tailored for rain-flood regulation simulation in urban basins. This phase also includes categorizing indicators into the four aforementioned subsystems.

Using the Guiyang River Basin in Changsha as a practical case study, model parameters are determined, and the model's accuracy is verified. Different parameter values for control volumes are set to establish four developmental scenarios for rain-flood regulation space planning, simulating the planning scheme for the Guiyang River Basin's space from 2023 to 2035.

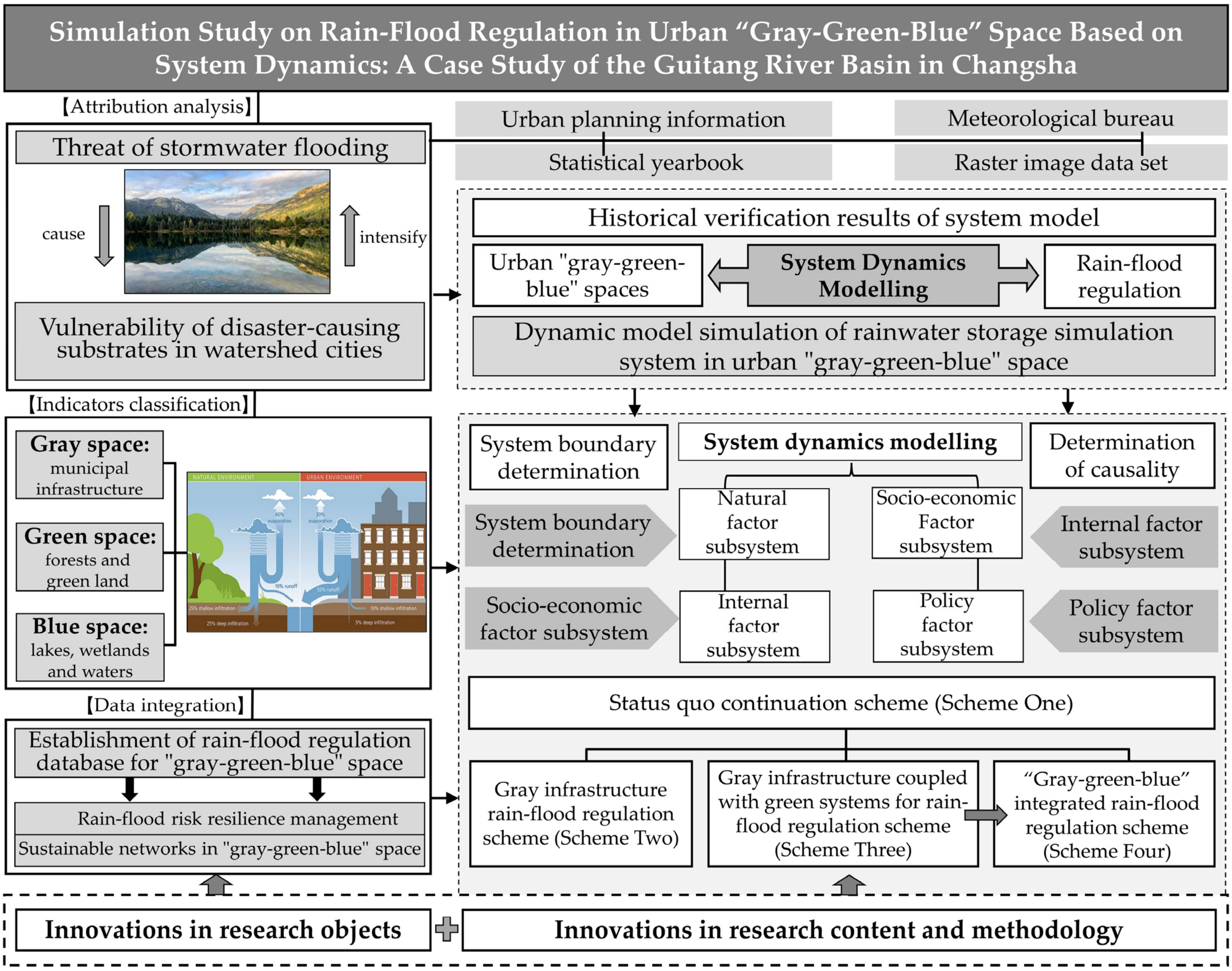


Figure 2. Technology pathway diagram.

The final phase involves comparing the outputs of future rain-flood regulation planning scenarios. An efficacy assessment and early warning mechanism for rain-flood regulation within the "gray-green-blue" system are initiated. This provides crucial theoretical and technical support for the resilient development and planning control of cities with intensive water networks.

2.3. Urban "Gray-Green-Blue" Spatial Rain-Flood Regulation System Dynamics Model

2.3.1. System Boundary Determination

Establishing the system boundary is a fundamental prerequisite for conducting research using the system dynamics approach [44]. Traditionally, researchers and engineers have predominantly relied on natural factors such as rainfall and runoff for calculating and designing rain-flood flow management to mitigate flood disasters. However, the rapid pace of urbanization in recent years, coupled with the escalating severity of flood disasters, has led to a growing recognition among the public, academia, and governmental bodies that urban drainage and flood prevention systems are influenced by a multitude of factors. Drawing from domestic and international research findings [45–47], four primary categories have been identified as influential in the effectiveness of rain-flood regulation: natural, socio-economic, internal, and policy factors. Natural factors, like rainfall and runoff, are essential in determining the magnitude and frequency of flooding, forming the cornerstone of traditional rain-flood management strategies. However, in the context of accelerated urbanization, socio-economic factors, which encompass urbanization processes, social advancement, and financial capabilities, significantly influence the demand and sustainability of urban drainage infrastructure. Moreover, internal factors, such as the scale and structural characteristics of the rain-flood regulation space, are pivotal in dictating the efficiency and effectiveness of the system. Lastly, policy factors, including ecological protection measures, sponge city initiatives, and land use policies, play a crucial role in guiding and supporting rain-flood management. These factors impact resource distribution and long-term strategic planning. Therefore, the selection of these four categories of spatial factors represents a holistic and multi-dimensional approach to rain-flood disaster management, ensuring the plan's effectiveness and adaptability (Table 1).

Table 1. System boundary list.

Number	System Category	Rain-Flood Regulation Space Influencing Factors
A	Natural Factors	A1. Annual evaporation A2. Precipitation A3. Urban heat island effect coefficient A4. Greenhouse gas coefficient A5. Climate change coefficient A6. Inflow runoff A7. Outflow runoff A8. Watershed area A9. Microscale rain-flood regulation capacity A10. Mesoscale rain-flood regulation capacity A11. Macroscale rain-flood regulation capacity A12. Excessive rainwater volume A13. Construction completion level A14. Microscale rain-flood regulation area A15. Mesoscale rain-flood regulation area A16. Macroscale rain-flood regulation area A17. Total required rain-flood regulation space area
B	Socio-economic Factors	B1. Financial capacity B2. Annual growth rate of financial revenue B3. Annual increase in financial revenue B4. Annual increase in financial expenditure B5. Annual growth rate of financial expenditure B6. Investment amount provided by rain-flood regulation facilities B7. Flooding impact coefficient B8. Direct economic loss B9. Indirect economic loss B10. Disaster relief fund investment B11. Proportion of medical expenditure to financial expenditure B12. Medical level B13. Education level B14. Proportion of education expenditure to financial expenditure B15. Urbanization rate B16. Total population B17. Urban population B18. Population growth B19. Newly available land area for development B20. Land transfer fees and related taxes

Table 1. *Cont.*

Number	System Category	Rain-Flood Regulation Space Influencing Factors
C	Internal Factors	C1. Total river length C2. Total watershed area C3. Changes in river length C4. Rate of river length change C5. Rate of change in lake and wetland areas C6. Water surface width C7. Changes in watershed area C8. Proportion of first-order tributary length C9. Length of first-order tributaries C10. Development coefficient of first-order river network C11. Main river length C12. Length of second-order tributaries C13. Proportion of second-order tributary length C14. Development coefficient of second-order river network C15. Proportion of third-order tributary length C16. Length of third-order tributaries C17. Development coefficient of third-order river network C18. River network connectivity C19. River network density C20. Total land area C21. Water surface ratio
D	Policy Factors	D1. Land area for construction D2. Residential land percentage indicator D3. Residential land area D4. Public management and public service facilities land percentage indicator D5. Public management and public service facilities area D6. Green space and square area D7. Municipal facilities land percentage indicator D8. Municipal facilities land area D9. Increase in construction land area D10. Runoff total control rate requirement D11. Required rain-flood regulation volume D12. Design volume for microscale rain-flood regulation D13. Comprehensive runoff coefficient D14. Per capita construction land indicator D15. Rain-flood regulation space investment percentage D16. Flood control standard D17. River channel flow rate D18. Network construction standard D19. Municipal pipeline drainage volume

In terms of the system's spatial boundary, it is acknowledged that the rainwater accumulated in the storage space is primarily governed by gravitational flow [48]. Consequently, the storage space simulation and planning optimization system, grounded in the system dynamics explored in this study, is confined within the water system basin delineated in the central urban area as per the comprehensive urban plan. The model's temporal boundary aligns with the timeframe of the overarching urban plan, which, for urban land space planning in China, is currently projected up to the year 2035.

2.3.2. Determination of Systemic Causality

Following the establishment of the research boundary for the system, an analysis of the causal relationships among elements within this boundary was undertaken. This analysis aimed to elucidate the feedback interactions among the factors involved. Figure 3 illustrates the causal feedback diagram, encompassing the four significant subsystems—natural, socio-economic, internal, and policy—within the Guitang River Basin.

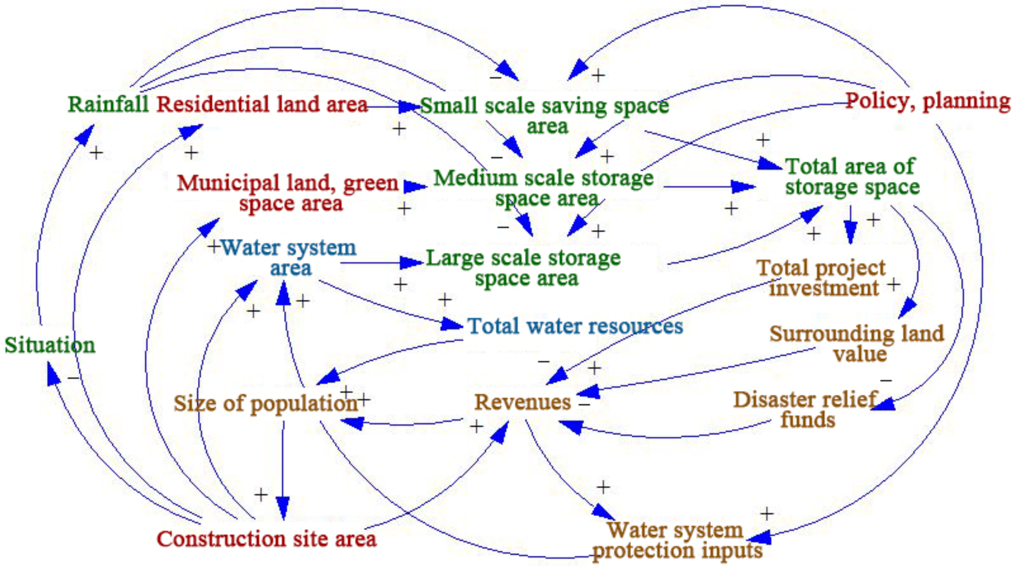


Figure 3. Causal relationship diagram of the system dynamics model for urban "gray-green-blue" space rain-flood regulation.

This model elucidates that the subsystems not only operate independently based on their internal structures but are also influenced by interactions with each other, with several primary feedback loops identified:

1. Natural Factors: The volume of water stored is impacted by variables such as rainfall, evaporation, and surface runoff coefficients. However, it is also influenced by factors like the standards of pipeline network construction and the available land area for establishing storage facilities. These elements interconnect, forming interactive feedback relationships.
2. Socio-Economic Factors: The economic level, particularly fiscal capacity, directly influences the investment in public infrastructure. This investment, in turn, dictates the actual construction area of rain-flood storage spaces. The extent of these storage spaces can mitigate the impact of flood disasters on the city, potentially reducing the need for government disaster relief funding, which then affects the government's fiscal capacity.
3. Internal Factors: If river systems capable of storage lose their functionality due to urban construction, it escalates the risk of flood disasters. This increase in risk leads to higher disaster relief funding requirements and can result in a decrease in the vitality of waterfront areas and land values.
4. Policy Factors: The layout of land uses in urban planning, especially the arrangement of municipal facility lands and the standards for pipeline network construction and flood prevention, are vital urban safety policies. These policies affect the rain-flood storage capacity and, consequently, the extent of city damage during flood events. In the aftermath of disasters, there is often a need to revise and adjust urban safety policies and strategies.

2.3.3. System Dynamics Modeling

Building upon the identified causal feedback loops within the urban "gray-green-blue" system for rain-flood storage, this study segments the system dynamics model into four distinct subsystems for simulating rain-flood storage in these spaces. These subsystems are classified as natural factors, socio-economic factors, internal factors, and policy factors. To effectively visualize and analyze these subsystems, a stock-flow diagram of the system has been created utilizing the specialized system dynamics software Vensim 9.2. This diagram is presented in Figure 4.

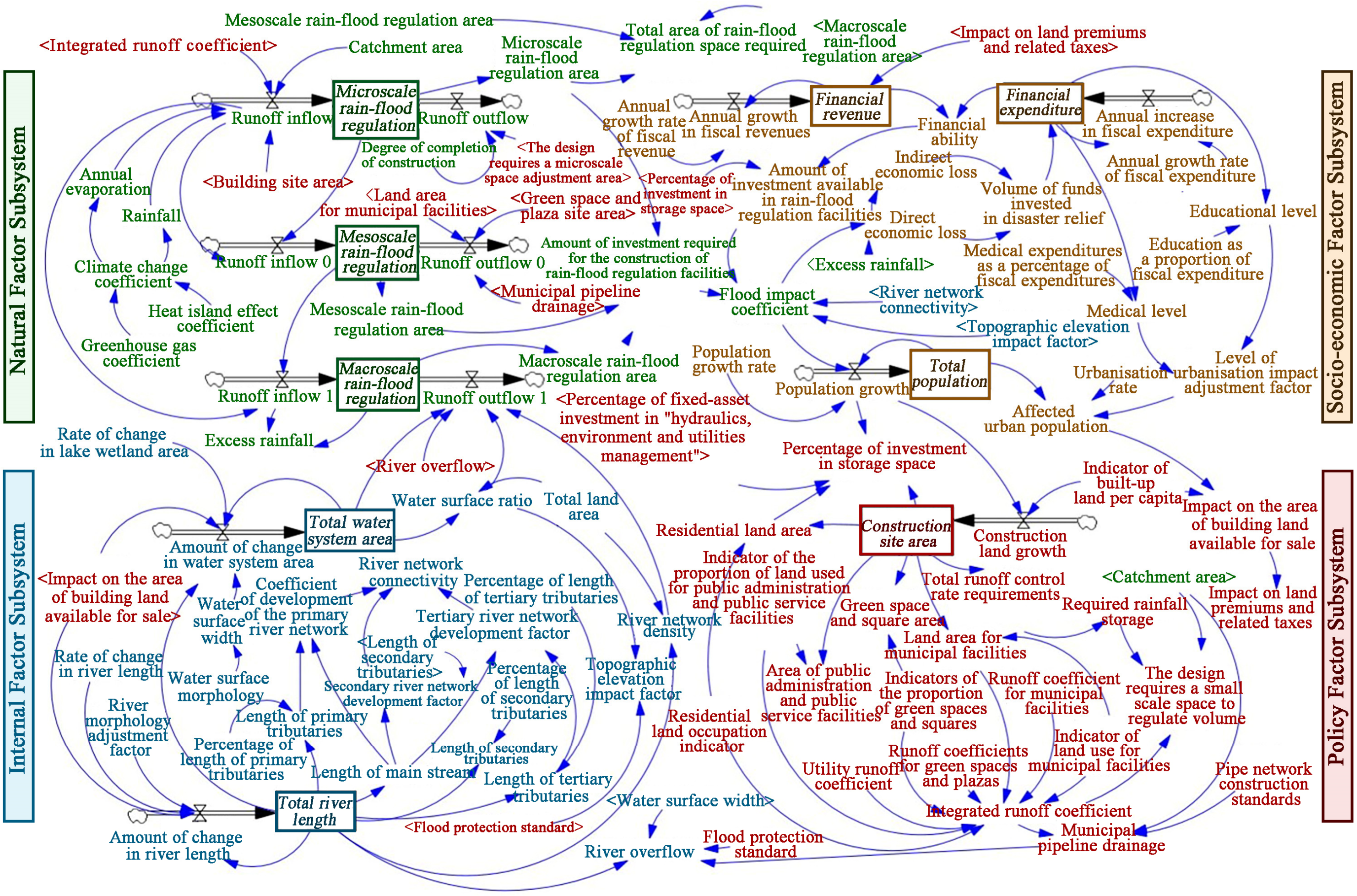


Figure 4. System dynamics model for rain-flood regulation in the urban "gray-green-blue" spaces.

(1) Natural Factor Subsystem

In the natural factor subsystem of the model, 21 indicator factors have been selected. These factors are represented as 12 auxiliary variables expressed through equations, nine constant-form rate variables, and state variables (Table 2).

Hydrodynamic models for rain-flood storage spaces at various scales require parameters that reflect natural conditions. For example, considering changes in water volume in mesoscale wetland storage spaces, this volume change is influenced by rainfall, evaporation, surface runoff coefficients, and also by the standards of pipeline network construction and the land area available for setting up storage facilities.

Table 2. Analysis of variables in the natural factor subsystem.

Variable Type	Variable Name	Notation	Unit	Clarification
State variable	Microscale rain-flood regulation volume	SFRS	10^4 m^3	IF THEN ELSE (RI $\leq$ RO, RI, RO)
	Mesoscale rain-flood regulation volume	MFRS	10^4 m^3	IF THEN ELSE (RI0 $\leq$ RO0, RI0, RO0)
	Macroscale rain-flood regulation volume	LFRS	10^4 m^3	IF THEN ELSE (RI1 $\leq$ RO1, RI1, RO1)
Speed variable	Runoff inflow	RI	10^4 m^3	$10 \times$ RF $\times$ ($\Psi \times$ CLA + $0.15 \times$ (CA $-$ CLA)) $-$ AEV $\times$ CA $\div$ 1000
	Runoff outflow	RO	10^4 m^3	CSC $\times$ DVS
	Runoff inflow 0	RI 0	10^4 m^3	IF THEN ELSE ($\Psi \times$ CLA $\leq$ RO0, 0, $\Psi \times$ CLA + SFRS)
	Runoff outflow 0	RO 0	10^4 m^3	SU $\times$ DST1 $\times$ PCS + SG $\times$ DST2 $\times$ PCS
	Runoff inflow 1	RI 1	10^4 m^3	$\Psi \times$ (RF $-$ MFRS)
	Runoff outflow 1	RO 1	10^4 m^3	

Table 2. *Cont.*

Variable Type	Variable Name	Notation	Unit	Clarification
Auxiliary variable	Coefficient of climate change	CCC	/	HIEC × GGC
	Annual evaporation	AEV	mm	1.5 × CCC
	Quantity of rainfall	RF	mm	$\mathrm{AEV} \times \frac{60}{1000} \times \frac{1392.1 \times \mathrm{t} \times (1 + 0.55 \times \mathrm{lgT})}{(\mathrm{t} + 12.548)^{0.5452}}$
	Microscale rain-flood regulation area	SFRR	$10^4\ \mathrm{m}^2$	SFRS ÷ H1
	Mesoscale rain-flood regulation area	MFRR	$10^4\ \mathrm{m}^2$	MFRS ÷ H2
	Macroscale rain-flood regulation area	LFRR	$10^4\ \mathrm{m}^2$	LFRS ÷ H3
	Total area of rain-flood regulation space required	TFSR	$10^4\ \mathrm{m}^2$	SFRR + MFRR + LFRR
	Excess rainfall	ESR	$10^4\ \mathrm{m}^3$	CONST × (RI1 − LFRR)
Constant	Heat island effect coefficient	HIEC	/	/
	Greenhouse gas coefficient	GGC	/	/
	Catchment area	CA	$10^4\ \mathrm{m}^2$	/
	Degree of completion of construction	CSC	/	/

(2) Socio-Economic Factor Subsystem

In the socio-economic factor subsystem, a combination of social and economic factors is considered, encompassing a total of 25 variables. This includes three rate variables, three state variables, and 19 auxiliary variables, as detailed in Table 3.

Table 3. Analysis of variables in the socio-economic factor subsystem.

Variable Type	Variable Name	Notation	Unit	Clarification
State variable	Revenue	Re	10^8 CNY	INTEG (ARG, Initial value of fiscal revenue) − AFT
	Financial expenditure	Fe	10^8 CNY	DRI + INTEG (AIFE, Initial value of financial expenditures)
	Total population	TP	10^4 people	INTEG (PG, Initial value of population)
Speed variable	Annual growth in fiscal revenues	ARG	10^8 CNY	WITHLOOKUP (Re)
	Annual increase in fiscal expenditure	AIFE	10^8 CNY	WITHLOOKUP (Fe)
	Population growth	PG	10^4 people	TP × PGR × ICF÷1000
Auxiliary variable	Financial ability	FC	10^8 CNY	Re − Fe
	Amount of investment that can be provided by rain-flood regulation investment facilities	RIF	10^8 CNY	PSI × FC
	Volume of funds invested in disaster relief	DRI	10^8 CNY	DEL + IEL
	Flood impact factor	ICF	10^8 CNY	RIF ÷ IRF × 1.1 × RNC × const
	Investment required for rain-flood regulation facilities	IRF	10^8 CNY	SFRR × 0.01 + MFRR × 3 × 0.8 + LFRR × 5 × 0.1
	Direct economic loss	DEL	10^8 CNY	67.4 × ESR × const
	Indirect economic loss	IEL	10^8 CNY	2.43 × DEL
	Educational level	EL	10^8 CNY	Fe × EPF
	Medical level	ML	10^8 CNY	Fe × MPF
	Level of urbanization impact adjustment factor	ULA	/	EL÷ (EPF × Fe + DRI) × ML ÷ MPF × (Fe + DRI)
	Population of affected towns	AUP	10^4 people	TP × UR × (1 − ULA)
	Area of affected building land available for sale	ACL	km^2	AUP × 0.01 × PGR × 100
	Impact on land premiums and related taxes	AFT	10^8 CNY	/
Constant	Annual growth rate of facial revenue	ARGR	%	/
	Annual growth rate of fiscal expenditure	AGER	%	/
	Education expenditure as a proportion of fiscal expenditure	EPF	%	/
	Medical expenditures as a percentage of fiscal expenditures	MPF	%	/
	Urbanization rate	UR	%	/
	Population growth rate	c	%	/

The economic level plays a pivotal role in determining the capacity for constructing urban rain-flood storage facilities. Fiscal capacity stands out as a critical measure of this economic level. This indicator directly influences the volume of investment allocated to public infrastructure within the city, which subsequently shapes the actual construction area of rain-flood storage spaces. The size of these storage areas can mitigate the impact of flood disasters on urban areas, potentially reducing the necessity for government disaster relief funding. In turn, this dynamic also influences the government's fiscal capacity.

Additionally, this economic indicator is intricately linked to the construction land area, land transfer fees, and associated taxes. From a social perspective, the total population is extracted as a state variable. An increase in population heightens urban populace numbers, thereby promoting the expansion of the construction land area. This expansion drives government fiscal revenue growth, which influences the capacity for infrastructure investment, leading to improvements in education and medical services. These enhancements in living standards can, in turn, fuel further population growth, creating a cyclical socio-economic dynamic.

(3) Internal Factor Subsystem

The internal factor subsystem is composed of 22 variables, which consist of two rate variables, two state variables, and 18 auxiliary variables, as detailed in Table 4.

Table 4. Analysis of variables in the internal factor subsystem.

Variable Type	Variable Name	Notation	Unit	Clarification
State variable	Total river length	TLR	km	INTEG (VRL, Initial value)
	Total water system area	TRWS	km^2	INTEG (VWR, Initial value)
Speed variable	Amount of change in river length	VWR	km	TLR × RLR × (1 + Area of new building land available for sale/total area of building land)
	Amount of change in water system area	VWR	km	(TRWS − W × TLR) × LWR + W × TLR
Auxiliary variable	Length of primary tributaries	FBL	km	TLR × PFL
	Length of secondary tributaries	STL	km	TLR × PSL
	Length of tertiary tributaries	TTL	km	TLR × PTL
	Main stream length	MSL	km	TLR − FBL − STL − TTL
	River network density	RND	%	TLR ÷ TLA
	Coefficient of development of the primary river network	FRNDC	/	FBL ÷ (TLR − FBL − STL − TTL)
	Secondary river network development factor	SRNDC	/	STL ÷ (TLR − FBL − STL − TTL)
	Tertiary river network development factor	TRNDC	/	TTL ÷ (TLR − FBL − STL − TTL)
	River network connectivity	RNC	/	K1 × FRNDC + K2 × FRNDC + K3 × SRNDC
	Average terrain elevation	AE	m	Const × Wp × IF (100, a1:200, a2)
	Water surface ratio	Wp	%	TRWS × 100 ÷ TLA
	Rate of change in river length	/	%	/
	Rate of change in lake wetland area	/	%	/
Constant	Water surface width	/	m	/
	Total land area	/	ha	/
	Percentage of length of primary tributaries	/	%	/
	Percentage of length of secondary tributaries	/	%	/
	Percentage of length of tertiary tributaries	/	%	/

Within this subsystem, key quantitative characteristics of the rain-flood storage spaces are represented. Variables, such as the river network density and the water surface ratio, provide insights into the quantitative aspects of these storage areas. Additionally, variables like river network connectivity and average elevation shed light on the structural characteristics and connectivity of the rain-flood storage spaces.

For instance, river network density is influenced by factors such as the total length of rivers and the total land area. The water surface ratio is impacted by variables, including the total length of rivers, the total area covered by water systems, and the overall land area. River network connectivity is influenced by the length of the main river channel and various tributaries, while the average elevation is affected by flood prevention standards. These variables collectively provide a comprehensive view of the internal characteristics of rain-flood storage spaces.

(4) Policy Factor Subsystem

The policy factors subsystem includes a total of 20 variables, comprising one rate variable, one state variable, and 18 auxiliary variables, as detailed in Table 5.

Table 5. Analysis of variables in the policy factor subsystem.

Variable Type	Variable Name	Notation	Unit	Clarification
State variable	Construction site area	CLA	km^2	INTEG (CLG, Initial value)
Speed variable	Construction land growth	CLG	km^2	PG × PCI
Auxiliary variable	Residential land area	SR	km^2	CLA × ISR
	Land area for public administration and public service facilities	SA	km^2	CLA × ISA
	Green space and plaza land area	SG	km^2	CLA × ISG
	Land area for municipal facilities	SU	km^2	CLA × ISU
	Integrated runoff coefficient	Ψ	/	$ISR \times 0.68 + ISA \times 0.7 + ISG \times 0.3 + ISU \times 0.3 + (1 - ISR - ISA - ISG - ISU) \times 0.5$
	Required rainfall storage	RR	mm	IF (70%, 20.16: 75%, 24.14: 80%, 29.29: 85%, 36.19)
	Design requires microscale space to accommodate volume	DVS	$10^4\ m^3$	$10 \times \Psi \times RR \times CA$
	Municipal pipe drainage	MPD	$10^4\ m^3$	$\frac{1392.1 \times (1 + 0.55 \times \lg PCS)}{(t + 12.548)^{0.5452}} \times t \times CA \times \Psi \times 60 \div 1000$
	River overflow	RF	$10^4\ m^3$	TLR × W × IF (100, 1.0: 200, 1.5) − MPD ÷ 1000
	Percentage of investment in storage space	PSI	%	Const × (SR ÷ CLA) ÷ 0.45
	Indicators of the proportion of residential land use	ISR	%	/
	Indicators of the percentage of land used for public administration and public service facilities	ISA	%	/
	Indicators of the percentage of green space and plaza land use	ISG	%	/
Constant	Indicator of land use for municipal facilities	ISU	%	/
	Total runoff control rate requirements	RCR	/	/
	Timing of rainfall	t	min	/
	Indicator of built-up land per capita	PCI	m^2	/
	Pipe network construction standards	PCS	a	/
	Flood protection standard	FCS	a	/

Within this subsystem, various policy-related factors are considered, each with its own set of influencing variables and impacts. For instance, variables such as the total runoff control rate, the proportion of investment in public infrastructure, and the proportion of investment in storage space are linked to the Sponge City ecological protection policy. These policy factors are influenced by factors like construction land area, population growth, and residential land area.

Additionally, indicators, such as per capita construction land, the proportion of residential land in construction land, the proportion of public management and public service facilities land, the proportion of green space and square land in construction land, and the proportion of municipal facilities land, are associated with urban land use policies. These indicators affect the allocation of land for various purposes within the city.

Furthermore, standards for pipeline network construction and flood prevention are categorized as urban safety policies. These standards play a crucial role in determining the capacity of municipal pipeline drainage and river channel water flow, thus impacting the city's ability to manage rain-flood events effectively.

3. Model Simulation and Empirical Analysis

3.1. Model Parameterization

The constant parameters for the simulation of rain-flood storage in the Guitang River Basin were determined by referencing the relevant standards, plans, and statistical yearbook data of Changsha City or the Guitang River Basin, as shown in Table 6. Regarding the temporal boundary, since Changsha City experienced extreme rainfall weather and a major flood disaster from 22 June to 2 July 2017, which was historically recorded, we organized the current data up to 2017 and built the model. This allows us to compare the simulation results with the actual disaster situation in 2017.

Table 6. Basis for determining the parameters of the constant indicators in the model.

Constant Indicator	Basis for Parameterization
Indicators of the proportion of residential land use, public administration and public service facilities land use, green spaces and plazas land use, built-up land per capita, and municipal facilities land use	Obtained in the detailed control plan or village plan of the area where the study area is located
Total runoff control rate requirements	The research scope of the city's Sponge City special planning for obtaining the corresponding indicators, such as no Sponge City special planning, according to the Ministry of Housing and Construction issued by the Sponge City construction planning guidelines.
Timing of rainfall	Determined on the basis of information provided by the Meteorological Office
Pipe network construction standards	Determined in accordance with the drainage special plan
Flood protection standard	Determined in the city's master plan or special plan for urban flood control
Rate of change in river length, rate of change in lake wetland area	Determined on the basis of information from previous years
Water surface width	Calculate the average value after taking measurements from the topographic map
Total land area, percentage of length of primary tributaries, percentage of length of secondary tributaries, percentage of length of tertiary tributaries, catchment area	Determined from topographic maps

3.2. Model Validation

For the model verification, this article repeatedly compares statistical data and field survey data, selecting six variables that best test for errors and are most representative: total population, urbanization rate, fiscal revenue, fixed asset investment, construction land area, and total area of the water system. We compared the historical statistical data of the system model from 2008 to 2017 (obtained from statistical yearbooks) with the simulated data (obtained from the flood regulation system dynamics model constructed in this article) for testing, as shown in Table 7. Based on this, we set a simulation period of 5 years, with the system dynamics simulation period set for 2017–2023. The historical change stages of each indicator correspond to 2010–2015, used for verifying the accuracy of the model. The verification results showed that the error in the simulated prediction values does not exceed 10%, indicating that the model has a high degree of fit, strong applicability, and good replicability.

Table 7. Historical verification results of the system model.

Particular Year	Total Population (10^4 People)			Urbanization Rate (%)			Fiscal Revenue (10^8 CNY)		
	Historical Value	Analog Value	Inaccuracies (%)	Historical Value	Analog Value	Inaccuracies (%)	Historical Value	Analog Value	Inaccuracies (%)
2007	652.92	680.6	4.24	60.2	57	−5.32	266.38	266.4	0.01
2008	658.56	704.4	6.96	61.25	69	12.65	318.87	341.2	0.01
2009	664.22	734.9	10.64	62.63	70	11.77	372.97	407.1	7.00
2010	704.07	747.08	6.11	67.69	71	4.89	511.28	559.9	9.15
2011	709.07	758.09	6.91	68.49	74	8.04	688.96	717.3	4.11
2012	714.66	770.6	7.83	69.38	75	8.10	796.58	866.9	8.83
2013	722.14	780.3	8.05	70.6	77	9.07	883.88	914.2	3.43
2014	731.15	793.2	8.49	72.34	79	9.21	1003.08	1074.6	7.13
2015	743.18	800	7.65	74.38	80	7.56	1113.48	1201.7	7.92
2016	764.52	802.1	4.92	75.99	81	6.59	1231.02	1262.5	2.56
2017	791.81	805.1	1.68	77.59	82	5.68	1403.29	1480.3	5.49
Particular Year	**Fixed Asset Investment (10^8 CNY)**			**Construction Land Area (km^2)**			**Total Area of Water Systems (km^2)**		
	Historical Value	**Analog Value**	**Inaccuracies (%)**	**Historical Value**	**Analog Value**	**Inaccuracies (%)**	**Historical Value**	**Analog Value**	**Inaccuracies (%)**
2007	1445.18	1485.36	2.78	181.23	187.65	3.54	5.11	5.11	0.06
2008	1873.33	1927.09	2.87	210.1	217.77	3.65	5.03	5.057	0.51
2009	2441.78	2513.81	2.95	242.43	251.45	3.72	4.96	5.007	1.01
2010	2779.26	2863.19	3.02	272.39	282.69	3.78	4.88	4.96	1.56
2011	3214.26	3312.94	3.07	276.91	287.57	3.85	4.83	4.909	1.60
2012	4011.96	4137.53	3.13	282.46	293.50	3.91	4.78	4.86	1.67
2013	4593.39	4739.54	3.16	287.52	298.96	3.98	4.73	4.82	1.93
2014	5435.75	5610.24	3.21	294.39	306.20	4.01	4.68	4.775	2.07
2015	6363.29	6570.10	3.25	312.3	324.98	4.06	4.63	4.728	2.15
2016	6693.32	6916.88	3.34	322.73	336.70	4.33	4.58	4.685	2.32
2017	7567.77	7826.59	3.42	330.54	345.25	4.45	4.53	4.643	2.49

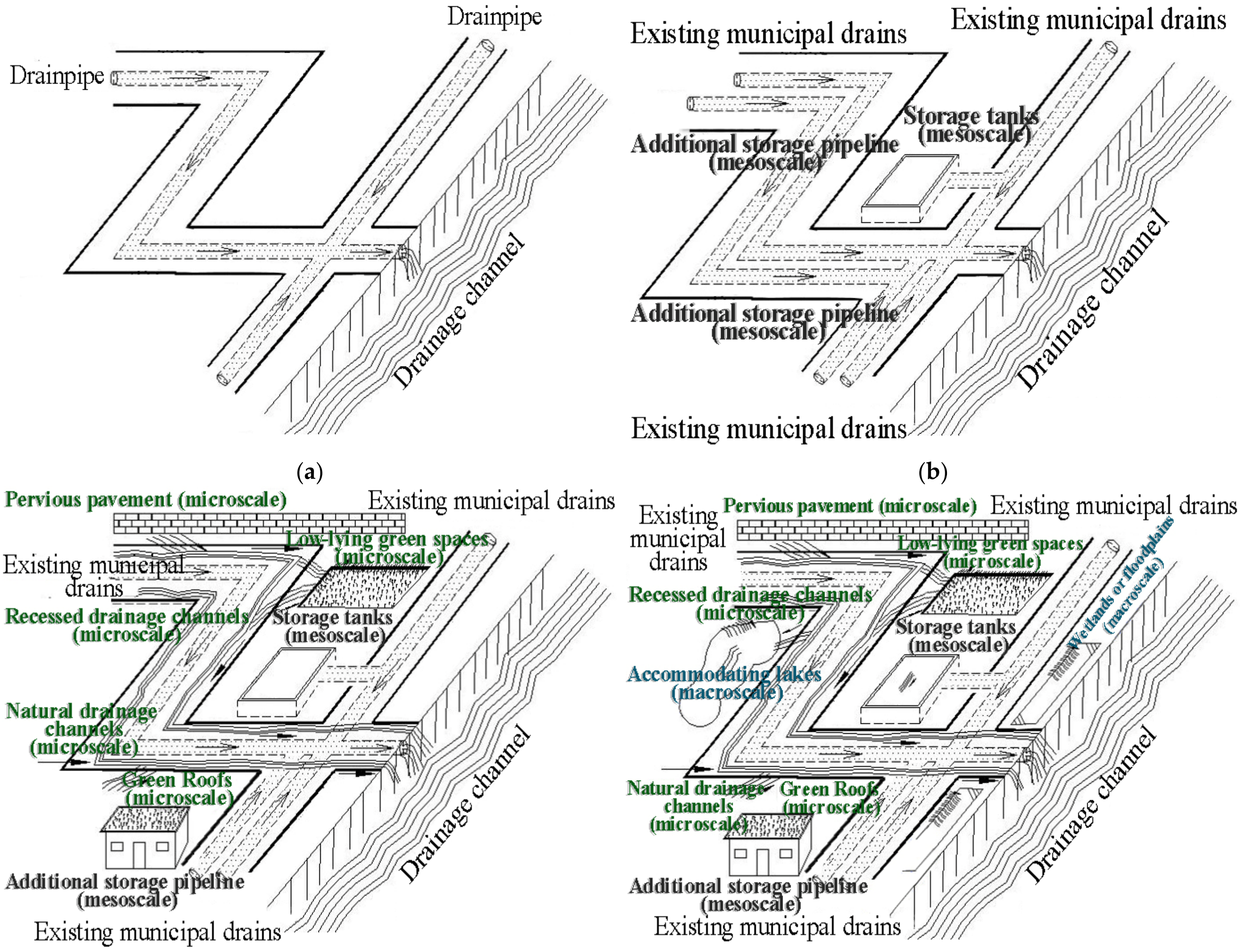
3.3. Determination of Rain-Flood Regulation Scenarios in Urban "Gray-Green-Blue" Spaces

The "Natural-Socio-Economic-Internal-Policy" system dynamics model for the Guitang River Basin, covering the years from 2017 to 2035, has been employed to simulate rain-flood storage scenarios in the basin. In this simulation, nine control variables representing various aspects of the subsystems were selected. These control variables included the standards for pipeline network construction, total runoff control rates, proportions of municipal facility land allocated for storage facilities, proportions of green spaces and plazas used for storage facilities, the ratio of green spaces and plazas to building land, total river length, flood control standards, water surface width, and rates of change in lake and wetland areas.

Four distinct rain-flood storage spatial planning development schemes were established based on these control variables. Each scheme represents a different approach to managing rain-flood events in the Guitang River Basin, as follows:

1. Status Quo Continuation Scheme (Scheme One): This scheme assumes that land use and drainage facility planning in the Guiyang River Basin will continue according to the existing development model. The drainage system primarily relies on municipal drainage pipes for rainwater management.
2. Gray Infrastructure Planning Scheme (Scheme Two): This scheme is based on traditional engineering planning methods involving the construction of underground regulation facilities and the expansion of municipal pipelines.
3. Gray Infrastructure Combined with Green Infrastructure Planning Scheme (Scheme Three): This scheme integrates low-impact development facilities into urban planning. It builds upon the gray infrastructure of Scheme Two and includes small-scale rain-flood regulation facilities such as sunken green spaces, permeable pavements, green roofs, low-lying green spaces, and natural drainage channels.
4. "Gray-Green-Blue" Infrastructure Space Planning Scheme (Scheme Four): Building upon Scheme Three, this scheme adds planned new regulation lakes, wetlands, or flood detention areas to further enhance rain-flood management.

Each of these scenarios represents a different approach to rain-flood storage and urban planning, aiming to assess their effectiveness and impact on disaster resilience and ecological sustainability in the Guitang River Basin (Table 8). The structural schematic and spatial planning layouts for each scenario are illustrated in Figures 5 and 6, respectively.



(**a**) (**b**)

(**c**) (**d**)

Figure 5. Schematic diagram of various rain-flood regulation schemes. (**a**) Status Quo Continuation Scheme; (**b**) Gray Infrastructure Planning Scheme; (**c**) Gray Infrastructure Combined with the Green Infrastructure Planning Scheme; (**d**) "Gray-Green-Blue" Infrastructure Space Planning Scheme.

Table 8. Planning schemes for rain-flood regulation.

Type of Indicator	Status Quo Continuation Scheme	Gray Infrastructure Planning Scheme	Gray Infrastructure Combined with the Green Infrastructure Planning Scheme	"Gray-Green-Blue" Infrastructure Space Planning Scheme
Pipe network construction standards	Once every three years	Once every five years	Once every three years	Once every three years
Total runoff control rate	0	55%	75%	80%
Proportion of municipal facility land used for storage facilities	0	20%	20%	20%
Proportion of green space and plaza land used for storage facilities	0	0	30%	30%

Table 8. *Cont.*

Type of Indicator	Status Quo Continuation Scheme	Gray Infrastructure Planning Scheme	Gray Infrastructure Combined with the Green Infrastructure Planning Scheme	"Gray-Green-Blue" Infrastructure Space Planning Scheme
Proportion of green space and plaza land to building land	8.87%	17.01%	19%	17.01%
Total river length	23.3	23.3	23.3	24.34
Flood protection standard	Once every hundred years	Once every hundred years	Once every hundred years	Once every two hundred years
Water surface width	27.6	27.6	27.6	36.23
Rate of change in lake wetlands	−1.08%	−1.08%	−0.5%	0%

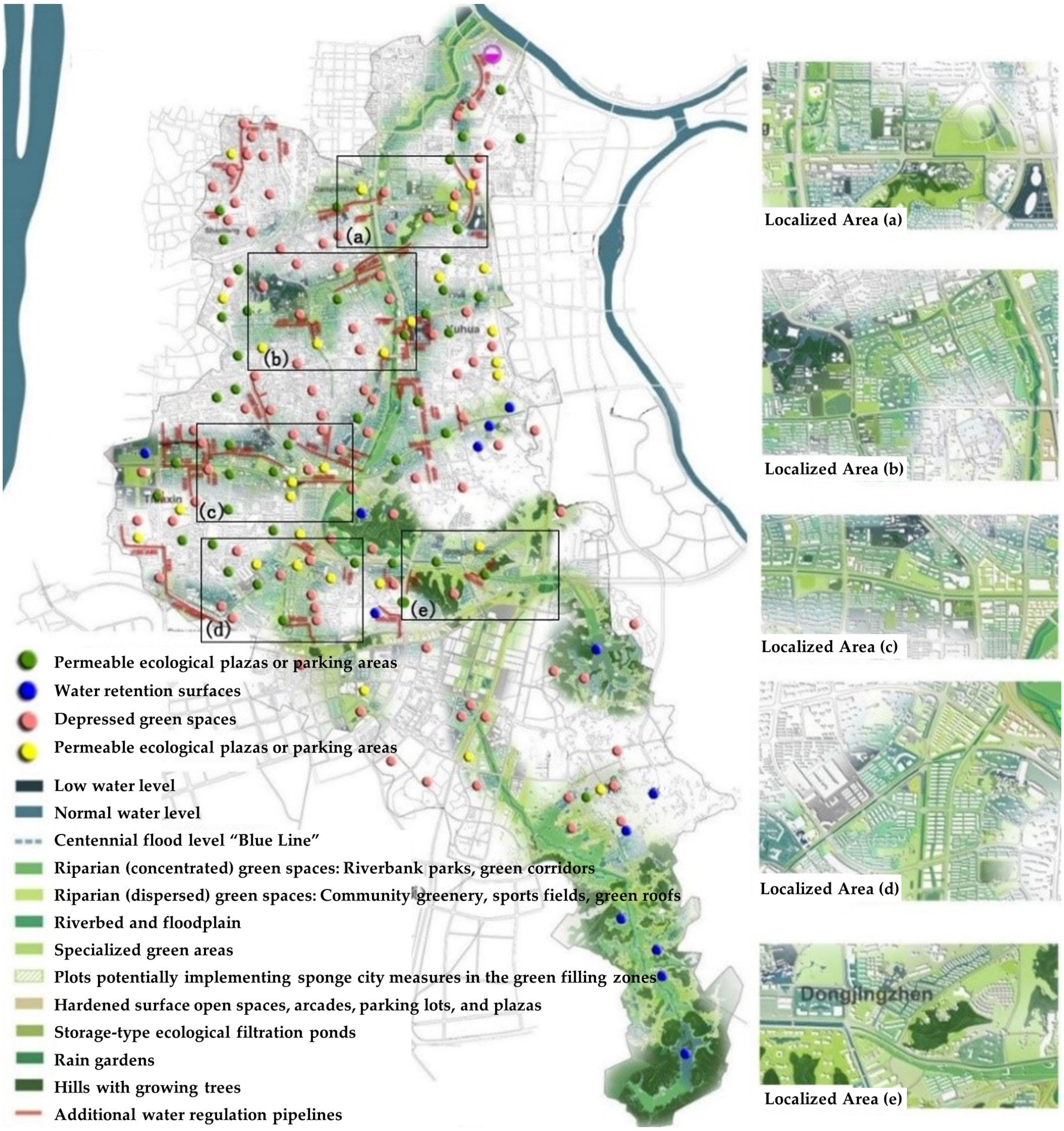


Figure 6. Spatial planning layout of "Gray-Green-Blue" infrastructure in the Guitang River Basin.

3.4. Analysis of Results

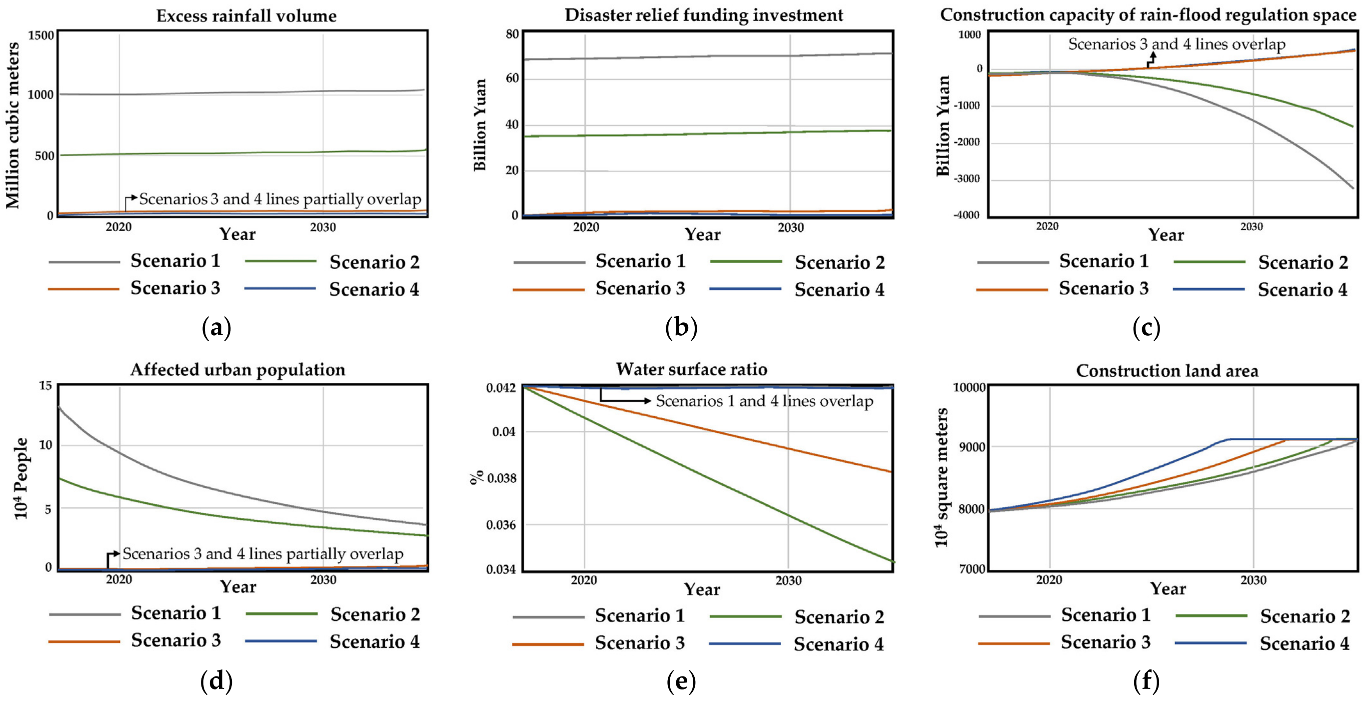
In response to the differentiated disaster-bearing scenario requirements previously mentioned, we conducted a comprehensive simulation of the entire rain-flood storage process based on system dynamics. Furthermore, to compare the merits of the four proposed schemes, we selected several key indicators. These included one indicator from the natural factor subsystem—the volume of excess rainwater—and three indicators from the socio-economic factor subsystem, namely, the amount of disaster relief funding, the construction completion capacity of rain-flood storage space, and the currently affected urban population. Additionally, we considered the water surface ratio indicator from the internal factors subsystem and the construction land area indicator from the policy factors subsystem. The specific significance of these variables for evaluating the efficacy of rain-flood storage in the Guitang River Basin is detailed in Table 9. Importantly, among these indicators, the construction completion capacity of the rain-flood storage space is identified as the core metric for evaluating rain-flood storage space simulation schemes. A positive value, in this context, signifies that the construction of rain-flood storage space is financially supported, thereby indicating the feasibility of the scheme. Conversely, a negative value suggests that the investment provided for the construction of rain-flood storage facilities is insufficient compared to the required investment, indicating that the scheme requires further optimization. The results of the simulation analysis for each indicator in the four scenarios are comprehensively presented in Figure 7.

Table 9. Key discriminating factors in the modeling of rain-flood regulation space simulation.

Number	Subordinate Subsystem	Variables	Meaning
1	Natural Factors	Excess rainfall volume	Reflecting whether the risk of rain-flood hazard still exists after the implementation of the programs
2	Socio-Economic Factors	Disaster relief funding investment	Reflecting the financial impact of rain-flood hazard risks
3		Construction capacity of rain-flood regulation space	Reflecting the difference between the amount of money the government can invest in the construction of rain-flood regulation facilities and the amount of money that needs to be invested
4		Affected urban population	Reflects the impact of rain-flood disasters on the social environment
5	Internal Factors	Water surface ratio	Reflecting the changes in the area of the water system caused by a rain-flood disaster
6	Policy Factors	Construction land area	Reflects the impact of rain-flood disasters on urbanization development

3.4.1. Status Quo Continuation Scheme (Scheme One)

Under the condition of unregulated rain-flood storage facility development, persisting with the existing approach in the Guitang River Basin, it is projected to culminate in a critical surplus of rainwater volume. This scenario is poised to exert substantial pressure on the allocation of disaster relief funds, adversely affecting the government's fiscal capabilities in pivotal sectors like healthcare and education. These sectors are instrumental in magnetizing urban population growth and enhancing government land concessions and tax revenues. Consequently, the populace residing in proximity to the Guitang River Basin is anticipated to confront a heightened vulnerability to rain-flood calamities, an outcome that is detrimental to prospective socio-economic progress.



(**a**) (**b**) (**c**)

(**d**) (**e**) (**f**)

Figure 7. Simulation results of each scheme. (**a**) Excess rainfall volume; (**b**) disaster relief funding investment; (**c**) construction capacity of rain-flood regulation space; (**d**) affected urban population; (**e**) water surface ratio; and (**f**) construction land area.

In terms of the detailed simulation outcomes for each phase, the status quo scheme, which eschews major investments in rain-flood storage facility construction, initially exerts a relatively minor impact on the population and environment during the nascent stages of urbanization. By 2019, this plan's capacity for completing rain-flood storage construction occupies a median position among the four evaluated schemes. The reduced necessity for disaster relief investment permits a more substantial allocation towards rain-flood storage. Nevertheless, as population growth escalates and urban expansion accelerates in subsequent phases, the magnitude of the population and land impacted by rain-flood disasters surges dramatically. The annually escalating expenditure on disaster relief leads to a continuous diminution in the rain-flood storage construction capacity, culminating in a deficit of 324.442 billion yuan by 2035—the most pronounced shortfall across all plans. These findings underscore the imperative of synchronizing drainage and flood prevention infrastructure with urbanization to mitigate the intensifying risk of rain-flood disasters in the Guitang River Basin, thereby safeguarding Changsha City's social, environmental, and economic stability.

3.4.2. Gray Infrastructure Planning Scheme (Scheme Two)

The gray infrastructure planning scheme is characterized by its emphasis on the modernization and transformation of existing municipal drainage systems, noted for their immediate efficacy. An overarching evaluation of the simulation results also positions this scheme in an intermediate rank among the four. It exhibits a lower excess in rainwater volume and a more proficient completion capacity of rain-flood storage compared to the Status Quo scenario, alongside a reduction in the affected population and disaster relief funding. These outcomes indicate that reliance on gray infrastructure for rain-flood storage can partially mitigate the risk of rain-flood disasters in the Guitang River Basin.

A detailed examination of the dynamic simulation results reveals that in 2019, the Guitang River Basin faced a funding shortfall of 9.393 billion yuan for rain-flood storage. Despite the comprehensive renovation of municipal pipelines to meet a 5-year recurrence standard over the subsequent 15 years, a substantial excess in rainfall persisted. This situation compelled the government to augment its investment in disaster relief, leading to a shortfall in financial resources for rain-flood storage facility construction and intensifying the fiscal burden of rain-flood disasters on Changsha City. By 2035, this investment gap for completing rain-flood storage construction in the Guitang River Basin is projected to reach 150.739 billion yuan, reflecting the government's strained capacity for funding these critical infrastructural needs. Hence, while gray infrastructure construction offers some resiliency against urban rain-flood disasters, it is primarily effective for events within the 3–5-year rainfall range specified in the urban drainage planning standards. Since 2014, national guidelines for mega-city municipal pipelines have mandated resilience not only to 3–5-year events but also to 50-year-recurrence urban waterlogging incidents. Evidently, the current capability of the gray infrastructure planning scheme for managing rain-flood risk remains considerably limited.

3.4.3. Gray Infrastructure Combined with the Green Infrastructure Planning Scheme (Scheme Three)

The hybrid approach of integrating gray infrastructure with green space systems, an extension of Scheme Two, includes the incorporation of low-impact development features like concave green spaces, green roofs, and green zones in urban layouts. Collectively, this scheme demonstrates robust resilience against most rain-flood disaster risks within the study period, with both disaster relief funding and affected populations nearing negligible levels. This positions it as a commendably effective long-term plan for rain-flood storage space.

Analyzing the simulation results at various stages, the period from 2019 to 2024 saw significant investment by the Changsha municipal government in rain-flood storage facilities, leading to an initial negative index in the construction completion capacity of rain-flood storage in the Guitang River Basin. Particularly from 2019 to 2020, this scheme exhibited the largest capacity gap among the four plans. However, post-2021, this gap began to diminish steadily, reaching its lowest point in 2022. By 2025, the infrastructure amalgamating gray and green systems became effectively operational, rendering the government's financial dynamics unaffected by rain-flood disasters. The construction completion capacity for rain-flood storage turned positive, indicating a well-managed and controlled state of rain-flood risk storage. By 2035, the rain-flood storage construction completion capacity in the Guitang River Basin achieved a mark of 52.259 billion yuan. These results signify that the combined scheme, marrying traditional municipal systems with green space strategies, not only satisfies the city's criteria for a 50-year recurrence of urban rain-flood waterlogging but also considerably reduces the impact of rain-flood disasters on human life, thereby facilitating stable socio-economic functioning.

3.4.4. "Gray-Green-Blue" Infrastructure Space Planning Scheme (Scheme Four)

The "gray-green-blue" scheme, encompassing traditional municipal facilities, low-impact development mechanisms, and aquatic ecological storage facilities, aims to preserve the natural environmental essence of lakes and wetlands in the watershed. This holistic approach utilizes existing water bodies and river channels in the Guitang River Basin as ecological storage areas. Consequently, this scheme requires lower investment for rain-flood storage compared to Scheme Three and eliminates the need for additional disaster relief funding, maintaining unaffected fiscal revenues and expenditures.

The stage-wise simulation results reveal that in 2019 and 2020, the rain-flood storage-space completion-capacity gap of Scheme Four was more pronounced than in Schemes One and Two but showed better performance than Scheme Three. This improvement was partly due to lakes assuming a portion of the rain-flood storage function, thereby reducing the initial investment required for storage facility construction. By 2022, this scheme achieved the lowest completion capacity gap among all four, with the buffering capabilities of blue infrastructure becoming increasingly evident in managing the rain-flood risks and alleviating governmental fiscal strain. From 2024 onwards, the "gray-green-blue" integrated rain-flood storage facilities formed a cohesive system, transitioning the construction completion capacity of rain-flood storage space to a positive value, a year ahead of Scheme Three. Notably, by 2035, the construction completion capacity of rain-flood storage space in the Guitang River Basin exceeded that of Scheme Three by 1.973 billion yuan. Thus, the "gray-green-blue" network system under this scheme emerges as the most effective in coping with extreme rain-flood disaster risks, promoting harmonious economic development and substantially boosting the resilience of the urban living environment, rendering it the superior choice for future government disaster management planning.

4. Discussion

This paper has constructed a comprehensive rain-flood storage model for urban "gray-green-blue" spaces based on system dynamics, comparing and comprehensively evaluating rain-flood storage simulation schemes under different constraint scenarios. In the future implementation of urban drainage, flood prevention, and rain-flood storage planning in cities similar to the Guitang River Basin, we should consider the micro, meso, and macro scales in coordination, enhance the construction completion capacity of rain-flood storage spaces, control the excess rainwater volume and affected populations to the greatest extent, ensure fiscal revenues and expenditures are unaffected by rain-flood disasters, and progressively build a comprehensive network system of rain-flood storage in "gray-green-blue" spaces for watershed cities. The specific measures are as follows:

1. On the microscale level, we can control rainwater, reduce the surface runoff coefficient, cut peak flow, and achieve staggered drainage;
2. On the mesoscale level, we can use models to simulate and evaluate municipal drainage facilities for the layout of rain-flood storage spaces. In cases of insufficient capacity of pipelines and pump stations, we should increase pipe diameters, expand the installed capacity of pump stations, increase the volume of pre-storage pools of pump stations, or integrate squares and green spaces to construct rain-flood storage facilities;
3. On the macroscale level, for the layout of rain-flood storage spaces, we aim to ecologically transform rivers while ensuring drainage safety and restoring their natural forms and ecological functions. Where conditions permit, we should connect water systems, considering the protection and utilization of water storage spaces like wetlands and polders while preserving water surfaces.

Furthermore, in the future, watershed cities should actively respond to China's Ministry of Water Resources policy, "Accelerate the Construction of Digital Twin Basins to Enhance National Water Security Capabilities". This policy advocates using physical basins as units, spatiotemporal data as a base, mathematical models as the core, and hydrological knowledge as a driver to digitally map and intelligently simulate all the elements of physical basins and the whole water management and governance processes. This aims to achieve a synchronous simulation operation with physical basins, virtual–real interactions, and iterative optimization. This requires watershed cities to build a digital twin storage-computation platform for water–land space in the basin area based on comparing optimal scenario simulation results of "gray-green-blue" space rain-flood storage in watershed cities. The specific measures cover the following three aspects:

1. We can integrate identified risk sensor data of rain-flood disasters, such as climate temperature, hydrological water levels, land use, geographical environment, and urban activities, to break through the barriers of essential tools for spatial planning and the design of basins. This will achieve spatiotemporal-distributed storage of massive data across various scales, from the patch units of watershed cities to geographic space and the overall basin.
2. We propose building a real-time spatial cloud computing platform to invoke water network spatial disaster data information rapidly and customize disaster scenario processes. This will implement extensive data mining analysis of the disaster clue chain, data visualization, and data-fusion sharing technology services.

3. We suggest integrating geographical service functions, such as the 3D GIS display, human–computer interactions, interpretation monitoring, data overlay, and remote sensing early warning, based on the built digital twin data storage-computation cloud platform. This will help establish a visual early warning platform for the geographical impact area of rain-flood disaster risks in the basin.

Rain-flood storage simulation involves multiple disciplines, and the application of system dynamics to a rain-flood storage simulation and spatial planning is unprecedented, making model construction challenging. Due to the limited time, personal expertise, and practical experience, the mathematical relationships among various factors in the model still need to be modified and perfected by actual situations. Consequently, there may be specific errors in the simulation conclusions. However, the model can roughly simulate the future effectiveness of each scheme. This research is merely a beginning. Future urban rain-flood storage studies should treat the watershed as a community of life, actively implement central strategic decisions and deployments, carry out resilient restoration and governance of the watershed water network's geographical pattern, implement China's ecological civilization construction and the high-quality development strategy of the Yangtze River Economic Belt, and create a comprehensive index system that includes resources, energy, land, economy, and the environment. We hope this case study of the Guitang River Basin can provide technical support and practical application guidance for similar cities in their drainage, flood prevention, and rain-flood storage planning.

5. Conclusions

In this study, a comprehensive assessment of the factors influencing rain-flood storage in watershed cities was conducted, resulting in the construction of an extensive rain-flood control indicator database covering four dimensions: natural conditions, socio-economic factors, internal factors, and policy conditions. This database encompasses a total of 88 influencing factors. Utilizing the causal and functional relationships among these factors, a system dynamics model for rain-flood storage in urban "gray-green-blue" spaces was developed.

The core indicator used to evaluate the rain-flood storage space simulation schemes in this study is the "Construction Completion Capacity of Rain-Flood Storage Space". This indicator serves as a crucial measure of the feasibility of rain-flood storage space construction. A positive value of this indicator indicates that the scheme is financially viable, while a negative value suggests that the investment falls short of the required funding for constructing rain-flood storage space, highlighting the need for optimization.

Four distinct rain-flood storage scenarios were simulated and evaluated within the planning period, including the following:

1. Status Quo Continuation Plan: This plan represents the continuation of existing urban development and drainage practices. It focuses on municipal drainage facilities without significant investment in rain-flood storage. By 2035, this plan showed a negative indicator for rain-flood storage construction completion capacity.
2. Gray Infrastructure Plan: This plan emphasizes the construction of traditional gray infrastructure, such as underground regulation facilities and expanded pipelines. Similar to the Status Quo plan, it resulted in a negative indicator for construction completion capacity by 2035.
3. Gray Infrastructure Combined with Green Space Systems Plan: This plan integrates low-impact green infrastructure elements into urban planning alongside traditional gray infrastructure. Although it shifted from a negative to a positive indicator by 2024, it still struggled to handle extreme rain-flood disasters by 2035.
4. "Gray-Green-Blue" Infrastructure Space Planning Plan: This comprehensive plan combines gray, green, and blue infrastructure elements and achieved a positive indicator of rain-flood storage construction completion capacity a year earlier than the previous plan. By 2035, it outperformed the other schemes, indicating its effectiveness

in addressing urban rain-flood disaster responses and simulations while considering socio-economic development and ecological environmental protection.

The results suggest that the "Gray-Green-Blue" Infrastructure Space Planning Plan, which incorporates a holistic approach to rain-flood storage, is the optimal scheme for managing rain-flood disaster risks in urban areas. This plan not only considers the disaster response but also accounts for socio-economic development and ecological protection benefits. To extend the implications of this study further, local governments should consider incorporating these findings into their urban planning and development policies. This could include revising zoning laws to support the development of "gray-green-blue" spaces and integrating the system dynamics model into the planning process for new urban developments. Internationally, this research can inform the global standards and guidelines for urban rain-flood storage, potentially being adopted by international bodies such as the United Nations or the World Bank in their urban development programs. This would help to ensure that the lessons learned from the Guitang River Basin case study can benefit cities worldwide, fostering a more resilient and sustainable approach to urban rain-flood management.

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