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Synergizing flood mitigation and water quality goals through green infrastructure in Dali City, China

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ABSTRACT

Many cities have implemented strict drainage regulations to preserve the water quality of rivers and lakes; however, these measures can inadvertently exacerbate urban flooding. Dali City, located in southwestern China, faces similar challenges and is exploring governance solutions through the implementation of green infrastructure. This study examines the behaviors of various actors within the water management system and models the effectiveness of green infrastructures interventions in Dali. Our flood simulation experiments based on Storm water management model (SWMM) and Personal Computer Storm Water Management Model (PCSWMM) confirmed the potential of green infrastructure in coordinating water quality preservation and flood management objectives. The combination of 71 % green infrastructure deployment rate with gray infrastructure helps to achieve a volume capture ratio exceeding 94 % and a pollutant reduction rate of over 60 %. However, scenario analyses at various scales indicate that excessively large-scale green infrastructure can reduce the synergistic efficiency of achieving both objectives. Specifically, after reaching an 85 % volume capture ratio under typical rainfall conditions, each additional 1 % increase in green infrastructure coverage would require an investment of at least 12 million RMB, which is no longer cost-effective. The optimal solution is to implement green infrastructure at 71 % coverage while prioritizing its integration with gray infrastructure. Our findings highlight the need to balance technical design with institutional coordination, and we propose a governance framework that integrates hydrological and social processes to enhance policy synergy. This study contributes a case-based perspective from China's planning system, offering transferable insights for other rapidly urbanizing regions.

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1. Research background

Climate change and rapid urbanization are the main drivers of the increasing risks in urban water systems [1–4]. These factors significantly affect the self-regulation capacity of urban water cycle, resulting in negative impacts on cities [5]. Among the most pressing issues are urban flooding and water pollution, which, when combined, can further threaten human health [5,6].

Enhancing the resilience of urban water systems has therefore become imperative [7]. Targeted management measures, such as stricter emission standards and improved water treatment rates, can effectively mitigate point-source water pollution in cities [8,9]. However, these measures remain insufficient in addressing non-point source pollution caused by rainfall, particularly during prolonged or intense rain events [10]. During such periods, traditional drainage systems and isolated management approaches may fail or even exacerbate conflicts between water quality protection and urban flood management.

1.1. Conflicts of urban water governance goals

While runoff quantity control and water quality improvement are often viewed as complementary goals in stormwater management, tensions may arise in practice, especially under specific development stage and infrastructural conditions [11]. Many municipal systems rely on infrastructure designed primarily for fast stormwater discharge to mitigate flooding. However, during high-intensity rainfall, when the capacity of urban drainage infrastructure is exceeded, combined sewer overflows or other bypasses can occur, and part of the stormwater avoids collection and treatment, resulting in the discharge of untreated runoff that still carries residual pollutants into natural water bodies [10,12–14].

Addressing both flood risk and water quality challenges requires coordinated governance across departments. However, balancing these governance goals is often difficult, particularly when governmental responsibilities are fragmented and resources are limited [15]. In recent years, coordination has increasingly been featured in urban and environmental governance literature as a key discourse [16–19]. Effective governance coordination must extend beyond intra-governmental efforts to include collaboration between government agencies and individuals [20]; failure to do so may exacerbate inequalities [21].

An integrated analytical approach is therefore needed to support coordinated governance. Although significant progress has been made in water and flood management [22–24], hydrological and governance studies in rapidly developing contexts often remain disconnected, with hydrological research tending to dominate. This dominance is partly due to the stronger capacity of hydrological approaches for quantitative performance assessment. Many studies specialize in specific hydrological processes, such as urban hydrological modeling, optimizing infrastructure layouts, and pollutant modeling [25–27].

Rapidly developing countries like China, however, often face particularly severe environmental pressures, making internal conflicts within governance systems more likely. Some studies have incorporated governance-related dimensions. These include the evaluation of individual responses [28], management strategies, or policy recommendations [29–31], as well as efforts to involve communities in flood and pollution management [32] or water pollution control [33]. Nevertheless, these efforts typically focus on isolated aspects of governance rather than the functioning of governance systems as a whole, and due to the lack of integration with environmental modeling, they offer limited insights into concrete planning solutions.

1.2. Potential of green infrastructure

Many countries have been keen on integrating social, ecological, and economic themes into their water management practices [34], and Green Infrastructure (GI) is among the most exposed concepts [35]. The benefits of GI span a wide range of ecosystem services, commonly categorized into ecological functions, disaster mitigation, economic development, public health, recreational value, and cultural ecosystem services [27,36,37]. Among these, ecological and hydrological functions are the most extensively studied and are often viewed as foundational to other social and economic co-benefits [27,38].

Proactively addressing complex urban challenges, such as those explored in this study, is inherently difficult. Urban development and human activities that alter natural landscapes often lead to increasingly complex and compounded problems [39,40]. GI is increasingly expected to play a critical role in mitigating these challenges and enhancing urban resilience, not only through biophysical functions but also by promoting social cohesion, inclusivity, and adaptability [41,42]. A substantial body of literature highlights GI's potential to support urban resilience by addressing risks associated with urbanization and climate change [41,43]. Specifically, GI increases surface permeability, helping regulate rainfall runoff to mitigate flooding [44], and filters pollutants, thereby improving water quality [45,46]. These attributes underscore the critical role of GI in harmonizing urban flooding and water pollution management.

Despite growing attention to multifunctionality and cross-sectoral relevance, many studies still examine GI benefits in isolation [47]. Studies in cities like Baltimore, Portland, and Detroit have begun to examine how governance frameworks manage functional synergies and trade-offs [22,24], however, such integration remains limited in developing country contexts. Research in these settings typically focuses on the development and application of optimization algorithms [48,49]. Nevertheless, as noted earlier, these technical studies are often disconnected from governance research, limiting their relevance in policy contexts that require coordination across institutional and social dimensions. Misalignments between policy objectives, driven by internal government coordination, and public perceptions of rights and responsibilities can strain relationships between governments and individuals, undermining social resilience [47,50]. Understanding the needs and perspectives of diverse stakeholders is therefore crucial.

In summary, although considerable research has examined flood management and water quality control, limited integrated

analysis exists on how governance systems address these interlinked challenges under the institutional and socio-environmental conditions of rapidly urbanizing contexts such as China [38,51]. This study contributes to these ongoing conversations by examining GI governance and performance in a rapidly urbanizing Chinese city that faces tangible governance conflicts.

Dali City, located in southwest China, exemplifies the challenges of coordinated governance. Like many cities in the Southwest Mountain regions, Dali frequently experiences flooding and has implemented various flood control measures over time [52]. Simultaneously, Dali bears a unique responsibility for the restoration and protection of Erhai Lake, a vital alpine lake ecosystem [53]. Balancing these dual challenges is of critical importance to Dali's governance framework.

This research explores strategies for coordinating governance, focusing on interdepartmental collaboration and the interplay of rights and responsibilities between government entities and individuals. A mixed-methods approach was adopted to analyze the causal relationships within Dali's urban flooding and water pollution governance systems, as well as the performance of GI within these systems [47]. Unlike many SWMM-based studies that focus purely on hydrological outcomes, this study links simulation results with institutional coordination mechanisms, providing an integrated view of GI's technical performance and governance challenges in a Chinese urban context. The study area, the Tianjing District of the Dali Economic and Technological Development Zone (DETDZ), was selected as it is the most flood-prone area in Dali City. The research comprised two main components.

- **Qualitative analysis:** Semi-structured interviews were conducted with affected residents (n = 29) and government officials (n = 2) on August 4, 2023, following severe flooding in late July and early August. A review of gray literature, including government reports and policy documents, provided additional insights into the governance framework and actor behaviors, emphasizing the necessity of GI interventions and coordination.
- **Quantitative analysis:** Hydrological modeling and multi-scenario simulations were performed to assess the impacts of different GI scales on flood management and water pollution control.

The paper is structured as follows: Section 2 examines Dali's urban flooding and water pollution governance systems, including local water challenges, the governance framework, and stakeholder relationships. Section 3 focuses on hydrological modeling and the effectiveness of GI in Dali, along with its limitations. Section 4 provides practical and policy implications for governance and GI implementation. Finally, Section 5 concludes with key findings and their broader implications.

2. Water governance system in Dali

2.1. Introduction of the study area

The study area for this research is located in Dali City, a region that has developed significantly due to its proximity to the vital natural resource of Erhai Lake. To the west of the lake lies Cangshan Mountain, forming a distinctive geographical feature of the area. In recent years, an ecological corridor has been established along the western side of Erhai Lake as part of a large-scale GI initiative. This project primarily focuses on controlling water pollution and enhancing tourism development. The specific study area is the Tianjing district, a management unit within the DETDZ. It is bordered by Erhai Lake to the north and surrounded by mountainous

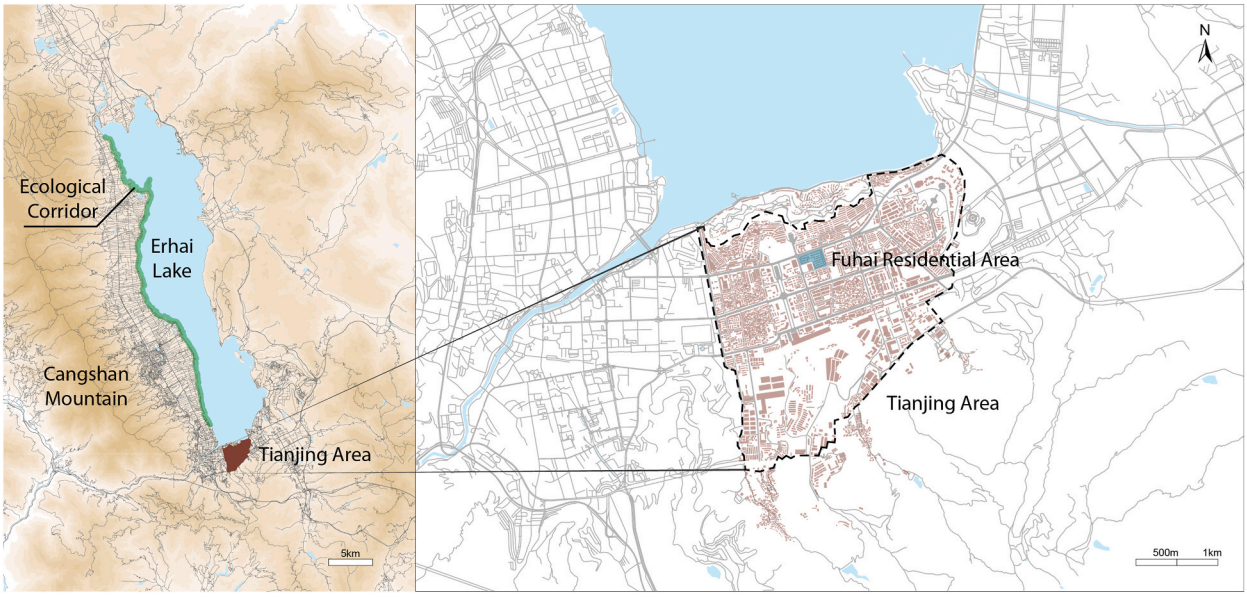

Fig. 1. Overview of the study area in Dali City, Southwest China.

terrain on its other three sides (Fig. 1).

The northern portion of the Tianjing area consists predominantly of enclosed residential complexes and "urban villages," both of which are characteristic urban forms in China [54,55]. Enclosed residential areas are typically developed by real estate companies, consisting mostly of multi-story or high-rise buildings. These areas are often enclosed by walls or commercial buildings and have high floor area ratios. In contrast, "urban villages" are organically developed by residents within pre-existing village structures. They generally lack unified urban planning and drainage infrastructure, resulting in high building densities while retaining some original permeable land [56]. In the southern part of the Tianjing area, closer to the surrounding mountains, some villages with lower levels of impervious surfaces remain. However, the central part of the Tianjing area, around the Fuhai residential district, serves as the primary focus of this study. This zone, characterized by lower terrain, experiences the most frequent and severe instances of urban flooding. To facilitate the analysis, land types within the Tianjing area were categorized into four classes: roofs, roads, green spaces, and bare land [57,58]. The proportion of each land type is presented in Table 1.

2.2. Water governance policies

China's urban water governance operates within a dual system of vertical and horizontal accountability, commonly referred to as the "Tiao-Kuai" (bar-block) structure. Vertically, sectoral ministries such as the Ministry of Housing and Urban-Rural Development set national agendas, while horizontally, local governments oversee implementation through their own bureaus. This arrangement results in dual subordination, where local departments are accountable both to local governments and to their national counterparts [31].

Several government ministries in China are involved in water-related governance, including the Ministry of Housing and Urban-Rural Development, the Ministry of Ecology and Environment, and the Ministry of Natural Resources, which was established during the 2018 national institutional reform [59]. This reform reassigned key responsibilities related to urban planning and water management, transferring certain planning functions from the Ministry of Housing and Urban-Rural Development to the Ministry of Natural Resources. However, at the local level, there is considerable overlap between the responsibilities of the Natural Resources and Housing departments. Meanwhile, the Ecology and Environment department concentrate solely on water pollution control, with limited engagement in flood risk management. As a result, compared to the more centralized and enforcement-driven approach to pollution control, flood governance remains fragmented.

Due to Erhai Lake's national ecological significance, Dali City has faced strong central mandates to protect water quality. This has created institutional misalignments, where overlapping responsibilities across environmental protection, planning, and infrastructure departments hinder integrated responses to flood and pollution management. Fig. 2 summarizes the evolution of key policies, environmental interventions, and flood events from 1992 to 2023, highlighting how persistent emphasis on water quality has outpaced flood mitigation efforts.

2.2.1. First stage: 1992–2015

The first stage, spanning from 1992 to 2015, marked the gradual emergence of water-related challenges. Following the establishment of the DETDZ in 1992, urban construction, including the Fuhai residential area and its surroundings, leading to a surge in human activity around Erhai Lake. By 2001, these activities had caused a significant decline in the lake's water quality. In response, the local government initiated preliminary pollution control measures. Pollution control efforts were strengthened in both 2006 and 2015, leading to noticeable improvements in water quality. However, starting in 2002, minor flooding incidents were recorded in the Fuhai residential area.

2.2.2. Second stage: 2015–2019

The second stage, from 2015 to 2019, was characterized by stringent measures enforced by regional and municipal governments under central government pressure. Strict water quality standards were imposed on major rivers flowing into Erhai Lake. However, urban infrastructure development lagged behind these environmental protection policies. The combination of rigorous water protection policies and inadequate drainage infrastructure led to inefficient urban drainage systems, culminating in severe urban flooding. In 2019, the Fuhai residential area experienced a maximum flood depth of 1.4 m.

2.2.3. Third stage: 2020-present

Since 2020, urban renewal in Dali has focused on gray infrastructure, but flooding persisted. Interviews with residents ($n = 4$) reported major floods in 2020, averaging 10 h in duration and reaching 61.25 cm in depth. A local community pump helped reduce flooding within the Fuhai residential area but redirected water onto adjacent roads. From 2021, sewer renovation projects aimed at protecting Erhai Lake's water quality further reduced stormwater discharge capacity. In 2022, severe flooding recurred, disproportionately affecting migrant-owned roadside shops and exacerbating social inequalities.

The situation worsened in 2023. Continuous heavy rains in late July led to flooding in the homes of 19 surveyed residents, with an

Table 1
Proportion of different land types within the study area.

Types	Unit	Roofs	Roads	Green land	Bare land
Area	km^2	2.136	0.912	3.882	2.339
Proportion	%	23.05	9.83	41.88	25.24

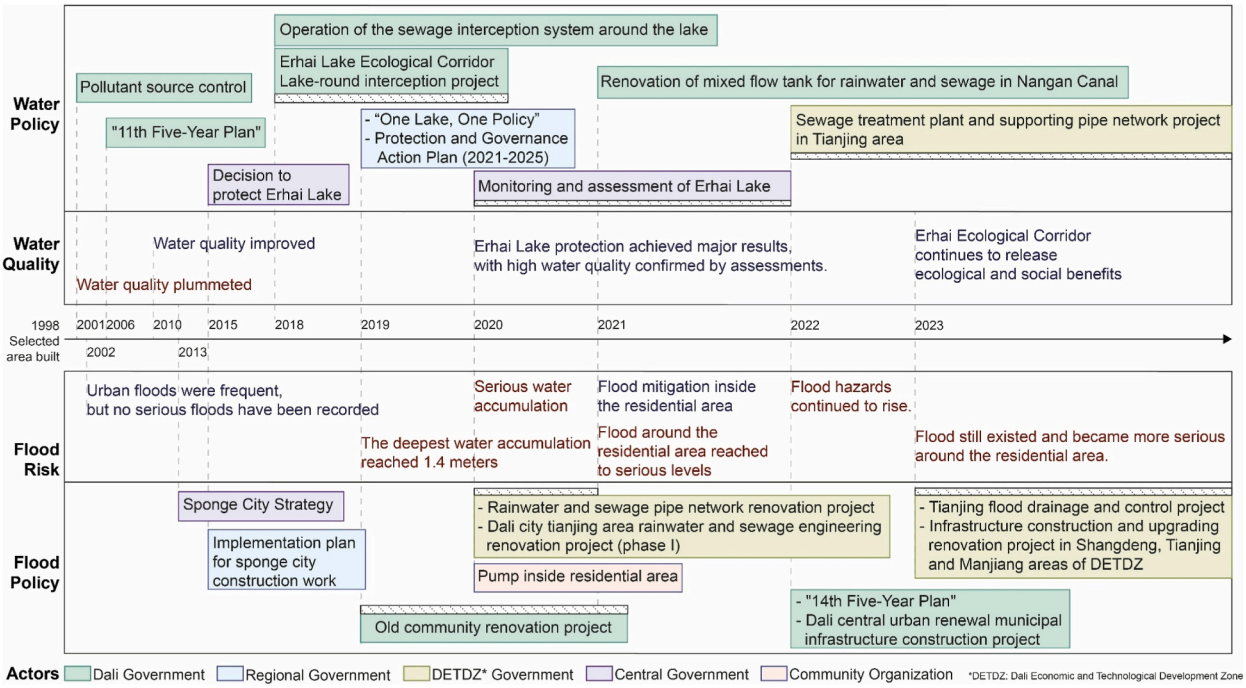

Fig. 2. Evolution of water-related disasters and policy interventions.

average duration of 15.26 h and a maximum depth of 72.11 cm. Debris in the floodwaters included household waste (n = 24), soil and gravel (n = 15), and vegetation and branches (n = 4). One respondent reported the presence of chemicals such as gasoline or pesticides. Seventeen described the water as murky and unlike typical stormwater. Prolonged exposure caused widespread dampness (n = 17), minor cracks (n = 10), and mold growth (n = 5); more serious damage included large cracks (n = 2), subsidence (n = 2), and compromised structural components (n = 3).

These severe flood impacts reflect underlying coordination problems in Dali's governance system. The environmental department, wielding substantial influence, continues to prioritize water quality protection, often at the expense of effective flood management. This imbalance limits infrastructure responses and reinforces systemic trade-offs. Jurisdictional tensions also emerge: governments of areas outside the DETDZ, lacking direct environmental responsibilities, discharge excess water downstream, aggravating flood risks locally.

By 2023, Erhai Lake's water quality had significantly improved under stringent management, and a comprehensive protection regime was in place. Yet urban flooding persisted as a critical and unresolved issue, increasingly recognized by both government and residents. Emerging policy responses suggest a growing shift toward addressing this long-overlooked challenge.

2.3. Stakeholder relationships

Throughout the development process, governments at different levels exhibit significantly different behavioral logics. While the central government formulates policies to address two main objectives, water pollution control and urban flood management, it tends to prioritize water pollution control. This is partly due to the central government's sensitivity to long-term ecological issues, while the sudden and localized nature of urban flooding often leads to its impacts being overlooked or underestimated. Consequently, the central government emphasizes the ecological value of the Erhai Lake system over the immediate efficiency of urban drainage systems, directing more pressure and resources toward water pollution control efforts.

Local governments, as the primary implementers of policies, bear the dual responsibility of ensuring policy effectiveness and safeguarding residents' safety and well-being. They operate under pressure from both higher-level governments and grassroots communities, requiring them to address both water pollution policies and urban flood challenges. Among these, Dali City's local government has shown the promptest responses. However, their capacity to enforce policy implementation remains limited, as the protection of Erhai Lake is prioritized as the primary policy task.

Most respondents believe the local government should take responsibility for their safety (n = 25). However, only three respondents feel that the city currently provides adequate flood protection. A significant portion of respondents expressed doubts about future flood control efforts, with 12 believing the government will not take effective measures and 9 considering it unlikely. Over 85 % of respondents reported dissatisfaction (n = 15) or partial dissatisfaction (n = 8) with flood control governance. Additionally, 14 respondents noted a lack of progress in governance measures over the years, citing stagnation.

Existing government measures mainly focus on constructing gray infrastructure, such as water diversion and drainage channels.

These measures are largely perceived as ineffective; among 10 residents who reported such measures, 2 considered them effective, 2 rated them as average, 4 deemed them ineffective, and 2 viewed them as completely ineffective. Conversely, the Erhai Lake ecological corridor, a large-scale GI project, is generally viewed positively by affected residents. It has delivered ecological and economic benefits to Dali City, contributing to tourism development and fostering greater investment in ecological initiatives among residents. However, complaints about the unfair distribution of government resources remain prevalent among those affected.

Due to ambiguous responsibilities and a lack of clear policies, individuals largely relied on their own resources to cope with flooding. Social capital, such as assistance from neighbors (n = 8) and relatives (n = 6), played a role in recovery efforts, but most residents had to rely entirely on their own means (n = 13). Despite repeated petitions to local government for assistance, these efforts yielded little success, with only two respondents reporting any form of government aid.

Personal circumstances significantly influenced how individuals coped with flooding. Residents within the Fuhai residential area, for instance, organized the purchase and installation of water pumps through their community organization and used sandbags to prevent water from entering the area. This approach proved relatively effective for those within the residential area, with 7 residents reporting the use of these measures: 2 found them very effective, 2 effective, 2 average, and 1 uncertain. However, these measures inadvertently exacerbated the flood risk for residents living along the outer edges of the Fuhai residential area. Lacking similar resources, these residents were limited to using waterproof boards to block water from entering their homes, significantly disrupting their livelihoods. The behavioral interactions among actors are summarized in Fig. 3.

Within the traditional gray infrastructure management model, water protection and urban flood control often represent conflicting policy objectives. On the one hand, local governments face constraints in terms of available funds and resources, which typically results in policies that focus on a single issue rather than providing comprehensive solutions. Given the ecological significance of Erhai Lake, the central government has consistently maintained high vigilance against water pollution. Top-down policy pressure, coupled with substantial financial and resource support from the state, has kept local governments highly proactive in addressing water pollution. However, the core challenge for local governments lies in allocating limited resources between these two competing objectives. At present, the majority of resources are directed toward ecosystem protection, with relatively less attention given to enhancing flood resilience. Simultaneously, inequalities arising from differing capacities for individual adaptation further diminish overall resilience.

Strict management of drainage systems can effectively reduce non-point source pollutants entering water bodies. However, such measures can inadvertently slow water discharge, thereby increasing both the risk and duration of flooding. In the second year following the implementation of water interception and rainwater-sewage diversion measures in Dali City, the risk of flooding rose significantly. Although gray infrastructure can greatly enhance the efficiency of drainage systems, it may also contribute to higher pollutant emissions.

For Dali City's local government, the planning and construction of systematic gray infrastructure present persistent challenges. Integrating the multifunctionality of GI with strategic planning alongside gray infrastructure offers a promising solution to this policy conflict. A quantitative analysis of GI's potential to balance these two issues is presented in the next section.

3. Hydrological modeling with green infrastructure in Dali

3.1. Drainage and surface runoff simulation

In the hydrological simulation component, we utilized the classical SWMM (Storm Water Management Model) and PCSWMM (Personal Computer Storm Water Management Model) to model the infrastructure in the Tianjing area. SWMM, widely applied in urban drainage and flood control planning, design, and management [60,61], was employed to simulate the one-dimensional

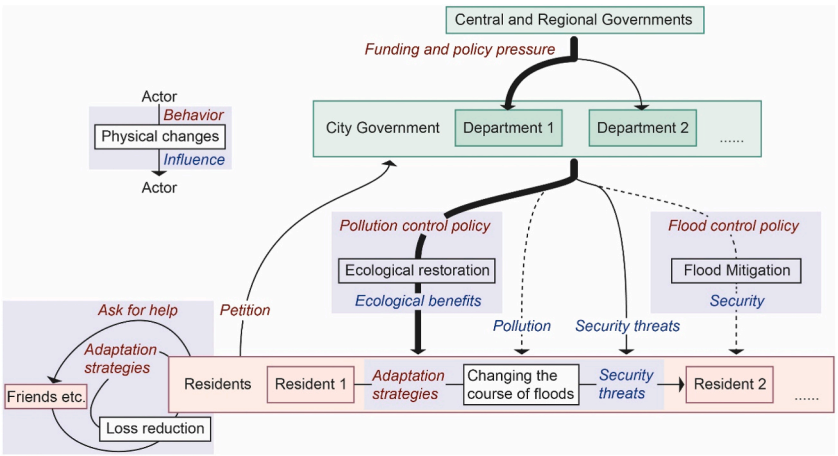

Fig. 3. Actors, their behaviors and impacts in the governance system.

mechanisms of flood formation in the natural environment, focusing on the effects of complex surface conditions on stormwater runoff and pollutant reduction. However, since SWMM is limited to one-dimensional simulations, we complemented it with PCSWMM to model two-dimensional urban flood runoff. The pipe network data for the simulation was provided by the Housing and Urban-Rural Construction Bureau of the DETDZ Management Committee, with missing data supplemented using the road network.

We employ widely used tools for evaluating GI performance as part of a broader mixed-methods framework. Rather than focusing solely on optimizing infrastructure layout, the emphasis is placed on how GI planning aligns with existing institutional coordination challenges.

Building environment data were sourced from OpenStreetMap and further calibrated and supplemented through on-site inspections, government-provided land-use plans, and satellite imagery from Google. Additionally, the ALOS_PALSAR digital elevation model data (12.5m resolution) from the Alaska Satellite Facility was integrated into the model. The SWMM parameter settings in this study refer to the previous study in Yunnan [62–64], and after the model was built, the locations of flooding points under typical rainfall events were simulated, we further confirmed the results with the local officials and citizens, and the simulated locations of the flooding points were consistent with their experience, which proved that the model we constructed was reliable.

3.2. Ecological and economic benefit estimation

For ecological and economic indicators, we primarily considered the volume capture ratio of rainfall, pollutant concentrations, and the cost of Sponge City construction. The ecological benefits are mainly measured by the total runoff control rate and the new green area, as shown in Eqs. (1) and (2) [65,66].

$$RC = \frac{V_{rainfall} - V_{runoff}}{V_{rain}} \tag{1}$$

where RC is the total runoff control rate (%), $V_{rainfall}$ is the rainfall volumes for rainfall events with different return periods (m^3), and V_{runoff} is the total runoff volume under rainfall events (m^3).

$$S_{GA} = S_{LIDs} \times (R_{BRC} + R_{RG}) \tag{2}$$

where S_{GA} is the new green area (km^2), S_{LIDs} is the total area of low-impact development (LID) facilities under different scenarios (km^2), and R_{BRC} and R_{RG} are the construction area shares of bio-retention cell and rain garden, respectively (%).

The study area is characterized by a high proportion of green spaces and bare land, alongside outdated infrastructure in built-up areas. Based on these conditions, we selected Bio-Retention Cells (Bio-RC), Rain Gardens (RG), Green Roofs (GR), and Permeable Pavement (PP) as source facilities for green land, bare land, roofs, and roads, respectively. The construction costs for these Sponge City facilities were derived from reference prices provided in the *Technical Guide for Sponge City Construction* [67]. These reference prices were adjusted to reflect the construction complexity specific to the region (Table 2). Additionally, the cost of raw materials (e.g., grass, gravel, permeable pavement) in Dali was considered to refine the cost estimates for this study. Rainfall scenarios were simulated using the storm intensity formula (Eq. (3)) for Dali City [68]. From these scenarios, we calculated the volume capture ratio and pollutant concentration, focusing on suspended substances (SS), to assess the performance of the Sponge City facilities.

$$q = \frac{1534(1 + 1.035\, log\, P)}{(t + 9.86)^{0.762}} \tag{3}$$

where t is the rainfall duration (min), P is the repetition period of rainfall (a), and q is the storm intensity (L/s.ha). Based on the conversion relationship between the storm intensity q and the average rainfall intensity i, the storm intensity q can be converted to:

$$i = \frac{9.186(1 + 1.035\, log\, P)}{(t + 9.86)^{0.762}} \tag{4}$$

where i is the average rainfall intensity (mm/min).

The reduction effect of SS refers to the *Technical Guide for Sponge City Construction* [67] issued by the Ministry of Housing and Urban-Rural Development of China (Table 3), and the SS removal rates of Bio-RC, RG, GR, and PP were set to 80 %, 70 %, 75 % and 85 % respectively. The main function of the pump stations is to regulate the runoff, and the initial rainwater will be treated by LIDs before entering the pump stations, which would significantly improve the quality of the rainwater, and then it would be lifted to the outfall. This combination not only reduces the pressure of the drainage network, but also improves the quality of the rainwater that flows into the river.

Table 2
Costs of Sponge City projects in China.

Types	Unit	Reference	Chosen
Bio-Retention Cell	RMB/m^2	150–800	300
Rain Garden	RMB/m^2	30–200	100
Green Roof	RMB/m^2	100–300	200
Permeable Pavement	RMB/m^2	60–200	100

3.3. Scenario development

The specific parameters for GI design were determined by professional environmental engineers based on interviews with government officials. Dali City's requirements include an 85 % volume capture ratio, a minimum 60 % total SS removal rate, no overflows during 1- to 3-year return periods rainfall events, and the absence of high-risk areas during a 50-year return period rainfall event.

We further collected rainfall data for Dali from 1970 to 2020 (Fig. 4). Although Dali City is located in a humid region of China, rainfall events with return periods of 1–3 years occur with high frequency. During this period, there were a total of 5950 rainfall events, with 70.47 % occurring within 1–3 years return periods, and 10.4 % occurring over a return period of 50 years or more. Therefore, ensuring that these such small return period but high-frequency rainfall events do not cause overflow and that large return period but low-frequency rainfall events do not cause urban flooding will enable Dali to effectively manage rainfall events of all magnitudes.

The scenario design in this study is primarily based on local planning strategies and relevant literature. Two extreme cases were first introduced—no green facilities (S1, 0 %) and full coverage (S5, 100 %)—to capture the boundary conditions and comprehensively assess the relationship between construction costs and enhancement effects [69,70]. The intermediate scenarios (S2–S4) were developed based on the sponge city planning in Yunnan province, which reflects the local green infrastructure strategy, as well as relevant research by Jia [71] and Wang [72]. Moreover, the scenario development process was supported by green infrastructure and sponge city planning experts, ensuring contextual relevance and practical feasibility. The spatial layout of the green facilities follows the principle of differentiation: GR are used on the roof, PP are laid on the road, Bio-RC are set up in the green land, and RG are constructed on the bare land.

The detailed setup of GI design parameters is presented in Table 4. Given the soft and easily reconstructible nature of the green and bare ground in the Tianjing area, the surface berm height for Bio-RC and RG was set at 200 mm, with a soil thickness of 200 mm. Only Bio-RC includes storage, which was configured at 300 mm. Conversely, due to the challenges associated with reconstructing older buildings and roads, the parameters for GR were adjusted: surface berm height was set to 100 mm, soil thickness to 100 mm, and drainage mat thickness to 100 mm. For PP, the surface berm height was set at 50 mm, pavement thickness at 50 mm, and soil thickness at 100 mm.

Rainfall data for the study area, spanning July to August 2024, was sourced from NASA's [73] to reflect typical local rainfall conditions (Fig. 5). Additionally, rainfall scenarios for four different return periods were designed (Table 5) using the storm intensity formula (Eq. (4)). The observed typical rainfall conditions were employed to evaluate the cost-effectiveness of GI measures, while the formula-derived rainfall scenarios were utilized to develop feasible solutions that align with Dali's flood control and pollution prevention objectives.

3.4. Meeting governance goals through GI intervention

After running the model simulations, the volume capture ratio, capture water volume, and cost per cubic meter of stormwater managed for all scenarios are presented in Fig. 6(a). These simulations are based on typical rainfall conditions (Fig. 5). Scenario S1 serves as the baseline, with all its indicators set to zero. A 25 % implementation of GI (S2) achieves Dali City's target of an 85 % volume capture ratio. However, scenarios S3, S4, and S5 require additional investments of 0.479, 1.054, and 1.419 billion RMB over S2, respectively, yielding only marginal improvements in the volume capture ratio—6.71 %, 10.57 %, and 11.97 % higher than S2. While GI proves effective in pollutant reduction and flood risk mitigation, heavy investments to exceed the 85 % volume capture ratio are not cost-effective. Beyond this threshold, each additional 1 % improvement would cost at least 12 million RMB.

To further assess GI effectiveness, we conducted 2D flood simulations using PCSWMM for various rainfall events. The maximum flood depths are depicted in Fig. 7. Under current conditions (S1) in the Tianjing area, multiple ponding points with maximum depths exceeding 2 m appear during a rainfall event with a two-year return period. Expanding GI coverage increases the area's capacity to manage rainfall, especially during low-intensity events. In scenarios S4 and S5, ponding points are eliminated for rainfall events with 1-, 2-, and 3-year return periods. Additionally, under a one-year return period, no flooding occurs in scenario S3. Fig. 8 shows the flood hazard analysis based on the criteria in Table 6. This analysis visualizes surface water depths across different calculation units in the

Table 3
SS removal rates for some Low Impact Development (LID) facilities.

Name of the facility	Pollutant removal rate (in SS, %)
Permeable pavement	80~90
Permeable cement concrete	80~90
Permeable asphalt concrete	80~90
Green roof	70~80
Bio-retention cell	70~95
Wet pond	50~80
Rain garden	50~80
Water reservoir	80~90
Rainwater tank	80~90
Conveying grass-planting trench	35~90
Dry grass-planting trench	35~90
Vegetated buffer strip	50~75

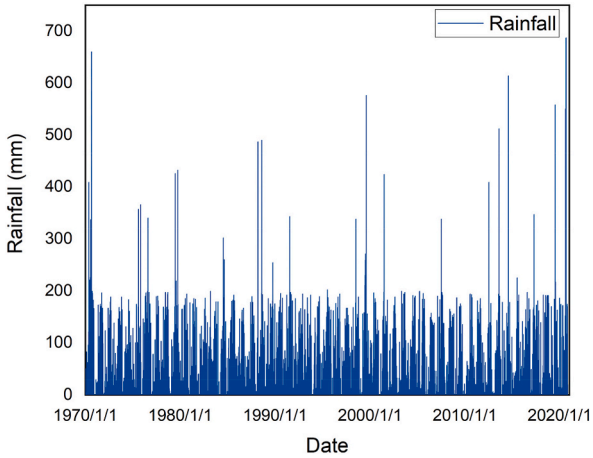

Fig. 4. Historical rainfall events in Dali.

Table 4
Coverage of Green Infrastructure for the studied scenarios.

Type	Unit	Scenario 1 (S1)	Scenario 2 (S2)	Scenario 3 (S3)	Scenario 4 (S4)	Scenario 5 (S5)
GI Percentage	%	0	25	50	75	100
Bio-Retention Cell	km^2	0	0.97	1.94	2.88	3.84
Rain Garden	km^2	0	0.58	1.17	1.74	2.32
Green Roof	km^2	0	0.53	1.07	1.59	2.12
Permeable Pavement	km^2	0	0.23	0.46	0.68	0.9

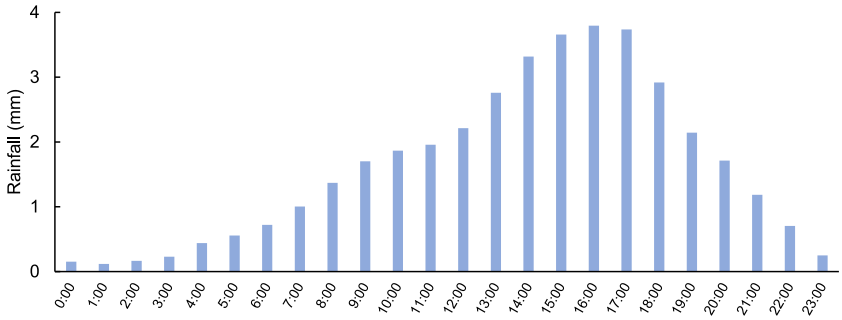

Fig. 5. Rainfall data for typical rainfall event in Dali.

Table 5
Rainfall events under different return periods.

Return period/year (a)	rainfall duration (min)	Depth (mm)
1	120	27.18
2	120	35.64
3	120	40.60
50	360	101.05

Tianjing area 2 h after rainfall events.

To address high-hazard areas identified in Fig. 8, two pumping stations (head: 3 m; flow rate: 3 m^3/s) were added, as shown by the purple circles in Fig. 9 (S3 with pumps). With these additions, we evaluated pollutant reduction rates under typical rainfall conditions (Fig. 6(b)). While the pumping stations slightly reduce pollutant (SS) reduction rates, the impact is negligible. Therefore, integrating gray infrastructure (e.g., pumps) with GI is recommended when funding is available.

The Chinese Central Government mandates that sponge city systems must handle a 50-year return period rainfall event without incurring flood-related losses. To meet this requirement, we simulated flooding across all scenarios under a 50-year return period rainfall condition. The resulting hazard maps are shown in Fig. 8. These maps indicate that, except for S5, all scenarios experience high-hazard areas (water depth >0.3 m) during heavy rainfall. The current scenario (S1) has particularly large high-hazard areas.

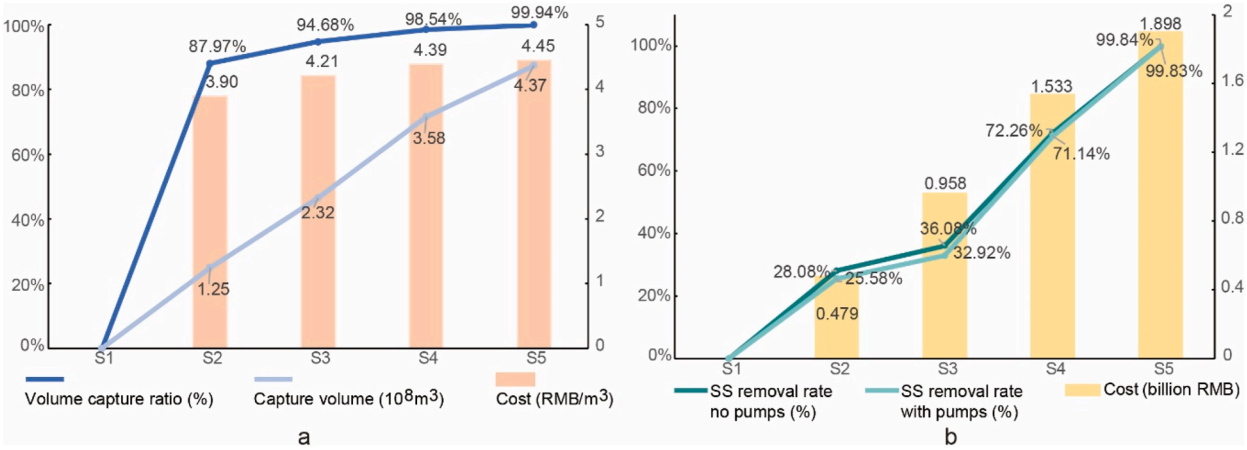

Fig. 6. Rainfall control and SS reduction simulation results.

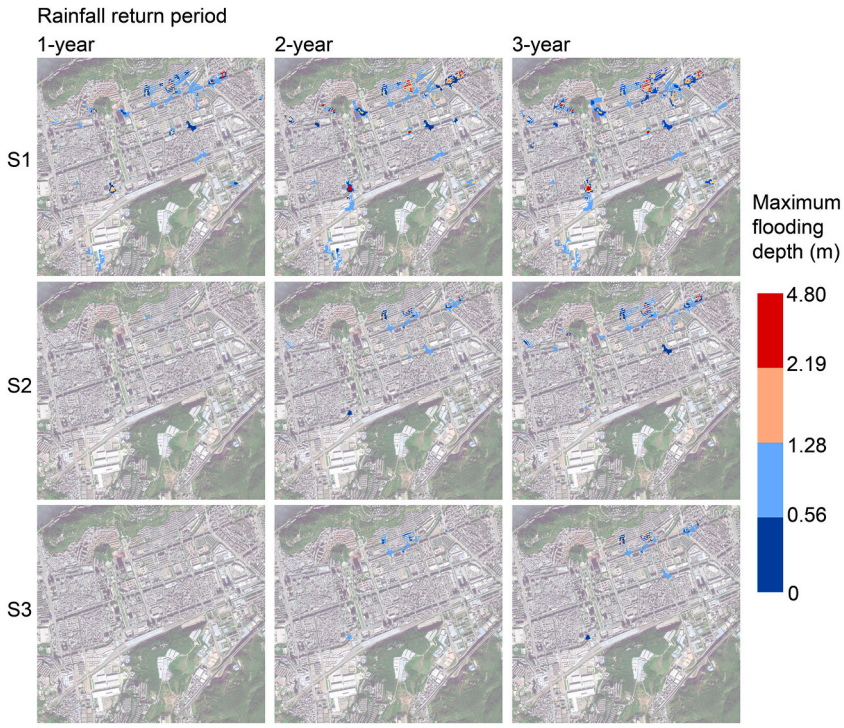

Fig. 7. Maximum depth of flooding under rainfall scenario of 1, 2, 3-year return period.

However, scenario S3, when combined with pumping stations, effectively manages 50-year rainfall events, resulting in only low-hazard areas (water depth <0.17 m) and no high-hazard areas. This highlights the capability of GI to handle extreme rainfall when supplemented by gray infrastructure.

The integration of GI and gray facilities significantly reduces flooding hazard areas for 50-year return period events. Low-, medium-, and high-hazard areas decrease from 10.05 ha, 0.2 ha, and 4.67 ha–6.41 ha, 0.1 ha, and 0 ha, respectively—a reduction of 36.26 %, 51.25 %, and 100 %. According to Dali City's policy objectives (85 % volume capture ratio, 60 % pollutant reduction rate, and effective management of 50-year rainfall events), the optimal GI coverage is calculated to be 71 % of the total area, interpolated between scenarios S3 and S4.

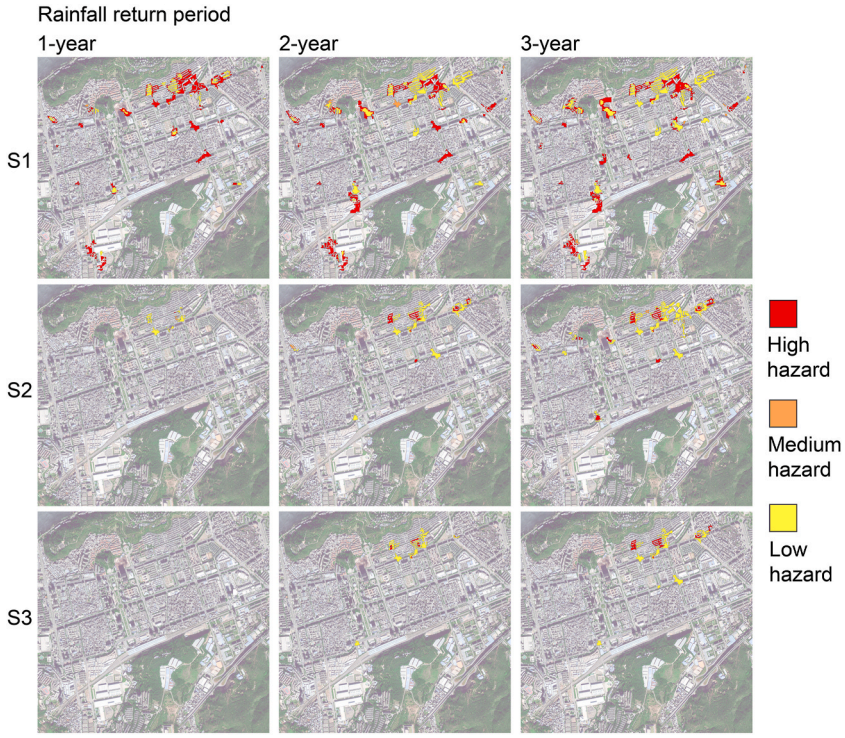

Fig. 8. Flood hazard maps for different return period rainfall events.

Table 6
Flooding hazard criteria.

	Depth (m)	Time
Low hazard	0.17≥Depth >0	Two hours after the rain stopped
Medium hazard	0.3≥Depth>0.17	Two hours after the rain stopped
High hazard	Depth>0.3	Two hours after the rain stopped

4. Insights for policy-decision and practice

4.1. Coordination across government departments

Our detailed analysis of governance processes for urban flooding and water pollution management in Dali City reveals several critical insights. The departments involved in addressing these issues have overlapping responsibilities, yet operate with separate agendas, driven by higher-level funding mechanisms and administrative pressures. Such institutional fragmentation is not unique to Dali; similar patterns have been observed in many cities attempting to implement multifunctional GI, where overlapping mandates and siloed planning practices hinder coherent governance outcomes [22,24].

In resource-constrained local governments, municipal investments targeting one issue often undermine efforts to address another. A similar issue was observed in Matsler et al.'s case study of Portland [74], where respondents expressed concern that too much funding was being directed toward ecological enhancements at the expense of essential stormwater management. While Matsler et al. suggest addressing fragmented decision-making through improved knowledge systems among decision-makers, the case also highlights a more fundamental governance challenge: funding allocation itself can create policy tensions.

In our Dali case, under strong top-down administrative pressure, water quality protection has become a politically unquestionable priority. As a result, ecological goals were achieved. However, local decision-makers' concerns proved justified, as conflicts between overlapping governance objectives eventually surfaced: flood management prioritizes rapid drainage to minimize exposure, whereas pollution control requires slowing discharge to reduce contamination. Similar trade-offs have also been documented in cities like Detroit, where ecological and flood control goals are not always aligned [22]. Yet compared to Portland or Detroit, such tensions are often more acute and urgent in rapidly developing cities, where institutional capacity and financial flexibility are more limited [66].

In addition, spontaneous adaptation measures by residents, driven by their available resources, further exacerbate inequalities. Individuals with greater financial and social capital implement more effective measures, leaving vulnerable populations increasingly exposed. This highlights how the absence of coordinated public investment can reinforce unequal adaptive capacities, which, as noted

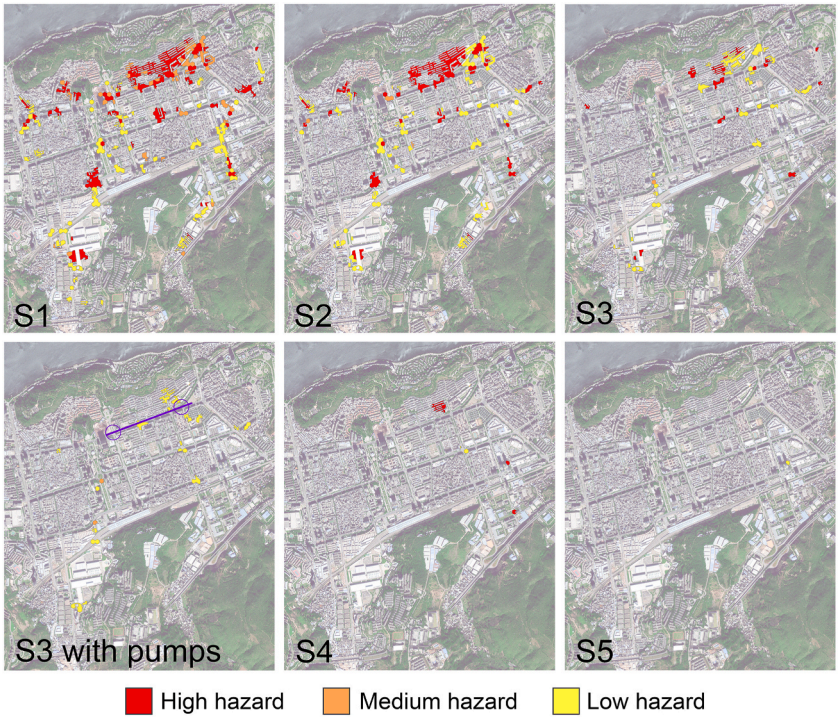

Fig. 9. Flooding hazard maps under rainfall scenario of 50-year return period in S1-S5.

in recent literature, undermines long-term social resilience and the transformative potential of GI interventions [19,24].

These challenges underscore the importance of establishing robust coordination mechanisms. Such mechanisms must address not only the fragmentation of institutional responsibilities and conflicting departmental agendas, but also the misalignment of funding structures, the unequal distribution of adaptive capacity among residents, and the physical contradictions between flood control and water pollution management. Confronting these issues requires more than sector-specific reforms; it demands institutional coordination across departments and administrative boundaries [19,20].

Establishing a special coordination agency is one possible solution [75]. This agency should bring together relevant departments, such as environmental protection, water management, urban planning, and infrastructure, along with financial and administrative authorities. Its core function is to enable joint planning, unified knowledge and information sharing, and the alignment of policy objectives across sectors. Such a coordination agency already exists in London, where the Greater London Authority plays a central role in aligning GI planning across different sectors and governance levels [23].

Our findings echo Hansen et al. [24], who highlight the importance of cross-sectoral coordination and collaboration observed in many cities. Rather than relying on isolated, sector-specific approaches, integrated governance frameworks are needed to align ecological functions with the fragmented structures of urban bureaucracies.

Ultimately, the coordination failures observed in Dali offer broader insights into how governance capacity and institutional integration influence the practical implementation of GI, particularly in rapidly developing and decentralized policy contexts. By aligning institutional efforts and optimizing investments across green and gray infrastructure systems, cities can mitigate policy conflicts and achieve more sustainable and equitable outcomes.

4.2. Balancing flood control in water pollution management through GI investment

GI is increasingly promoted as a transformative governance strategy [45]. Its multifunctional narrative provides policy-makers with greater flexibility in navigating complex environmental mandates [23,76]. Building on this potential, we recommend integrating flood management into existing financing structures for water quality protection in Dali through the use of GI policies. Such integration would enhance funding for flood governance while maintaining alignment with broader environmental goals. This reflects what Matsler et al. [74] describe, in the cases of Portland and Baltimore, as the strategic ambiguity of GI, where local actors leverage its multifunctionality to meet multiple mandates under constrained resources.

This approach addresses a common tension in multilevel governance, where local governments must reconcile national environmental targets with local flood resilience needs, often in the absence of adequate fiscal support [23]. In cities such as Portland, Baltimore, and Phoenix, there is already evidence that GI can help reconcile governance objectives across different sectors and levels of government [77]. This dual framing also responds to the environmental pressures faced by both government and society, highlighting GI as a solution capable of addressing institutional demands while delivering broader public benefits [78].

These findings are synthesized into a governance framework (Fig. 10), which illustrates the interactions among infrastructure types, policy mechanisms, and social feedbacks in the coordination of water pollution control and flood risk mitigation. The framework visualizes how GI can be strategically integrated into existing financing systems, how urbanization-related pressures reshape imperviousness and public risk, and how systemic measures and communication affect adaptation outcomes.

In parallel, our simulation results suggest that, given the development stage and fiscal capacity of cities like Dali, the crucial role of gray infrastructure in flood management should not be overlooked. Therefore, further improving the existing gray infrastructure system remains important. The framework incorporates this aspect by recognizing that gray infrastructure continues to provide essential drainage and flood protection functions, especially in high-risk areas. Importantly, public participation further reinforces the effectiveness of this integration by reducing inequalities in flood risk exposure and fostering mutual understanding and coordination among stakeholders.

In addition to offering a conceptual structure, the framework also incorporates the quantified outcomes of this case study, linking governance configurations to observable impacts. Rather than serving as a context-specific recommendation tool, it functions as a transferable analytical lens to unpack the governance dynamics behind multifunctional GI implementation in other fast-urbanizing regions.

However, while the multifunctional potential of GI has been highlighted in various international contexts, its practical realization depends heavily on institutional coherence, financing mechanisms, and local implementation capacity [23,76]. As Hoover [76] points out, multifunctional narratives can also obscure governance objectives and create challenges for practical implementation. It is therefore essential to establish coordination mechanisms as a foundation for effective delivery.

4.3. Technological recommendations for GI planning

Simulation results illustrate that GI can substantially reduce runoff and pollutant loads, particularly under small to medium-intensity rainfall scenarios. Under optimal scenarios, GI achieves a volume capture ratio exceeding 94 % and a pollutant reduction rate surpassing 60 %. By providing ecosystem services such as water retention, pollutant filtration, and water purification, GI mitigates the hydrological impact of impervious surfaces, restores natural hydrology, and reduces flood risks.

However, the results also highlight the limitations of GI under extreme conditions, such as 50-year rainfall events, reinforcing the need for hybrid approaches that combine green and gray infrastructure. Complementary gray infrastructure remains essential. To address these, the study explored strategic integration of gray infrastructure, with two pumping stations simulated near high-risk flood zones. The combined intervention significantly reduced flood hazard levels demonstrating the effectiveness of context-sensitive hybrid solutions.

This case study further highlights the relationship between the spatial placement of GI and the achievement of governance objectives [22]. In practice, the location of GI installations is often closely linked to the extent to which their intended objectives are achieved. Mismatches between planning expectations and actual outcomes may arise when siting decisions are not aligned with policy goals. For example, in Dali, many existing GI projects are concentrated in rural areas on the western side of Erhai Lake, where they primarily serve water purification purposes but have limited effect on mitigating urban flood risk. Our study explores the potential of extending GI implementation to urban areas in the southern part of Erhai, where its multifunctional benefits can be more effectively realized.

For ecologically sensitive cities like Dali, the case underscores how multifunctional GI planning can serve as a strategic bridge between overlapping mandates. By constructing a unified governance framework, the benefits of GI can be maximized, offering sustainable solutions to interconnected urban challenges. In line with the evolving GI literature, our case contributes not only performance metrics, but also governance insights that respond to the growing call for integrative, adaptive, and equitable infrastructure planning under climate uncertainty [74,76].

5. Conclusions

This study adopts an integrated approach to examine how governance systems can coordinate the dual challenges of urban flooding and water pollution through multifunctional GI, using Dali City as a case. By bridging hydrological modeling with qualitative governance analysis, it contributes to the growing literature on how technical and institutional dynamics interact in urban environmental planning. We propose a governance framework centered on GI investment and describe the social and hydrological processes underlying the dual objectives of flood risk mitigation and water quality improvement.

Thoughtful GI planning facilitates the efficient allocation of funds and resources, strengthens relationships between governments and communities, and reduces social inequalities, thereby enhancing both ecosystem and flood resilience. For cities like Dali, which boast significant ecological resources, we recommend prioritizing GI investment as a central policy tool, with a focus on integrating GI with gray infrastructure to maximize efficiency and cost-effectiveness. Establishing cross-departmental and inter-district collaboration mechanisms is equally critical for ensuring seamless planning, resource allocation, and implementation.

Experimental findings underscore the significant impact of GI deployment scale on governance efficiency and cost-effectiveness. After achieving an 85 % volume capture ratio under typical rainfall conditions, each additional 1 % improvement in runoff control requires a minimum investment of 12 million RMB in GI. The optimal scenario, featuring a GI deployment rate of 71 % combined with gray infrastructure, achieves a volume capture ratio exceeding 94 % and a pollutant reduction rate of over 60 %. This combination not only satisfies pollutant reduction requirements but also effectively mitigates flood risks, reducing low-, medium-, and high-hazard flood areas by 36.26 %, 51.25 %, and 100 %, respectively, during a fifty-year heavy rainfall event.

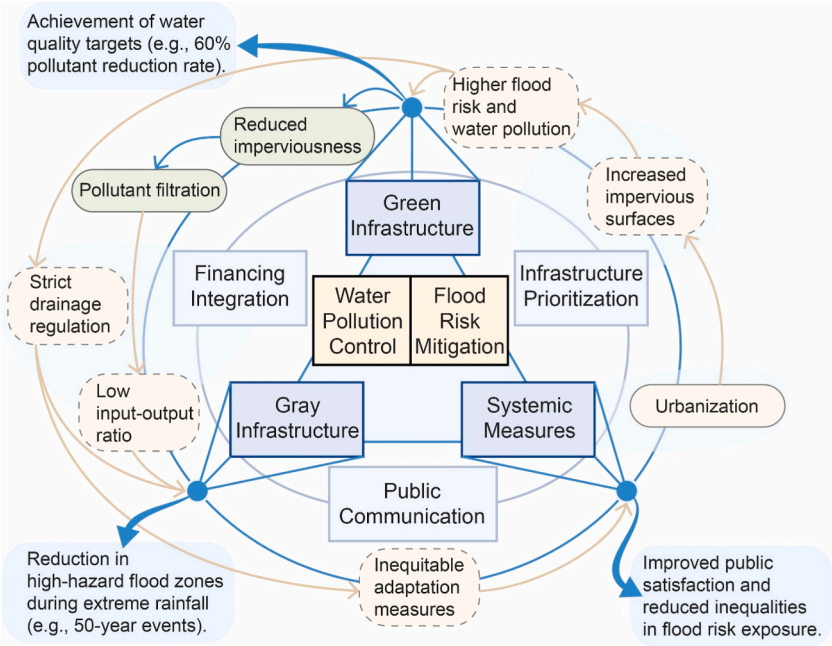

Fig. 10. Illustration of the coordination governance framework.

This study responds to the need for more grounded and context-sensitive GI planning approaches by situating technical evaluations of runoff and pollution control within an institutional analysis of policy conflicts and governance coordination. In rapidly urbanizing cities of the Global South, existing research tends to emphasize the hydrological performance of GI, while paying less attention to how cross-sectoral conflicts and implementation constraints shape planning decisions. By linking simulation results with institutional observations in Dali, this study presents an empirical case demonstrating that the effectiveness of GI depends not only on design parameters, but also on the alignment between multifunctional policy goals and existing governance conditions. This perspective may support the development of more realistic and adaptive GI strategies in similar contexts.

Despite its contributions, this study has certain limitations. First, the hydrological model incorporates simplifications, particularly in pollutant calculations, which necessitate further experimental calibration to enhance accuracy. Second, the social and behavioral factors influencing GI implementation are context-specific, requiring additional research to refine the framework's applicability across diverse settings, especially in comparative urban governance studies beyond China.

CRediT authorship contribution statement

Wenhan Feng: Writing – review & editing, Writing – original draft, Validation, Resources, Methodology, Investigation, Formal analysis, Conceptualization. **Bingyi Zhou:** Writing – review & editing, Writing – original draft, Validation, Methodology, Investigation, Formal analysis. **Ziyao Wang:** Writing – original draft, Methodology, Formal analysis. **Yifei Wang:** Writing – review & editing, Resources. **Haifeng Jia:** Writing – review & editing, Resources, Methodology, Investigation, Conceptualization. **Junxu Chen:** Writing – review & editing, Methodology, Investigation, Conceptualization. **Jingyu Wang:** Writing – review & editing. **Xiangzheng Deng:** Writing – review & editing, Resources, Methodology, Investigation, Conceptualization. **Matthias Garschagen:** Writing – review & editing. **Liang Emlyn Yang:** Writing – review & editing, Resources, Methodology, Investigation, Conceptualization.

Key points

1. Urban flood and water pollution problems call for coordinated water governance.
2. Model results demonstrate that green infrastructure has synergistic effects in solving both floods and pollution.
3. Balanced investment in green and gray infrastructures is recommended to Dali to maximize the efficiency and cost-effectiveness.
4. Urban water governance requires collaboration across sectors and administrative boundaries.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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