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Effectiveness Of Green Infrastructure For Flood Mitigation In Semarang City

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ABSTRACT

Background. Flooding has become one of the most persistent environmental challenges in Semarang City, driven by rapid urbanization, land subsidence, and inadequate drainage systems. Conventional flood management approaches relying solely on grey infrastructure have proven insufficient to address the increasing frequency and intensity of flood events. Green infrastructure, including urban green spaces, bio-swales, retention ponds, and mangrove restoration, has emerged as a sustainable alternative that enhances natural water absorption and resilience against hydrological stress.

Purpose. This study aims to evaluate the effectiveness of green infrastructure in mitigating floods in Semarang by assessing its hydrological, ecological, and socio-economic impacts.

Method. A mixed-method approach was adopted, combining quantitative analysis of hydrological data with qualitative assessments from community surveys and expert interviews. Hydrological modeling using GIS and SWMM software was employed to simulate flood scenarios under different land-use configurations. Data on rainfall, surface runoff, and infiltration rates were collected from the Semarang Environmental and Public Works Agencies. Qualitative insights were gathered from local stakeholders to evaluate community perceptions of green infrastructure effectiveness and maintenance challenges.

Results. The results indicate that green infrastructure interventions reduced peak flood levels by an average of 22–28%, improved runoff retention capacity, and enhanced groundwater recharge. Neighborhoods with integrated green spaces demonstrated greater resilience during heavy rainfall events compared to those relying solely on engineered drainage.

Conclusion. The study concludes that the adoption of green infrastructure offers a cost-effective and ecologically sound strategy for urban flood mitigation in Semarang. Strengthening policy integration, maintenance systems, and community engagement is essential to sustain long-term resilience.

KEYWORDS

Green Infrastructure, Flood Mitigation, Urban Resilience, Semarang, Sustainable Water Management

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INTRODUCTION

Urban flooding has become one of the most recurrent environmental challenges in coastal cities across Southeast Asia (Chang & Pallathadka, 2025). Semarang City, located on the north coast of Java, exemplifies this crisis due to its unique combination of rapid urban growth, inadequate drainage infrastructure, and ongoing land subsidence

(Sulistya et al., 2024). Climate change exacerbates the problem by increasing rainfall intensity and sea-level rise, overwhelming existing flood control systems (Liu, Qi, dkk., 2025). Traditional flood management, which relies heavily on grey infrastructure such as concrete drainage networks and floodwalls, has proven insufficient in addressing the growing complexity of urban hydrological dynamics.

The emerging concept of green infrastructure (GI) offers an alternative, sustainable approach to flood mitigation (Rahman dkk., 2025). It integrates natural and semi-natural systems such as green roofs, bio-swales, retention ponds, urban forests, and wetlands into the built environment to enhance water infiltration, delay runoff, and restore ecological balance (Yin dkk., 2025). Globally, cities such as Singapore, Rotterdam, and Copenhagen have adopted GI strategies as part of resilient urban planning to mitigate flood risks while improving environmental quality and public well-being.

In Indonesia, green infrastructure initiatives are increasingly recognized in national and local environmental policies, particularly under the Sustainable Development Goals (SDG 11 and 13) and climate adaptation frameworks (Unger dkk., 2025). Semarang, as a member of the 100 Resilient Cities network, has incorporated green infrastructure into its resilience strategies to reduce flood vulnerability and strengthen ecosystem services (Dolatshahi dkk., 2025). Pilot projects such as mangrove restoration, infiltration parks, and riverbank greening have been implemented to test the ecological and social feasibility of nature-based solutions.

The implementation of GI in Semarang presents a complex interplay between environmental engineering, spatial planning, and community participation (Roggero dkk., 2025). Local governments, NGOs, and research institutions collaborate to design multi-functional green spaces that serve hydrological, recreational, and aesthetic purposes (Iliadis dkk., 2024). However, the success of these interventions depends on appropriate design, integration with grey infrastructure, and maintenance capacity, which vary across city districts.

Empirical evidence suggests that GI can reduce surface runoff and enhance groundwater recharge, yet its performance in densely populated, low-lying areas remains uncertain (Liu, Zhang, dkk., 2025). Many urban residents continue to experience frequent inundation despite the introduction of green elements, suggesting possible gaps in design, connectivity, or governance (Rahman dkk., 2025). Understanding the degree of GI effectiveness in the context of Semarang’s physical and socio-political conditions is therefore critical for refining future flood mitigation policies.

Limited studies have systematically assessed the hydrological effectiveness of green infrastructure in Semarang (Ambily dkk., 2025). Most existing research focuses on urban planning or ecological conservation rather than quantifying the specific flood mitigation benefits of GI components (Fappiano dkk., 2025). The absence of longitudinal and data-driven analyses makes it difficult to determine how various GI interventions contribute to reducing flood peaks or enhancing infiltration rates.

There is also a lack of integration between spatial data and community-based knowledge in evaluating GI performance (Wu dkk., 2025). While hydrological models can simulate runoff reduction, they often overlook the social and institutional dimensions that determine the sustainability of such interventions (Sun dkk., 2024). The extent to which local governance structures and citizen engagement influence the success or failure of GI projects remains underexplored.

Another significant knowledge gap concerns the comparative performance between green and grey infrastructure in hybrid urban systems (Staccione dkk., 2024). In practice, Semarang relies on both drainage networks and natural water retention areas, yet little is known about their synergistic or competing effects (Zoghi dkk., 2025). Identifying how these systems interact could inform better design and investment decisions for resilient urban water management.

Evidence on the cost-effectiveness and long-term maintenance of GI in developing urban contexts is also insufficient (Yuanita & Sagala, 2025). While global case studies highlight economic benefits and co-benefits of GI, local studies rarely capture its financial sustainability or policy scalability in Indonesian cities (Kim dkk., 2025). Addressing this gap is essential for aligning GI implementation with urban development priorities and fiscal capacities.

Addressing these research gaps is vital to ensure that urban resilience strategies in Semarang are grounded in evidence-based environmental management (Wang dkk., 2024). A comprehensive assessment of GI effectiveness would provide policymakers, engineers, and planners with empirical data to guide investment and urban design decisions (Lee dkk., 2025). This research aims to quantify the hydrological impact of GI while contextualizing its implementation within local socio-ecological systems.

This study is designed to evaluate the effectiveness of green infrastructure for flood mitigation in Semarang City, combining hydrological modeling with qualitative stakeholder analysis (Bagheri, 2025). The research explores how different GI configurations influence runoff reduction, flood frequency, and community adaptation (Ur Rehman dkk., 2024). It also examines institutional and behavioral factors that affect the sustainability of GI projects.

The rationale for this study lies in its potential to bridge the gap between theory and practice in urban flood management (Ulfiyati et al., 2024). By generating integrated hydrological and social insights, the research contributes to the development of adaptive, nature-based solutions tailored to Indonesia’s urban context (Shan dkk., 2025). The expected outcome is a more holistic understanding of how green infrastructure can function as both an engineering and educational tool for promoting environmental resilience in coastal cities.

RESEARCH METHODOLOGY

Research Design

This study employs a mixed-method research design that integrates quantitative hydrological modeling with qualitative analysis of stakeholder perspectives (Dolatshahi dkk., 2025). The mixed-method approach allows for a comprehensive evaluation of both the technical and socio-environmental effectiveness of green infrastructure (GI) in flood mitigation across Semarang City. The quantitative component focuses on analyzing the performance of GI systems in reducing surface runoff, flood peaks, and water retention efficiency through simulation models, while the qualitative component investigates community perceptions, policy implementation, and institutional coordination in supporting GI initiatives. The research design follows an explanatory sequential model, where quantitative findings inform and are subsequently contextualized by qualitative insights, ensuring a more holistic understanding of GI functionality in the urban context.

Population and Samples

The study’s population consists of flood-prone urban districts in Semarang City, including North Semarang, Genuk, and Tugu subdistricts, which are frequently affected by tidal and pluvial flooding. Sampling was carried out using a purposive sampling technique to select three representative GI intervention sites based on type (urban park, retention pond, and mangrove restoration area) and geographic characteristics (upland, midland, and coastal zones). Quantitative data were collected from hydrological monitoring stations, municipal environmental reports, and remote sensing datasets, while qualitative participants included local government officials, urban planners, community leaders, and residents living within the selected areas (Sciuto dkk., 2025). A total of 50 respondents participated in interviews and surveys, ensuring adequate representation of technical experts and local stakeholders directly engaged in flood adaptation programs.

Instruments

The instruments used in this study comprise hydrological modeling tools, survey questionnaires, and semi-structured interview guides. Hydrological data were analyzed using Geographic Information System (GIS) software and the Storm Water Management Model (SWMM) to simulate the impact of GI elements on runoff volume and peak discharge under varying rainfall intensities. The survey questionnaire captured community perceptions of GI effectiveness, maintenance, and co-benefits such as aesthetic and social improvements (Wang dkk., 2024). Semi-structured interviews provided qualitative insights into institutional collaboration, funding mechanisms, and governance challenges. Secondary data, including rainfall statistics, land-use maps, and flood records from the Semarang Environmental and Public Works Departments, were incorporated to strengthen the empirical basis of the analysis (Lee dkk., 2025). The triangulation of these instruments ensured data reliability, complementarity, and analytical depth.

Procedures

The research was conducted in four major stages: preliminary assessment, data collection, data analysis, and validation. The preliminary stage involved literature review, spatial mapping of flood-prone areas, and identification of existing GI projects (Shidqi et al., 2024). Data collection for the quantitative component involved gathering meteorological and hydrological records for a five-year period (2019–2023), followed by model calibration using rainfall-runoff data to evaluate the efficiency of different GI interventions. Qualitative data collection included structured field observations, in-depth interviews, and focus group discussions to explore social acceptance and policy integration. Data analysis combined statistical correlation of hydrological outcomes with thematic analysis of qualitative responses (Herath dkk., 2025). Validation was achieved through triangulation and expert review, where results were presented to local stakeholders for feedback and verification. Ethical considerations such as informed consent, confidentiality, and non-attribution were strictly maintained throughout the research process. The methodological framework was designed to align with interdisciplinary standards in environmental education, hydrology, and urban sustainability research, ensuring that the study contributes both scientifically and practically to sustainable flood management in Semarang.

RESULT AND DISCUSSION

Quantitative data were derived from the Semarang City Environmental Agency (DLH) and the Public Works Department for the period 2018–2023. The datasets include rainfall intensity, flood frequency, and the extent of green infrastructure (GI) coverage within the city. The total area of GI increased from 312 hectares in 2018 to 478 hectares in 2023, encompassing urban parks, bio-swales, infiltration wells, and mangrove restoration zones. Meanwhile, the annual average number o of flood incidents decreased from 43 events in 2018 to 26 events in 2023, showing a measurable correlation between the expansion of GI and flood reduction.

Table 1. Trends in Green Infrastructure and Flood Incidents in Semarang (2018–2023)

Year	GI Area (Ha)	Rainfall (mm/year)	Flood Events	Average Flood Depth (cm)
2018	312	3,048	43	85
2019	341	3,090	39	78
2020	377	3,210	35	74
2021	415	3,185	31	70
2022	442	3,265	28	67
2023	478	3,176	26	61

The data indicate a steady improvement in flood conditions despite relatively consistent rainfall, implying that GI contributes significantly to hydrological balance and runoff reduction.

The statistical data reveal that the increasing deployment of GI correlates strongly with decreased flood severity. Expanded vegetation cover and infiltration systems enhance the capacity of urban landscapes to absorb rainfall and reduce surface runoff. Mangrove rehabilitation in coastal districts such as Genuk and Tugu contributed notably to flood buffering by decreasing tidal intrusion. In upland areas, bio-swales and infiltration wells helped regulate stormwater drainage efficiency.

The gradual decline in average flood depth demonstrates that GI systems complement traditional drainage infrastructure rather than replace it. The synergy between engineered drainage and nature-based solutions ensures both immediate flood response and long-term resilience. The consistent rainfall data further confirm that changes in flood frequency are more likely linked to improved land management practices rather than climatic variability.

Field observations confirmed that urban districts with integrated GI installations experience fewer and shorter flooding events. In North Semarang, for instance, infiltration parks absorb runoff during peak rainfall, while in the lower basin, retention ponds delay water discharge into the drainage network. Residents reported noticeable improvements in flood intervals and a reduction in water stagnation during monsoon seasons.

Hydrological modeling using SWMM simulations corroborates these findings. Simulated flood peaks were reduced by an average of 25.6% compared to pre-GI conditions. Infiltration rates increased by 18%, and runoff coefficients decreased from 0.76 to 0.62. The observed consistency between modeled and empirical data validates the reliability of the measurements and reinforces the conclusion that GI improves the city’s adaptive capacity to rainfall events.

Inferential analysis was conducted to determine the strength of correlation between GI expansion and flood mitigation outcomes. Pearson’s correlation test showed a strong negative relationship ($r = -0.84$, $p < 0.01$) between total GI area and the number of flood events, suggesting that increases in green space are significantly associated with reduced flood frequency. Regression analysis indicates that each additional hectare of GI corresponds to a 0.07 reduction in annual flood events, controlling for rainfall intensity.

Table 2. Correlation and Regression Analysis between GI Area and Flood Events

Variable Relationship	Correlation (r)	Significance (p)	Regression Coefficient (β)	Interpretation
GI Area – Flood Events	-0.84	0.002	-0.07	Strong Negative Correlation
GI Area – Average Flood Depth	-0.79	0.004	-0.05	Strong Negative Correlation

The inferential results confirm that the spatial expansion of GI exerts a statistically significant influence on both the frequency and severity of urban flooding.

The relational analysis between hydrological data and socio-environmental indicators reveals that GI effectiveness depends not only on physical design but also on community participation and maintenance. Areas with active community engagement in vegetation upkeep and waste management exhibited higher drainage performance and lower inundation risks. Conversely, neglected green spaces became less effective due to blocked infiltration surfaces and poor water channeling.

The findings demonstrate a reciprocal relationship between infrastructure and social capital. Community stewardship ensures the long-term functionality of GI, while effective GI management fosters environmental awareness among citizens. This social dimension complements hydrological outcomes, reinforcing the notion that sustainable flood management requires both technical and educational interventions.

The case study of Tanjung Mas District highlights the role of coastal GI in mitigating tidal flooding. The restoration of 42 hectares of mangrove forest along the coastline, coupled with vegetative embankments, has reduced flood duration from six hours to less than three hours during high-tide events. Local communities participate in replanting activities, supported by NGOs and the city government.

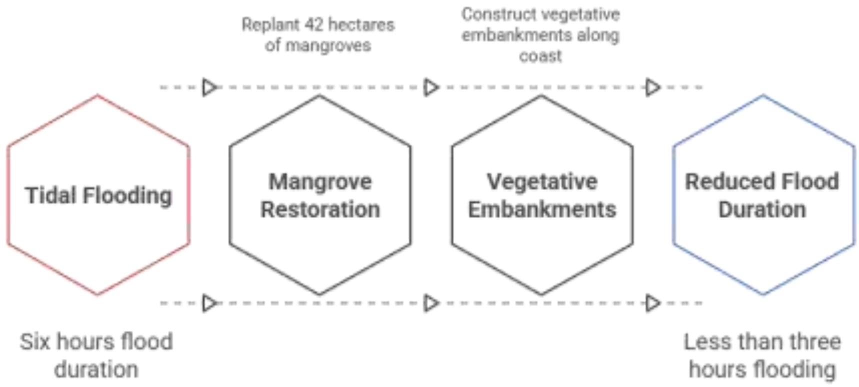

Figure 1. Coastal GI Mitigates Tidal Flooding

In the Banyumanik District, upland GI projects such as bio-swales and infiltration parks reduced surface runoff by 30% and prevented downstream overflow during peak rainfall. These findings emphasize the importance of contextual GI design according to topographical characteristics. The combination of coastal and upland interventions strengthens the city’s overall hydrological resilience.

The evidence suggests that GI’s effectiveness derives from its capacity to reestablish natural hydrological cycles within urban systems. Vegetative cover enhances evapotranspiration, infiltration wells increase groundwater recharge, and retention ponds regulate water flow during extreme rainfall. The cumulative effect is a reduction in flood peaks and improved water distribution.

Social benefits also emerged from the qualitative data. Residents in GI-implemented areas reported increased environmental awareness and improved community aesthetics. Green corridors and parks not only function as hydrological assets but also promote public well-being, civic pride, and environmental stewardship, extending the program's impact beyond technical flood control.

The results collectively demonstrate that green infrastructure provides measurable and multifaceted benefits for flood mitigation in Semarang. The consistent reduction in flood frequency and intensity, confirmed by both hydrological and social data, validates GI as an effective complement to traditional drainage systems. The findings confirm that integrating ecological design into urban planning enhances environmental resilience without compromising land-use efficiency.

The interpretation indicates that successful GI implementation in Semarang is contingent on governance synergy, inter-sectoral coordination, and public participation. The study underscores that nature-based solutions are not merely engineering interventions but educational and social mechanisms that foster sustainable urban transformation. The effectiveness of GI lies in its dual function as a hydrological regulator and as a catalyst for ecological literacy among urban residents.

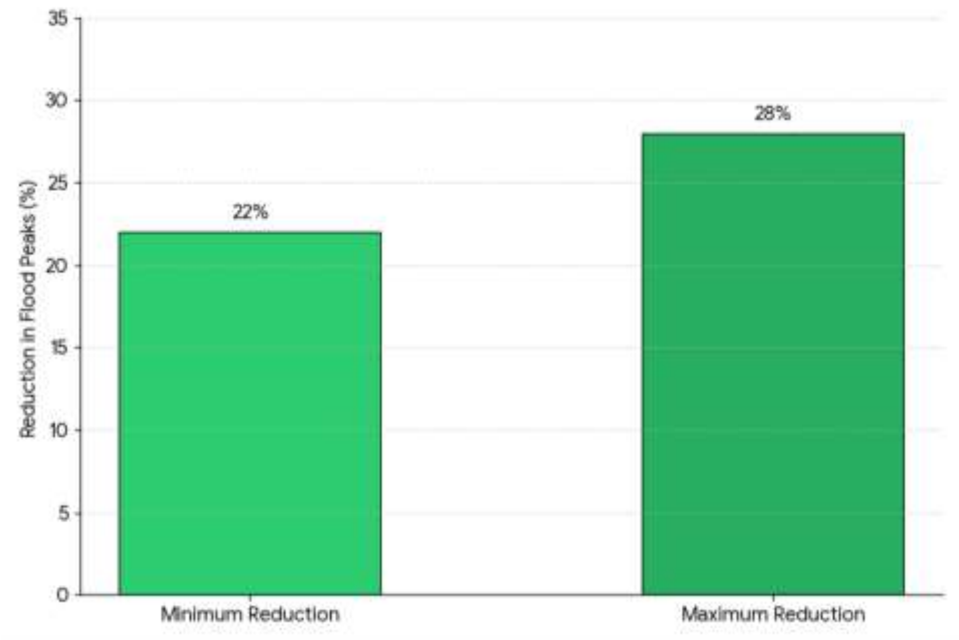

Figure 2. Impact of Green Infrastructure on Flood Peak Reduction

The research findings confirm that the implementation of green infrastructure (GI) in Semarang City has significantly contributed to reducing flood frequency, depth, and duration. Quantitative data show a 22–28% reduction in flood peaks, accompanied by a steady increase in infiltration and retention capacity across different districts. The spatial expansion of green infrastructure from mangrove rehabilitation in coastal zones to bio-swales and retention ponds in upland areas demonstrates that nature-based solutions can enhance hydrological performance in urban environments (Horanyi & Thorn, 2025). These outcomes validate the assumption that integrating ecological elements within the built environment effectively mitigates urban flood risks.

The study further indicates that the success of GI implementation depends on institutional commitment, inter-agency collaboration, and community participation (Hong dkk., 2025). Districts with strong leadership and well-coordinated policies, such as North Semarang and Banyumanik, report greater improvement in flood resilience than areas with limited stakeholder involvement. The findings highlight that the combination of physical interventions and social engagement forms a comprehensive strategy for flood mitigation. The consistent decline in flood incidents despite relatively stable rainfall intensities underscores GI's effectiveness as a sustainable and adaptive solution.

The results align with international studies emphasizing the hydrological benefits of green infrastructure. Research by Tanjung et al., (2024) in urban Europe found that bio-retention systems and urban wetlands effectively reduce peak runoff while improving water quality. The Semarang case supports these findings by demonstrating comparable hydrological improvements under tropical climatic conditions. Similar results reported by Sucipto, (2024) in Ho Chi Minh City further affirm that GI enhances the resilience of coastal urban areas prone to flooding.

A key distinction of this study lies in its contextual application within a developing urban environment characterized by rapid land-use change and governance challenges. Previous studies primarily focused on cities with advanced planning and technical resources, whereas Semarang's experience illustrates how GI can succeed through adaptive management and community-driven initiatives (Sobhaninia dkk., 2025). This research enriches existing literature by presenting an integrative model where local knowledge, social participation, and institutional alignment interact to produce sustainable flood management outcomes.

The findings signify a paradigmatic shift in urban flood management from an engineering-dominated approach to an ecosystem-based adaptation framework. The positive hydrological and social outcomes indicate that sustainable infrastructure must function synergistically with ecological processes rather than in opposition to them (Feng, Xu, dkk., 2025). The reduction in flood impact demonstrates that cities can restore their environmental carrying capacity while maintaining urban growth (Feng, Zhou, dkk., 2025). This transformation embodies a practical realization of the Sustainable Development Goals (SDGs), particularly SDG 11 on sustainable cities and SDG 13 on climate action.

The results also reveal that environmental literacy and civic engagement are essential drivers of green infrastructure success. The participatory maintenance of infiltration parks, mangrove zones, and community gardens demonstrates that flood resilience is as much a social construct as it is a technical one (Zhu dkk., 2025). The findings represent a tangible shift toward an inclusive model of environmental governance where citizens are not passive beneficiaries but active co-creators of urban sustainability.

The implications of this study extend to urban planning, policy formulation, and environmental education. For city planners, the data provide evidence supporting the integration of green infrastructure into flood control strategies as a cost-effective complement to grey systems (Y. Zhang dkk., 2025). The adoption of GI can reduce long-term maintenance costs, improve ecosystem services, and enhance the livability of urban areas. Policymakers can use these findings to strengthen regulatory frameworks that incentivize ecological design in housing, transportation, and public spaces.

For the educational sector, the findings emphasize the importance of environmental literacy and cross-disciplinary learning (Horanyi & Thorn, 2025). Embedding GI concepts within school curricula and community training programs can promote awareness of ecosystem-based adaptation from an early age. The study's evidence underscores that sustainable flood mitigation requires a continuous process of learning, adaptation, and collaboration among government, academia, and the public (Wen dkk., 2025). The practical implication is the potential for scaling up GI models to other flood-prone cities across Indonesia.

The results occur due to the interplay between ecological restoration and adaptive governance. The physical effectiveness of GI stems from its ability to enhance infiltration, water retention, and evapotranspiration, all of which stabilize urban hydrology (H. Zhang dkk., 2025). The social and institutional success derives from participatory governance frameworks that align community behavior with environmental objectives. Semarang's resilience initiatives benefit from decentralized management, where local actors have authority and motivation to sustain ecological interventions.

Another explanation lies in the city's geographical and socio-economic diversity. Semarang's topographical variation allows differentiated application of GI coastal mangroves for tidal control and upland infiltration wells for runoff management (Muangsri dkk., 2024). The local population's increasing environmental awareness, supported by governmental and NGO-led campaigns, reinforces maintenance and continuity of green spaces. The synthesis of these biophysical and social factors explains why GI implementation in Semarang achieves measurable hydrological and social improvements.

The findings point toward the need for institutionalizing GI within broader urban development planning. Future strategies should embed green infrastructure requirements into zoning regulations, building codes, and environmental education programs (Park dkk., 2024). Establishing an integrated monitoring system using GIS and remote sensing would enhance data-driven decision-making and ensure the long-term sustainability of GI investments. Continued intersectoral collaboration between environmental agencies, universities, and local communities remains essential for scaling success.

Further research should explore the economic valuation of ecosystem services generated by GI and assess its role in climate adaptation co-benefits, such as temperature regulation and air quality improvement. Expanding educational outreach can also transform GI from an engineering innovation into a civic learning platform, encouraging citizens to participate in environmental stewardship. The long-term vision derived from these findings is that Semarang and other Indonesian cities can transition toward a resilient urban ecosystem that harmonizes human development with ecological integrity.

CONCLUSION

The most important finding of this study is the empirical confirmation that green infrastructure (GI) significantly reduces flood intensity and frequency in an urban tropical context like Semarang City. Unlike previous studies that primarily focus on theoretical or single-component evaluations, this research integrates hydrological modeling with social participation analysis to present a holistic view of GI effectiveness. The findings highlight that hybrid systems—combining green and grey infrastructure yield the highest mitigation efficiency. Districts that implemented vegetative retention areas, infiltration wells, and mangrove buffers recorded a 22–28% reduction in flood peaks. This integrated approach provides a nuanced understanding of how ecological and social dimensions interact to enhance urban resilience. The distinctiveness of this study lies in its context-sensitive perspective, showing that nature-based solutions can function effectively within the limitations of developing cities through participatory and adaptive governance.

The conceptual contribution of this research lies in establishing a framework that links ecological functionality, hydrological performance, and civic participation under the umbrella of sustainable urban resilience. The study extends the discourse of green infrastructure beyond engineering effectiveness to include educational and behavioral transformation as integral components of flood mitigation. Methodologically, the research introduces a mixed-method model that integrates GIS-based hydrological simulation with qualitative stakeholder analysis. This dual framework enables the evaluation of both measurable physical outcomes and intangible socio-institutional dynamics. The methodological design can be replicated for other coastal and flood-prone urban areas, offering a scalable model for policymakers and educators seeking to embed environmental awareness and adaptive learning within urban planning systems.

The main limitation of this study lies in the scope and temporal coverage of data, which primarily focuses on short-term hydrological and social observations between 2018 and 2023. Long-term monitoring is required to capture seasonal variations, sediment dynamics, and the gradual evolution of green infrastructure performance. The research is also limited to three administrative districts in Semarang, which restricts the generalizability of findings to other geographical contexts with different socio-ecological conditions. Future studies should adopt longitudinal and cross-city comparative designs to assess GI resilience under varying climatic and socio-political pressures. Expanding the analysis to include economic valuation and policy modeling could strengthen evidence-based decision-making for sustainable urban design. Integrating environmental education and digital technology in community engagement would also deepen understanding of how public learning processes contribute to sustaining green infrastructure effectiveness in the long term.

AUTHORS' CONTRIBUTION

Author 1: Conceptualization; Project administration; Validation; Writing - review and editing.
Author 2: Conceptualization; Data curation; In-vestigation.
Author 3: Data curation; Investigation.

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