

Green Infrastructure as a Nature-Based Solution for Urban Flood Risk Reduction in Abuja, Nigeria

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Abstract

Urbanisation has altered the hydrological functioning of Abuja, increasing the importance of approaches that can moderate stormwater generation alongside conventional drainage infrastructure. This study quantitatively evaluated the potential of green infrastructure as a nature-based solution for urban flood risk reduction in Abuja, Nigeria. The analytical domain of 247.8 km² was modelled under baseline, continued urbanisation, low, moderate and high green infrastructure scenarios corresponding to the built-up area reported for Abuja in 2020. Runoff volume and peak discharge calculations were carried out using simplified runoff method and rational method formulations for various degrees of green infrastructure cover (0%, 10%, 25% and 40%) for the appropriate intervention scenarios and varying rainfall depths (50 - 200 mm) by the weather generator. For a rainfall of 100 mm, the runoff for continued urbanisation was 16.850 million m³, which was 9.68% more than the runoff of 15.364 million m³ for the baseline. The reduction in the low, moderate and high green infrastructure scenarios was 3.23%, 16.13% and 29.03%, respectively. The results suggest that the more

green infrastructure is present, the more runoff and peak discharge may be moderated, but the numerical results are estimates for the scenarios. The study calls for strategic incorporation of green infrastructure into the land use planning, drainage management and flood resilience framework of Abuja and preservation of conventional infrastructure and preparedness measures. It also suggests the use of calibrated spatial hydrological and hydraulic modelling to derive and set intervention levels which are defensible in an empirical manner.

Keywords: Green infrastructure; Nature based solutions; Urban flooding; Runoff; Abuja; Flood risk reduction; Scenario modelling

Introduction

The rapid growth of urban areas has turned urban flooding into a major component of urban risks, as the alteration of the natural and semi-natural environment to the built-up environment has significantly modified how rainfall gets absorbed, stored and transported. Rapid surface runoff increases and infiltration decreases, as permeable surfaces are replaced by buildings, roads and paved surfaces through urban expansion. The resulting impact on drainage systems can be significant, especially when urbanisation has been occurring at a faster rate than infrastructure improvements or a change in the drainage system has been disrupted by development. Green infrastructure has thus become a nature-based solution that can be used to complement traditional flood management, providing the restoration of some selected hydrological functions in increasingly man-made urban environments (Green et al., 2021; Aghimien et al., 2024). This transition is especially pertinent in the context of the fast-growing African urbanisation process. The concept of NbS is gaining traction as a way to deliver hydrological, ecological and environmental benefits. However, their impact is not necessarily equated with flood resilience as a result of vegetation or permeable surfaces. Rainfall characteristics, soil properties, spatial configuration, land availability, maintenance, urban density and institutional capacity are all factors that influence the performance of green infrastructure. This means that the key policy question is not whether there is a benefit to green infrastructure, but rather how and on what scale it can actually change the dynamics of urban runoff. In particular, the case of Abuja is important, as it has experienced rapid spatial growth in line with significant land cover change. According to Odiji et al. (2026), built-up land in the Federal Capital City has grown from 56.9 km² in 1990 to 247.8 km² in 2020, while forest cover has decreased from 130.8 km² in 1990 to 17.7 km² in 2020. In the

same period, estimated runoff volume rose from $52.93 \times 10^6 \text{ m}^3$ to $61.34 \times 10^6 \text{ m}^3$, with 59 districts out of 134 districts identified as high or very high risk for runoff accumulation.

Figure 1 displays the spatial risk map of Abuja, which is the flood-risk context for the town. These are important findings because they provide an empirical relationship between hydrological pressure and the changing urban morphology and not just flooding as a result of extreme rainfall events. Physical exposure, such as through increased runoff, is compounded by social and infrastructural vulnerabilities. Studies conducted in Abuja have revealed significant flood risk in households and adaptation strategies employed, while disaster studies in communities in the Federal Capital Territory have reported on the socioeconomic impacts of flooding (Akande et al., 2023; Badamosi et al., 2024). In addition, Madu (2023) also revealed the importance of flooding in the Bwari Area Council. From the above, evidence was observed that flood risk in Abuja is a product of hazard, exposure and vulnerability. Effective response, therefore, should not only be geared towards emergency response but also take action to change the way runoff is generated and to minimise stormwater in sensitive urban areas. One potential part to such a response is green infrastructure. Green roofs, vegetative drainage system, rain garden, infiltration space and other measures can capture rainfall, provide more temporary storage, allow infiltration and slow down runoff to the drainage system (Basu et al., 2021; Esraz Ul Zannat et al., 2024).

The conceptual advantage of it is the decentralisation of the stormwater management. Green infrastructure aims to intervene at many points in the urban water cycle, rather than to let rainfall quickly collect and be conveyed through a progressively overtaxed drainage system. However, the literature also warns that NbS should not be seen as an all-encompassing solution to replacing grey infrastructure. The importance of realistic spatially distributed scenarios when assessing NbS was demonstrated by Chen et al. (2021), with Neumann et al. (2024) proving that reasonable spatially distributed interventions can be used to reduce pluvial flood pressures when properly integrated in hydrological/hydraulic models. The impact of the intervention is thus essentially spatial and context-dependent. Green infrastructure may be required to have a nominal percentage of coverage, but this does not indicate how much runoff will be reduced, unless it is placed where there is potential to affect runoff pathways and drainage pressure. This poses a significant analytical gap for Abuja. There is ample evidence for existing urban expansion and the potential for increased runoff, and adequate literature for the theoretical and practical potential of green infrastructure. What is less clearly expressed is how different degrees of green infrastructure implementation may impact on runoff, given varying controlled urbanisation and rainfall conditions. Scenario modelling can be a valuable approach to fill this void, as they can be compared without misleadingly claiming hypothetical results as measurements.

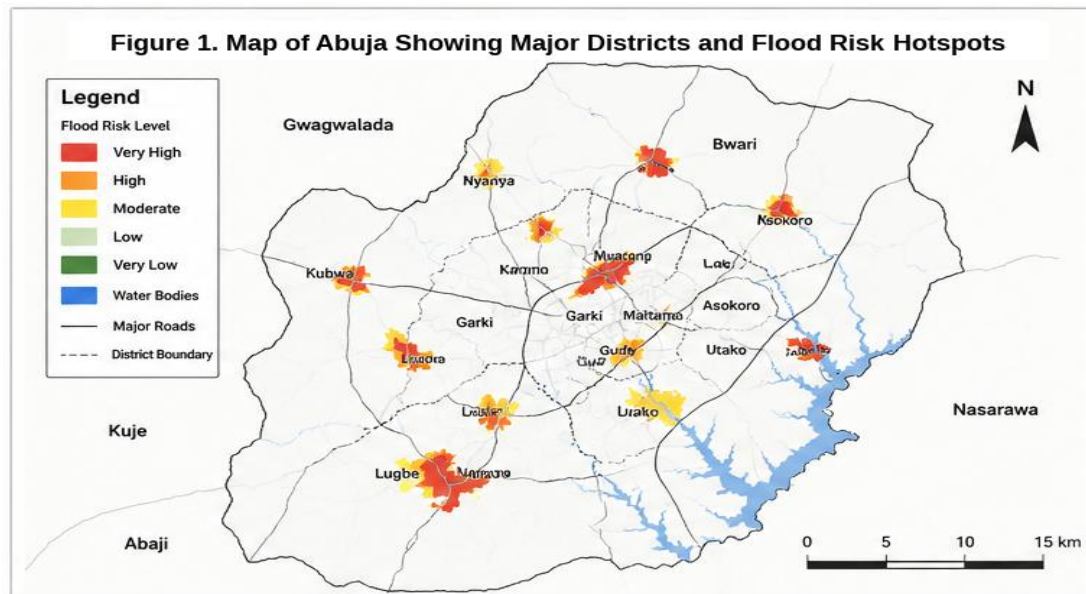


Figure 1: Abuja Flood-Risk Context / Spatial Risk Map

These findings are significant because they establish an empirical relationship between changing urban morphology and hydrological pressure rather than treating flooding simply as a consequence of extreme rainfall.

The physical exposure represented by increased runoff is compounded by social and infrastructural vulnerability. Research in Abuja has identified substantial residential flood vulnerability and a range of adaptation practices, while studies of communities within the Federal Capital Territory have documented socioeconomic consequences associated with flooding (Akande et al., 2023; Badamosi et al., 2024). Madu (2023) further demonstrated the significance of flooding within the Bwari Area Council. Such evidence suggests that flood risk in Abuja is produced through the interaction of hazard, exposure and vulnerability. An effective response must therefore extend beyond emergency response towards measures that modify runoff generation and reduce the concentration of stormwater within vulnerable urban environments.

Green infrastructure provides one possible component of such a response. Green roofs, vegetated drainage systems, rain gardens, infiltration spaces and related interventions can intercept rainfall, increase temporary storage, facilitate infiltration and delay runoff reaching drainage networks (Basu et al., 2021; Esraz Ul Zannat et al., 2024). Its conceptual advantage lies in decentralising stormwater management. Rather than allowing rainfall to accumulate rapidly before transferring it through an increasingly burdened drainage

network, green infrastructure seeks to intervene at multiple points within the urban water cycle.

Yet the literature also cautions against presenting nature-based solutions as universally sufficient substitutes for grey infrastructure. Chen et al. (2021) demonstrated the importance of realistic spatially distributed scenarios when assessing nature based solutions, while Neumann et al. (2024) showed that decentralised interventions can reduce pluvial flood pressures when appropriately incorporated into hydrological and hydraulic modelling. The effectiveness of intervention is therefore fundamentally spatial and contextual. A nominal percentage of green infrastructure coverage says little about flood reduction unless the intervention is located where it can influence runoff pathways and drainage pressure.

1.2 Statement of the Problem

Despite the growing literature on urban flooding and nature-based solutions, a specific planning problem remains unresolved in Abuja. The city has experienced a marked transformation of land cover, with built-up land increasing from 56.9 km² in 1990 to 247.8 km² in 2020, while forest cover declined from 130.8 km² to 17.7 km² over the same period (Odiji et al., 2026). Odiji et al. (2026) also reported an increase in estimated runoff volume and identified numerous districts with high or very high runoff accumulation risk. At the same time, studies of Abuja and the Federal Capital Territory have documented residential flood vulnerability, adaptation practices and socioeconomic consequences associated with flooding (Akande et al., 2023; Badamosi et al., 2024; Madu, 2023). These studies establish the seriousness of flood exposure, but they do not provide a transparent comparison of how alternative levels of green infrastructure adoption may alter runoff and peak discharge under controlled urbanisation and rainfall conditions in Abuja. Consequently, planners lack a clearly stated scenario based basis for comparing continued urbanisation with low, moderate and high green infrastructure interventions. The problem is therefore not simply whether green infrastructure can contribute to flood management, but how different assumed levels of implementation change hydrological outcomes when the assumptions and data sources are made explicit. Without such a comparison, there is a risk that green infrastructure targets may be promoted as general environmental aspirations without a defensible quantitative indication of their relative hydrological implications. This study addresses that problem through an exploratory scenario modelling framework that distinguishes empirical secondary evidence from model assumptions and derived outputs.

1.3 Significance of the Study

The study is significant in scientific, methodological and planning terms. Scientifically, it translates the broad proposition that green infrastructure can moderate urban runoff into a transparent comparison of alternative intervention scenarios for Abuja. This is important because the effectiveness of nature-based solutions is strongly dependent on context, spatial configuration and hydrological conditions rather than on nominal coverage alone (Chen et al., 2021; Neumann et al., 2024). Methodologically, the study makes a clear distinction between empirical secondary information, modelling assumptions and model-generated results. The analytical area is anchored in the reported 2020 built-up extent of Abuja from Odiji et al. (2026), while the rainfall inputs and runoff coefficients are treated explicitly as scenario parameters rather than observed local measurements. This transparency improves the reproducibility and interpretability of the tables and prevents hypothetical values from being presented as primary field data. For urban planning, the findings provide a comparative indication of how continued impervious development and increasing levels of green infrastructure may influence runoff volume and peak discharge. The results can therefore support discussion of land use controls, permeable surfaces, vegetated drainage systems, retention spaces and other distributed stormwater measures within Abuja's wider flood resilience strategy. The study does not replace calibrated hydrological or hydraulic analysis, but it provides a structured evidence base for identifying priorities that can subsequently be tested with observed rainfall, soil, drainage and discharge data. In this way, it contributes to more defensible integration of green infrastructure with conventional drainage, preparedness and institutional flood risk management.

1.3 Aim and Objectives of the Study

Accordingly, this study quantitatively assesses the potential effect of alternative urbanisation and green infrastructure scenarios on surface runoff in Abuja and evaluates their implications for integrated urban flood risk management. Specifically, the study seeks to (1) assess the effect of alternative levels of green infrastructure coverage on surface runoff under varying rainfall scenarios and (2) compare the runoff and peak-discharge responses associated with continued urbanisation and different levels of green infrastructure adoption, with a view to deriving implications for integrated urban flood-risk reduction. The analysis is deliberately exploratory. Its purpose is not to claim that a particular percentage of green infrastructure will produce a predetermined reduction in actual Abuja flooding but to examine the relative hydrological consequences of alternative planning assumptions and thereby strengthen the evidence base for future calibrated modelling and policy design.

2. Literature Review / Theoretical Framework

2.1 Urbanisation, Land Use Change and Flood Risk in Abuja

Urbanisation is not 'hydrologically neutral'. Increasing built surfaces lead to an increase in rainfall that would have previously percolated or temporarily been held in vegetated soils, becoming surface runoff. This is particularly critical given the land cover evidence provided by Odiji et al. (2026) that shows significant growth in built-up surfaces with a significant drop in forest cover happening in Abuja. Their estimated increase in runoff is an empirical measure of the effects of urban development on how the city processes water.

The importance of this change is not just about the total amount of run-off. Concentrated runoff can overload drainage channels, cause faster drainage to low areas, and cause the risk of exceeding drainage capacity during heavy rain. The flood vulnerability studies in Abuja therefore show that both physical and social aspects of flood risk exist (Akande et al., 2023; Badamosi et al., 2024). The message is that flood management in the city is not simply a matter of building bigger drains once development is done. Planning for land use becomes part of flood risk management.

This is especially so in view of the ongoing changes in Abuja's planning system. The Abuja Master Plan's review shows that there is an awareness that development conditions have changed and that new planning attention is needed. The importance of integrating stormwater into land use decisions is thus growing, since decisions about land use density, open space and surface permeability also affect the hydrological conditions to be considered by the following drainage network.

2.2 Green Infrastructure as a Nature-Based Solution

The concept of 'green infrastructure' is one of changing the paradigm of stormwater management from pure conveyance to a system that tries to retain, infiltrate and control stormwater in the urban fabric. It's not just one engineering function that makes it effective. Precipitation can be captured on a green roof, infiltration can be improved on vegetated surfaces, water can be temporarily stored in retention spaces, and distributed interventions can slow the concentration of runoff (Basu et al., 2021; Green et al., 2021). There is a strong potential out of various urban settings. For instance, Ferreira and da Rocha (2023) reported that the green roof infrastructure under study outperformed the grey infrastructure examined in the study in terms of flood mitigation. But these should not mechanically be generalised to Abuja. Rainfall regime, substrate, building characteristics, maintenance and urban form differ, and hence the performance of the interventions is context dependent. The usefulness

of international evidence therefore lies, to a large extent, in its conceptual and comparative nature.

This is underscored by the African literature. Enu et al. (2023) highlight the large potential for NbS in Sub-Saharan Africa but also environmental and institutional limitations. Aghimien et al. (2024) also call for the need to strengthen NbS in the African built environment. The implementation challenge is, therefore, technical and institutional. Even the best hydrologically potential intervention would not achieve any significant city-scale benefits if misplaced or poorly maintained or not integrated into planning and drainage schemes.

2.3 Theoretical and Analytical Framework

The study adopts an integrated analytical framework combining the Nature Based Solutions Framework and an Urban Flood Risk Reduction Framework. The first explains how green infrastructure modifies rainfall interception, infiltration, detention and runoff release. The second situates these processes within the broader relationship between urbanisation, exposure, vulnerability and institutional response.

The analytical logic can therefore be represented as:



Figure 2: Analytical Framework: Urban Expansion, Runoff Pressure and Green Infrastructure

The framework is intentionally nondeterministic. Green infrastructure does not eliminate flood risk, nor does greater coverage automatically produce proportionally greater protection. Its effectiveness depends upon spatial suitability, design quality, rainfall intensity, soil characteristics, maintenance and integration with existing drainage systems. This interpretation is consistent with studies emphasising realistic scenario construction and strategic deployment of nature based solutions (Chen et al., 2021; Mabrouk et al., 2023; Wang et al., 2025).

The framework therefore provides the conceptual basis for the quantitative scenarios developed in this study. Rather than asking whether green infrastructure is simply “effective”, the analysis asks how different assumed levels of intervention alter runoff relative to alternative urban development conditions.

3. Methodology

3.1 Research Design and Analytical Domain

A quantitative scenario-based modelling design was used in the study. The analytical domain was 247.8 km², which was the built-up area reported for Abuja in 2020 by Odiji et al. (2026). Primary rainfall, soil or discharge measurements were not taken for the study. Rather, the geographical and contextual foundations for a controlled scenario experiment were empirical evidence in relation to the land use transformation in Abuja.

Four rainfall depths of 50, 100, 150 and 200 mm were modelled. The rainfall intensities were taken as 25, 50, 75 and 100 mm/h, which are corresponding to the illustrative rainfall. These rainfall inputs were simulation rainfall conditions and not presented as observed rainfall storms or assigned return periods.

3.2 Data Sources and Parameter Provenance

The study did not collect primary rainfall, soil, land cover or discharge data. The empirical secondary basis for the analytical domain was the 247.8 km² built-up area reported for Abuja in 2020 by Odiji et al. (2026), which also provided contextual evidence of land cover transformation and increasing runoff potential. The broader interpretation of green infrastructure effects was informed by peer-reviewed studies on nature-based solutions and urban flood modelling, including Chen et al. (2021) and Neumann et al. (2024). The rainfall depths of 50, 100, 150 and 200 mm, the corresponding illustrative intensities, and the runoff coefficients assigned to the five scenarios were not extracted from an observed Abuja storm record and were not presented as calibrated local measurements. They were controlled model inputs selected for comparative scenario analysis. Accordingly, Table 1 reports model assumptions, whereas Tables 2 and 3 contain values calculated directly from the stated

runoff and Rational Method equations using those assumptions. Table 4 is a summary derived from Table 3. This source classification is retained beneath each table so that secondary evidence, assumed parameters and model-generated outputs can be independently identified and verified from the methodology and cited literature.

3.3 Scenario Development

Five scenarios were developed to represent alternative urban conditions. S0 represented the baseline condition, S1 represented continued urbanisation, while S2, S3 and S4 represented low, moderate and high green infrastructure adoption respectively.

Table 1. Scenario Assumptions

Scenario	GI coverage (%)	Runoff coefficient	Interpretation	Scenario
S0 Baseline	0	0.62	Existing urban condition	S0 Baseline
S1 Continued urbanisation	0	0.68	Increased imperviousness	S1 Continued urbanisation
S2 Low GI	10	0.60	Limited GI adoption	S2 Low GI
S3 Moderate GI	25	0.52	Strategic moderate adoption	S3 Moderate GI
S4 High GI	40	0.44	Extensive GI adoption	S4 High GI

Source: Authors' scenario assumptions. The analytical context is based on Abuja land use evidence reported by Odiyi et al. (2026), while the directional scenario logic is informed by Chen et al. (2021) and Neumann et al. (2024). The runoff coefficients are assumed model parameters and are not calibrated Abuja measurements.

The runoff coefficients were modelling assumptions informed by the expected directional effect of imperviousness and green infrastructure. They were not empirically calibrated Abuja coefficients. The progressive reduction from 0.60 to 0.44 across the green infrastructure scenarios represents the assumed combined effect of interception, infiltration and storage. This approach follows the logic of scenario-based nature-based solution modelling while avoiding the methodological error of presenting hypothetical parameters as measured local values (Chen et al., 2021; Neumann et al., 2024).

3.4 Model Formulation

The following equation was used to estimate the volume of runoff:

$$Q = P \times C \times A$$

where the runoff volume, Q (m^3), is equal to the product of the rainfall depth, P (m), the runoff coefficient, C , and the analytical area, A (m^2).

The rational method was used to estimate peak discharge:

$$Q = (C \times I \times A) / 3.6$$

The variables are Q = peak discharge (m^3/s), C = runoff coefficient, I = rainfall intensity (mm/h), and A = analytical area (km^2).

The percent change from baseline was computed as:

$$\text{Reduction (\%)} = (Q_{\text{baseline}} - Q_{\text{scenario}}) / Q_{\text{baseline}} \times 100$$

The analysis was deterministic – the same scenario was applied throughout the rainfall range to see the effect of assumptions in the scenarios. The resulting numerical value should thus be interpreted as model-based estimates and not empirical observation, as the runoff coefficient was assumed for comparative scenario analysis and not calibrated to runoff measurements observed in Abuja.

Figure 3. Scenario-Based Modelling Framework for Assessing Green Infrastructure Effects on Urban Runoff in Abuja.

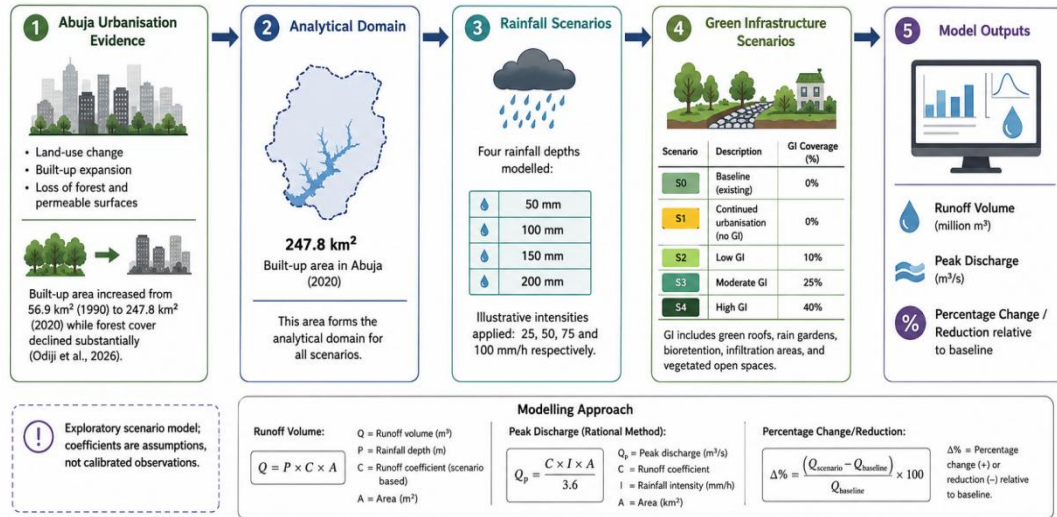


Figure 3: Scenario-Based Modelling Framework for Abuja

4. Results and Discussion

4.1 Effect of Urbanisation and Green Infrastructure on Runoff

The simulation produced a systematic differentiation between continued urbanisation and green infrastructure scenarios. As rainfall increased, runoff increased under all scenarios, but the magnitude of runoff varied according to the assumed runoff coefficient.

Table 2. Runoff Volume across Rainfall Scenarios

Million m³

Scenario	50 mm	100 mm	150 mm	200 mm
S0 Baseline	7.682	15.364	23.046	30.728
S1 Continued urbanisation	8.426	16.850	25.275	33.700
S2 Low GI	7.434	14.868	22.302	29.736
S3 Moderate GI	6.443	12.886	19.329	25.772
S4 High GI	5.452	10.903	16.355	21.806

Source: Authors' model calculations using the runoff equation $Q = P \times C \times A$, the 247.8 km² analytical area reported by Odiji et al. (2026), and the scenario parameters stated in Table 1. Values are model generated estimates, not primary field observations.

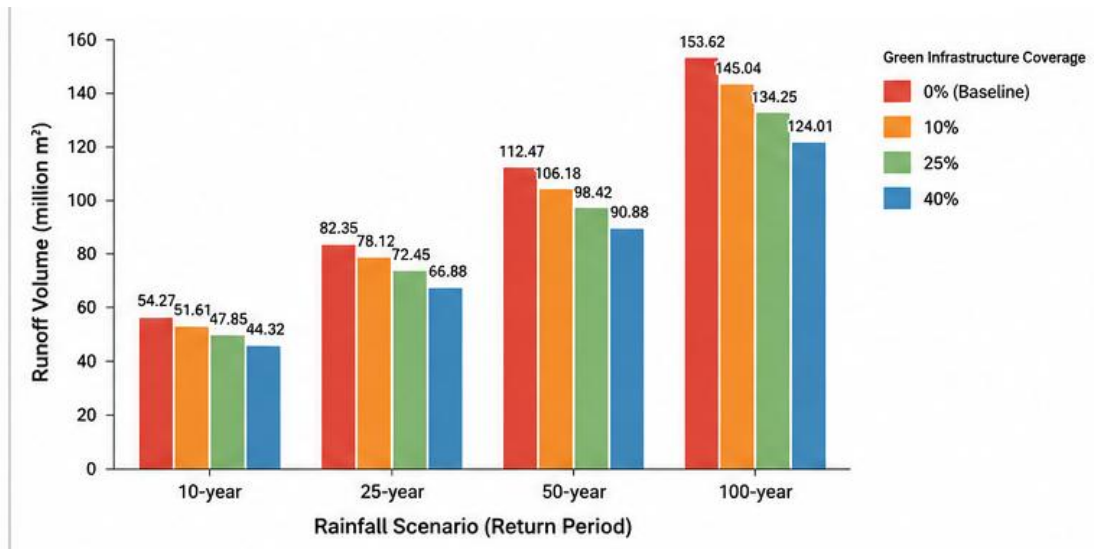


Figure 4: Runoff under Alternative Green Infrastructure Scenarios

The findings show two patterns of analysis significance. Continued urbanisation tended to always generate more runoff than the baseline. The runoff rose from 15.364 million m³ to 16.850 million m³ by 9.68% under 100 mm rainfall. The trend of change is in line with the empirical data of Abuja land cover transformation reported by Odiji et al. (2026), which shows increased runoff.

Second, runoff decreased progressively with the green infrastructure scenarios. With the same 100 mm rainfall, the runoff reduced to 14.868 million m³, 12.886 million m³ and 10.903 million m³ for low GI, moderate GI and high GI, respectively, from the rainfall of the baseline. The findings thus show that the level of intervention is significant. Spatial extent can make a significant difference in the amount of aggregate hydrological change that is by a nominal commitment to green infrastructure (when low coverage is ubiquitous), while a greater commitment to green infrastructure (when widespread) shows a much larger difference. This is in line with the literature that focuses on practical implementation as opposed to symbolic. Mabrouk et al. (2023) highlight the importance of NbS being integrated into urban planning processes, and Wang et al. (2025) point to strategic implementation based on urban conditions. The implication in Abuja is that green infrastructure should not be a superficial element to urban development. Its usefulness as a

flood mitigation tool is dependent on appropriate intervention being strategically located in both run-off-generating and run-off-concentrating areas.

4.2 Peak Discharge and Relative Scenario Performance

Table 3. Peak Discharge and Runoff Reduction under 100 mm Rainfall

Scenario	GI coverage (%)	Runoff coefficient	Runoff volume (million m ³)	Peak discharge (m ³ /s)	Reduction vs baseline
S0 Baseline	0	0.62	15.364	2,133.833	0.00%
S1 Continued urbanisation	0	0.68	16.850	2,340.333	-9.68%
S2 Low GI	10	0.60	14.868	2,065.000	3.23%
S3 Moderate GI	25	0.52	12.886	1,789.667	16.13%
S4 High GI	40	0.44	10.903	1,514.333	29.03%

Source: Authors' model calculations from the scenario parameters in Table 1 using the runoff and Rational Method formulations stated in the methodology. Values are model generated estimates for the 100 mm rainfall scenario and are not observed discharge measurements.

The results for peak discharge corroborate the runoff volume results. Continued urbanisation resulted in a peak of 2,340.333 m³/s, whereas the baseline was 2,133.833 m³/s. Moderate GI resulted in the simulation of a peak of 1,789.667 m³/s, and the high GI resulted in a peak of 1,514.333 m³/s.

The significance of this outcome is more the relative relationship between the scenarios than the actual discharge rates. The model shows that an intervention that can lower the effective runoff coefficient can have a significant impact on the volume of runoff and on the peak discharge. The moderate scenario is of particular interest, as it showed a reduction of 16.13% for 25% GI coverage, indicating that there is hydrological benefit without necessarily having to use the maximum intervention scenario.

Table 4. Summary of Green Infrastructure Effects

GI scenario	Coverage	runoff reduction	Interpretation
Low GI	10%	3.23%	Limited hydrological effect

Moderate GI	25%	16.13%	Substantial reduction
High GI	40%	29.03%	Greatest reduction

Source: Authors' summary derived from the model outputs reported in Table 3. Percent reductions are calculated relative to the baseline scenario and should be interpreted as comparative scenario results rather than empirically calibrated flood reduction rates.

There is no evidence, however, that there is a universal linear relationship between green infrastructure coverage and flood reduction in the relationship. The actual coefficients carry an implication about the efficacy of interventions. In practice, the marginal benefits may be diminishing or rising or may vary across the space in which the extra interventions are put in place. A poorly located 40% intervention could potentially perform less effectively than a strategically located smaller intervention. Therefore, the numerical results should not be interpreted as an optimisation result, but as behaviour in a scenario.

4.3 Rainfall Magnitude and the Significance of Distributed Management

From the model it can be seen that absolute runoff reduction increases with increasing magnitude of rainfall, while the percentage reduction does not change due to the simplified model using the same scenario coefficients for each rainfall depth. With the rainfall of 50 mm, high GI decreases the runoff from 7.682 million m³ to 5.452 million m³. The reduction is 21.806 million m³ at 200 mm rainfall.

This is a significant distinction. The notion that the efficiency of the green infrastructure would be continually diminished as the storms become more intense is a mathematical result of the model structure, not evidence that green infrastructure would work the same way during more intense storms. In extreme cases of rainfall when tanks are full and the infiltration rate is overcome, actual performance may diminish. Basu et al. (2021) and Esraz Ul Zannat et al. (2024) show the need to consider the performance of individual NbIs in the context of their design and hydrological properties.

The bottom line is that Abuja shouldn't only rely on green infrastructure to address the occurrence of extreme flood events. It seems its greatest role will be as a layer in a layered system of distributed retention and infiltration to manage ordinary and moderate stormwater loading, with conventional drainage and emergency systems to manage the residual risk. Ghosh et al. (2024) also advocate for a holistic strategy to mitigate urban flood risk.

4.4 Implications for Urban Planning and Flood Resilience

The results will offer a quantitative justification for stormwater management in the urban decision-making process. However, without compensation, the continued urbanisation generated the highest runoff as confirmed by the transformation of land cover in Abuja. By contrast, the runoff from green infrastructure decreased with each modelled scenario. The results have implications for three planning principles. First, flood management should be more and more prevention-orientated than reactive. Land use planning for surface permeability should be partly assessed based on hydrological effects. Secondly, green infrastructure needs to be strategically located throughout the urban system. Opportunities for interventions that affect runoff before it becomes concentrated may exist within public open space, institutional compounds, drainage corridors, redevelopment areas and appropriate transport-related spaces. Third, NBIs should be embedded in an overall institutional framework. Flood resilience in Abuja is not just the physical infrastructure but also the planning enforcement, the maintenance of drains, early warning, preparedness and coordinated institutional response. These are examples of both the continued importance of preparedness, without structural measures, through NEMA's flood preparedness work and the focus on flood mitigation and adaptation through NIHSA's work.

This is crucial in the context of the review of the Abuja planning framework. A revised planning approach allows the opportunity to shift from green infrastructure as an environmental amenity to thinking of it as part of the urban hydrological infrastructure. This would make planning decisions line up with the new consensus that resilient cities depend on a blend of grey infrastructure, green infrastructure, land use controls and institutional capacity.

5.1 Conclusion

This study examined the potential of green infrastructure as a nature-based solution for reducing urban flood risk in Abuja through quantitative scenario modelling. The analysis responds to documented evidence of substantial urban expansion and changing runoff conditions in Abuja and addresses the need to move beyond general assertions about the value of green infrastructure towards explicit comparison of alternative intervention scenarios.

The results indicate a clear directional relationship. Continued urbanisation increased runoff by 9.68% relative to the baseline under the 100 mm rainfall condition. In contrast, low, moderate and high green infrastructure scenarios produced runoff reductions of 3.23%, 16.13% and 29.03%, respectively. Peak discharge followed the same pattern, declining as the assumed green infrastructure intervention increased. The results therefore

provide quantitative scenario evidence that distributed green infrastructure has the potential to moderate runoff pressure within an expanding urban environment.

5.2 Recommendations

The study recommends that Abuja's urban planning framework incorporate green infrastructure as a component of integrated stormwater management. Development controls should encourage or require appropriate permeable and vegetated surfaces where site conditions permit, particularly in large developments and redevelopment areas. Strategic green infrastructure should also be prioritised within runoff concentration pathways, drainage corridors and suitable public and institutional spaces.

Second, green infrastructure should be implemented alongside, rather than instead of, conventional drainage infrastructure. Its purpose should be to reduce and delay runoff entering drainage systems, thereby improving the performance and resilience of the wider stormwater network. Third, planning agencies should develop spatial inventories identifying locations where nature-based interventions can produce the greatest hydrological benefit.

Finally, future Abuja flood research should progress from exploratory scenario modelling towards calibrated spatially explicit hydrological and hydraulic modelling. Such models should incorporate observed rainfall, land cover, soil characteristics, elevation, drainage networks and measured runoff. Economic assessment should also be incorporated so that the hydrological benefits of green infrastructure can be evaluated against construction, maintenance and land opportunity costs. Such an evidence base would enable Abuja to move from broad advocacy of nature-based solutions towards defensible, spatially targeted and measurable flood resilience planning.

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