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Nature-Based Flood Buffers in Informally Developed Settlements

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Abstract

Informally developed settlements experience disproportionate flood risk because housing expansion frequently occurs ahead of formal drainage provision, land-use regulation, secure tenure arrangements, and coordinated environmental management. Conventional flood-control infrastructure remains necessary in many high-risk locations, yet exclusive dependence on engineered drainage can be financially, spatially, and institutionally difficult in dense low-income settlements. This study develops a simulation-based framework for evaluating nature-based flood buffers as decentralized components of neighborhood-scale flood-risk reduction.

The assessment considers bioswales, rain gardens, pocket wetlands, riparian buffers, and hybrid green–gray systems using five criteria: hydraulic attenuation, spatial compatibility, maintenance feasibility, social co-benefits, and tenure-related implementation feasibility. A weighted Flood Buffer Suitability Index is used to compare interventions under standardized hypothetical settlement conditions. The simulation indicates that hybrid green–gray arrangements provide the highest overall suitability score of 77.4, followed by rain gardens at 70.2, riparian buffers at 69.2, pocket wetlands at 68.4, and bioswales at 67.3. Simulated peak-runoff reductions range from 18% for bioswales to 46% for hybrid systems.

The findings suggest that nature-based buffers should not be viewed as substitutes for essential drainage infrastructure. Their strongest contribution lies in forming distributed retention, infiltration, conveyance, and ecological-buffer networks that reduce pressure on conventional drainage while providing environmental and social benefits. Successful implementation depends on co-design with residents, protection against displacement, maintenance arrangements, waste-management integration, and adaptation to local land-tenure conditions. The study provides a transferable planning framework for evaluating flood-buffer portfolios before site-specific hydraulic modeling and field implementation.

Keywords: nature-based solutions, informal settlements, urban flooding, flood buffers, green infrastructure, climate adaptation, urban resilience, stormwater management

1. Introduction

Rapid urban expansion has produced extensive residential areas in which physical development precedes formal planning, drainage installation, land-tenure regularization, and reliable municipal service provision. These informally developed settlements are often concentrated on environmentally vulnerable land, including floodplains, river margins, wetlands, steep drainage corridors, and low-lying urban spaces that remain unattractive or inaccessible to formal property markets. Flood risk in such neighborhoods is therefore not simply a hydrological phenomenon. It is produced through the interaction of intense rainfall, impermeable surfaces, constrained drainage channels, inadequate solid-waste management, insecure housing, limited public investment, and socioeconomic vulnerability. Douglas and colleagues demonstrated that urban flooding affecting low-income communities is intensified by floodplain occupation, hard surfaces, inadequate waste management, and obstructed drainage, illustrating how environmental exposure and social inequality become mutually reinforcing.

Traditional urban flood management has commonly emphasized pipes, culverts, embankments, channels, pumping systems, detention structures, and other engineered defenses. These measures remain indispensable where flood depths, velocities, or critical infrastructure exposure create serious life-safety risks. Nevertheless, dense informally developed settlements present difficult conditions for large infrastructure projects. Rights-of-way may be unavailable, roads may be narrow, property boundaries may be uncertain, and the displacement required for major drainage widening can impose substantial social costs. In addition, increasing runoff created by urban surface sealing can exceed the capacity of downstream drainage even after localized engineering improvements. A more distributed approach is therefore required in which stormwater is slowed, stored, infiltrated, filtered, and safely conveyed through multiple small interventions located across the settlement and its surrounding catchment.

Nature-based solutions provide one framework for developing such distributed interventions. The concept encompasses actions that protect, restore, manage, or emulate ecological processes while addressing societal challenges and generating benefits for human well-being and ecosystems. Cohen-Shacham and colleagues established nature-based solutions as an umbrella framework linking ecosystem services with practical societal challenges, while later work emphasized landscape-scale thinking, integration with other forms of infrastructure, stakeholder participation, and adaptive governance. In urban flood management, relevant interventions can include vegetated swales, infiltration gardens, restored stream margins, constructed or rehabilitated wetlands, permeable surfaces, retention landscapes, and combinations of vegetation with conventional drainage infrastructure.

Evidence from urban flood-management research indicates that such interventions can reduce runoff and provide ecological, environmental, and social co-benefits. Huang and colleagues found that nature-based measures can be effective for managing relatively frequent pluvial flooding while noting that their performance can be constrained during extreme short-duration rainfall. Their synthesis consequently supports combining nature-based measures with conventional infrastructure rather than treating the two approaches as mutually exclusive. This insight is particularly important in informal settlements, where a purely ecological intervention may be insufficient for severe flooding, but exclusively engineered drainage may be unaffordable, disruptive, or poorly maintained.

The present study therefore investigates how nature-based flood buffers can be evaluated specifically for informally developed settlements. Rather than claiming observations from an implemented project, it constructs a transparent simulation-based decision framework using standardized hypothetical conditions. The central proposition is that effective flood adaptation in informal settlements depends not only on hydraulic efficiency but also on spatial fit, maintenance feasibility, social usefulness, and implementation under uncertain tenure conditions. By integrating these dimensions, the study contributes a neighborhood-scale approach for selecting combinations of green and gray infrastructure that are technically credible, socially appropriate, and adaptable to highly constrained urban environments.

2. Objectives of the Study

2.1 Evaluation of Flood-Buffer Performance

The first objective is to evaluate the relative suitability of different nature-based flood-buffer interventions for dense informally developed settlements. The study compares bioswales, rain gardens, pocket wetlands, riparian buffers, and hybrid green–gray systems. Instead of evaluating interventions solely through stormwater retention, the analysis considers multiple dimensions that influence real-world viability.

Particular attention is given to hydraulic attenuation and spatial compatibility because informal settlements frequently contain little unoccupied land. An intervention capable of retaining considerable stormwater may still be unsuitable when it requires extensive relocation or blocks essential access routes. The study consequently treats flood-buffer performance as a multidimensional planning problem rather than a single engineering optimization problem.

2.2 Development of an Equitable Implementation Framework

The second objective is to establish planning principles through which nature-based flood buffers can be implemented without transferring environmental benefits into social disadvantages. Green infrastructure can improve drainage and neighborhood environmental quality, but poorly designed upgrading can also create land-value pressures, relocation risks, maintenance disputes, or unequal distribution of benefits.

The study therefore evaluates maintenance feasibility, social co-benefits, and tenure-related feasibility alongside hydraulic criteria. This approach seeks to identify interventions that can be incorporated progressively into settlement upgrading while retaining community access, minimizing displacement, and establishing realistic responsibility for long-term maintenance.

3. Review of Literature

3.1 Nature-Based Solutions and Urban Flood Management

Nature-based solutions have evolved from earlier traditions of ecosystem-based adaptation, ecological restoration, sustainable drainage, green infrastructure, and ecosystem-based disaster-risk reduction. Cohen-Shacham and colleagues provided an influential conceptual framework that positioned nature-based solutions as actions addressing societal problems while sustaining ecosystem functions and human well-being. Kabisch and colleagues subsequently emphasized the relationship between science, policy, and urban climate adaptation, illustrating that nature-based interventions need to be incorporated into broader systems of urban governance rather than implemented as isolated landscape projects.

Urban stormwater applications are particularly relevant because vegetation, soil, wetlands, and restored hydrological pathways can influence runoff generation and movement. Bioswales slow shallow surface flow and promote infiltration. Rain gardens temporarily retain runoff from roofs, paths, and small paved areas. Pocket wetlands provide additional storage while supporting water-quality improvement. Riparian vegetation stabilizes channels and creates space for controlled flood conveyance. These measures differ substantially in their required area, cost, maintenance, storage capacity, and sensitivity to local soils.

Huang and colleagues reviewed nature-based approaches for urban pluvial flooding and concluded that they can effectively manage many frequent precipitation events while producing additional environmental, economic, and social benefits. However, the authors also cautioned that extreme precipitation may exceed the capacity of individual green interventions. Such evidence supports a treatment-train approach in which runoff passes through multiple retention and conveyance elements before reaching conventional drains or receiving waters.

Raymond and colleagues further demonstrated that urban nature-based solutions generate benefits beyond their primary engineering function. Their framework identifies interactions among climate resilience, health, environmental quality, biodiversity, economic conditions, and social well-being. For informal settlements, these co-benefits can be especially significant because a flood-retention space may simultaneously serve as public open space, reduce localized standing water, improve shade, stabilize soil, and strengthen environmental quality.

3.2 Flood Vulnerability in Informally Developed Settlements

Flood exposure within informal settlements is shaped by both physical geography and uneven urban development. Douglas and colleagues documented how low-income urban populations can experience repeated flooding because they occupy vulnerable sites and simultaneously lack adequate drainage, waste services, resilient housing, and institutional protection. Flooding may therefore occur even during relatively common rainfall events when drains are undersized, channels are obstructed, or runoff is concentrated by surrounding development.

The spatial structure of informal neighborhoods introduces further complexity. Dwellings may be separated by paths too narrow for conventional drainage machinery. Water may travel through improvised alleys, household plots, road depressions, or open wastewater channels. A technically desirable drainage alignment can cross structures occupied by households lacking secure tenure. Infrastructure decisions therefore become inseparable from questions of housing security, access, compensation, relocation, and governance.

Douglas's later synthesis of flooding in African cities similarly emphasizes that flood risk emerges across interacting spatial scales, from local drainage obstruction to major river flows and wider catchment processes. A neighborhood intervention can reduce local ponding while remaining ineffective when upstream development sends larger runoff volumes into the settlement. Effective nature-based buffering consequently requires catchment awareness. Small-scale infiltration measures should be connected to safe conveyance pathways, downstream storage, and wider watershed management.

The literature therefore suggests that vulnerability reduction requires more than increasing drainage capacity. Communities need systems capable of responding to frequent rainfall while retaining safe exceedance pathways for exceptional events. This distinction is important because designing every small nature-based intervention for the most extreme possible storm would be spatially and

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economically unrealistic. Instead, distributed buffers can manage routine runoff and delay flood peaks while engineered routes safely convey flows exceeding their retention capacity.

3.3 Governance, Co-Benefits, and Scaling

Nature-based solutions are strongly dependent on governance quality. Cohen-Shacham and colleagues identified integration with broader policies, landscape-scale design, and combination with other interventions as essential principles for successful implementation and scaling. These principles challenge approaches in which a municipality installs a demonstration rain garden or landscaped drain without establishing maintenance responsibilities, hydrological connectivity, community ownership, or long-term monitoring.

For informally developed settlements, governance extends beyond municipal engineering departments. Residents, community organizations, water authorities, land agencies, waste-management services, disaster-management institutions, and civil-society organizations may all influence the performance of flood buffers. A vegetated drainage corridor cannot function when waste collection failures convert it into a dumping location. Similarly, a restored stream setback cannot be maintained where households face displacement without credible alternatives.

The practical implication is that ecological performance and social legitimacy must be treated as mutually dependent. A technically effective intervention that residents cannot maintain may deteriorate rapidly, while a socially popular landscape improvement that lacks sufficient drainage connectivity may provide little flood protection. The research gap lies in developing selection frameworks that combine engineering, spatial, institutional, and social dimensions specifically for constrained informal-settlement conditions. The present simulation framework addresses this gap.

4. Research Methodology

4.1 Research Design and Analytical Boundary

The study adopts a simulation-based multicriteria assessment rather than an empirical field experiment. No household survey, intervention trial, or observed hydrological dataset is represented as having been collected. The simulated settlement is conceptualized as a dense low-income urban neighborhood characterized by narrow circulation routes, limited open space, irregular plot boundaries, partial drainage coverage, recurring pluvial flooding, localized waste accumulation, and uncertain land tenure.

Five intervention classes were selected because they represent different combinations of infiltration, retention, vegetated conveyance, floodplain buffering, and conventional drainage support. These are bioswales, rain gardens, pocket wetlands, riparian buffers, and hybrid green–gray systems. Each intervention is evaluated using a standardized 0–100 score on five decision criteria.

4.2 Multicriteria Evaluation Framework

A Flood Buffer Suitability Index was developed to integrate technical and implementation dimensions. Hydraulic attenuation receives the highest weight because the primary purpose of each intervention is flood-risk reduction. Spatial compatibility and maintenance feasibility receive substantial weights because space scarcity and maintenance failure are major constraints in informal neighborhoods. Social co-benefits and tenure feasibility are also incorporated so that highly disruptive interventions are not ranked favorably merely because of theoretical hydraulic performance.

Table 1: Flood Buffer Suitability Index criteria and simulation weights

Criterion	Operational interpretation	Weight
Hydraulic attenuation	Capacity to slow, store, infiltrate, or safely redirect runoff	0.35
Spatial compatibility	Ability to fit within dense and irregular settlement layouts	0.20
Maintenance feasibility	Practicality of routine cleaning, vegetation care, and sediment removal	0.20
Social co-benefits	Potential contributions to environmental quality, public space, comfort, and neighborhood amenity	0.15
Tenure feasibility	Likelihood of implementation without extensive land acquisition or involuntary displacement	0.10

The weighting system is intentionally transparent rather than presented as universally optimal. A municipality applying the framework could modify the weights through stakeholder deliberation, hydrological modeling, expert judgment, or an analytic hierarchy process.

4.3 Simulation Procedure and Research Integrity

Standardized hypothetical scores were assigned to each intervention according to its expected functional characteristics. Narrow linear interventions such as bioswales received comparatively strong spatial and maintenance scores but more moderate hydraulic capacity. Riparian buffers received high hydraulic and social-benefit scores but lower spatial and tenure feasibility because continuous stream corridors can intersect occupied land. Hybrid systems combine decentralized green storage with engineered overflow drainage and therefore received the strongest simulated hydraulic score.

Peak-runoff reduction percentages used in the graph are also hypothetical scenario values designed to illustrate comparative behavior under equivalent assumed storm conditions. They are not measurements from a real settlement. The simulation assumes that interventions are appropriately sized, connected to drainage pathways, and maintained sufficiently to retain their intended function.

Because the study uses no human participants, personal records, identifiable information, or collected field data, human-subject ethical approval is not applicable to the simulation. Future empirical validation should obtain appropriate institutional approval and informed consent whenever household-level data, interviews, participatory mapping, or personally identifiable information are collected.

5. Analysis

5.1 Comparative Suitability of Flood-Buffer Options

The simulation indicates that no single nature-based intervention dominates every evaluation criterion. Bioswales perform strongly where narrow roadside or pathway corridors are available. Their principal advantage is spatial adaptability: shallow vegetated channels can often be introduced incrementally along existing movement routes or drainage alignments. Their limitation is storage volume. In dense settlements, available width and soil infiltration capacity may restrict the amount of stormwater that a bioswale can safely manage.

Rain gardens obtain a slightly higher overall suitability score because small distributed units can receive runoff from roofs, courtyards, footpaths, schools, community buildings, and other localized surfaces. Their modular character is particularly important in settlements where continuous land parcels are unavailable. Pocket wetlands and riparian buffers provide greater hydraulic and ecological capacity but become progressively more difficult to implement as required land area increases.

Table 2: Simulated multicriteria performance of flood-buffer alternatives

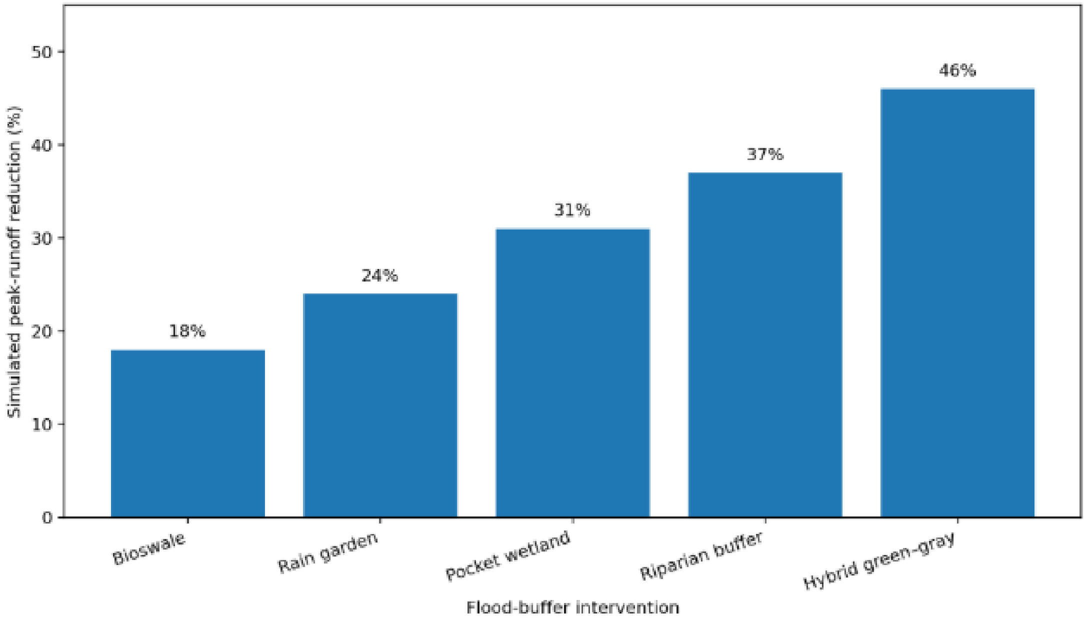
Intervention	Hydraulic attenuation	Spatial compatibility	Maintenance feasibility	Social co-benefits	Tenure feasibility	FBSI
Bioswale	55	82	76	60	74	67.3
Rain garden	65	78	72	68	72	70.2
Pocket wetland	78	55	62	78	60	68.4
Riparian buffer	85	46	68	83	42	69.2
Hybrid green–gray system	92	65	70	80	62	77.4

The hybrid green–gray system obtains the highest FBSI because it combines distributed ecological storage with reliable engineered overflow. This result supports the wider literature suggesting that nature-based systems can complement rather than completely replace conventional flood infrastructure. Huang and colleagues similarly emphasize the value of combining green measures and gray infrastructure, particularly where extreme rainfall can exceed the capacity of individual nature-based interventions.

5.2 Simulated Peak-Runoff Attenuation

The runoff simulation shows increasing attenuation as interventions move from small decentralized elements toward more integrated storage and conveyance systems. Bioswales produce an illustrative 18% reduction in peak runoff, rain gardens 24%, pocket wetlands 31%, riparian buffers 37%, and hybrid green–gray systems 46%.

Graph 1: Comparative Flood-Attenuation Performance of Nature-Based Buffer Options



The graph should be interpreted comparatively rather than as a prediction for a particular settlement. Actual attenuation would depend on rainfall intensity and duration, antecedent soil moisture, infiltration rate, storage depth, connected impervious area, vegetation condition, sediment accumulation, blockage, groundwater level, and outlet design.

The increasing performance of larger or combined interventions also reveals an important planning tension. The hydraulically strongest ecological buffer is not necessarily the easiest intervention to install. Riparian corridors and wetlands require relatively large continuous areas, whereas bioswales and rain gardens can be distributed through smaller fragments. Settlement-level adaptation therefore benefits from a portfolio rather than reliance on a single intervention type.

5.3 Spatial Sequencing and Buffer Networks

A practical nature-based strategy can be understood as a sequence of hydrological functions distributed across the neighborhood. Roof runoff may first enter household- or block-scale rain gardens. Excess water may then reach vegetated roadside swales. Lower areas can incorporate pocket retention spaces or wetlands, while restored stream margins provide downstream flood conveyance and temporary storage. Conventional drains or culverts remain available as safe overflow pathways when the storage capacity of the green network is exceeded.

This treatment-train configuration is preferable to isolated interventions because the effectiveness of each component is reinforced by upstream and downstream elements. A rain garden that overflows directly into a blocked alley may simply relocate flooding. Conversely, a chain of retention, conveyance, and controlled overflow reduces the probability that localized measures become disconnected landscape features.The simulation therefore supports the concept of a distributed flood-buffer network rather than a collection of independent greening projects. Such a network can be implemented incrementally as streets are improved, public spaces are upgraded, drainage is repaired, or river corridors are restored.

6. Discussion

6.1 Why Hybrid Systems Perform Strongly in Informal Settlements

The strong simulated performance of hybrid green–gray infrastructure reflects the physical realities of dense settlements. Nature-based measures are most effective when runoff can be intercepted before it becomes a fast and concentrated flood flow. Once rainfall accumulates across a large impermeable catchment or enters a confined channel, engineered conveyance and structural protection may become necessary.

Nature-based buffers can nevertheless reduce the burden placed on these structures. By delaying runoff and retaining a portion of rainfall near its source, decentralized green infrastructure can lower the volume and peak rate entering downstream drains. This does not eliminate the need for culverts, channels, or emergency overflow routes. It changes their role from being the only line of defense to becoming one component of a diversified flood-management system.

This interpretation is consistent with the wider evidence base. Huang and colleagues identify significant advantages of nature-based approaches while recognizing limits under extreme pluvial conditions. Cohen-Shacham and colleagues likewise emphasize that nature-based solutions can be implemented in combination with other measures and should be understood within wider landscape and policy systems.

6.2 Community Governance, Maintenance, and Environmental Justice

Maintenance is one of the most consequential variables in informal-settlement flood adaptation. Vegetated infrastructure can lose storage or conveyance capacity when sediment, litter, construction debris, or invasive vegetation obstructs its flow path. This problem cannot be addressed through design alone. Flood-buffer projects need clearly assigned maintenance responsibilities, practical access for cleaning, reliable waste collection, and financing for replacement or rehabilitation.

Community participation should therefore begin during site identification rather than after engineering decisions have been completed. Residents possess detailed knowledge of recurring ponding areas, informal drainage paths, blocked culverts, seasonal flow routes, safe walking corridors, and household-level flood impacts. Integrating this knowledge can improve siting while reducing conflict over land and maintenance.

At the same time, participation should not become a mechanism through which municipalities transfer infrastructure responsibility to households without adequate support. Flood management remains a public planning obligation. Community stewardship can strengthen maintenance and monitoring, but it should operate alongside municipal drainage, waste-management, emergency-response, and environmental services.

Environmental justice requires particular attention to tenure. Flood-control upgrading can unintentionally legitimize displacement where authorities interpret ecological restoration as requiring removal of low-income households from desirable urban land. Riparian restoration may sometimes require relocation for life-safety reasons, but such decisions should be based on transparent risk assessment, meaningful consultation, adequate compensation, and access to secure alternative housing rather than on generalized assumptions about informality.

6.3 Scaling from Individual Buffers to Settlement Resilience

The analysis demonstrates that the value of nature-based flood buffers increases when interventions are connected spatially and institutionally. A settlement containing several rain gardens but no functioning downstream outlet remains vulnerable. Similarly, a restored river corridor can still experience severe inflows when upstream neighborhoods continue generating uncontrolled runoff. Scaling therefore requires movement from project-level thinking toward catchment-level planning.

Raymond and colleagues argue that nature-based solutions should be evaluated through multiple co-benefits and through implementation processes that include stakeholder engagement, monitoring, and transferability. This broader perspective is particularly relevant to informal settlements because flood infrastructure is closely linked to public health, mobility, sanitation, housing quality, environmental restoration, and neighborhood governance.

A scalable program could therefore integrate flood buffers into routine settlement upgrading rather than establishing a separate category of environmental projects. Street rehabilitation can include bioswales. School improvements can incorporate rain gardens and temporary retention areas. River rehabilitation can establish vegetated setbacks. Public-space projects can create multifunctional detention landscapes. Drainage investments can include vegetated pretreatment and upstream retention.

Long-term monitoring is equally important. Nature-based infrastructure changes over time as vegetation matures, sediments accumulate, land uses shift, and residents modify surrounding spaces. Adaptive management is therefore more appropriate than a fixed design-and-completion model. Performance indicators should include not only flood depth and runoff reduction but also maintenance condition, accessibility, community use, ecological quality, and distribution of benefits.

7. Conclusion

This study examined nature-based flood buffers as components of flood-risk management for informally developed settlements through a transparent simulation-based multicriteria framework. The results show that intervention suitability depends on considerably more than theoretical stormwater capacity. Spatial constraints, maintenance requirements, social benefits, and tenure conditions can determine whether a technically promising flood buffer remains functional after implementation. Among the simulated alternatives, the hybrid green–gray system achieved the highest overall suitability score because it combined strong runoff attenuation with the reliability of engineered overflow infrastructure.

The findings do not support replacing conventional drainage with vegetation alone. Instead, they support a layered approach in which bioswales, rain gardens, pocket wetlands, riparian restoration, and similar interventions reduce and delay runoff before excess flows enter appropriately designed conventional drainage pathways. Such distributed buffering can improve the efficiency of existing infrastructure while producing additional ecological and neighborhood benefits. The most suitable configuration will vary according to settlement density, rainfall characteristics, soil conditions, existing drainage, land availability, and community priorities.

The study also demonstrates that social safeguards are integral to flood-buffer effectiveness. Projects that require substantial displacement, lack maintenance arrangements, or ignore waste-management failures may perform poorly regardless of their theoretical hydraulic capacity. Participatory planning should therefore be combined with public institutional responsibility, secure maintenance financing, transparent risk assessment, and protection against inequitable relocation. Nature-based flood adaptation becomes most credible when residents are treated not merely as beneficiaries but as participants in the interpretation of local flood pathways and long-term environmental management.

Because the numerical results are simulated, they should be validated before application to any specific settlement. Future research should combine high-resolution topography, rainfall-runoff modeling, soil infiltration measurements, drainage surveys, participatory flood mapping, household vulnerability assessment, and monitored pilot interventions. Comparative field studies would allow the Flood Buffer Suitability Index to be calibrated across different climatic and governance settings. Even with these limitations, the framework provides a practical basis for moving beyond the false choice between green and gray infrastructure and toward integrated, equitable, and locally adaptable flood-resilience systems.

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