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Nature-Based Solutions for Climate-Resilient Stormwater Management in Jakarta: A Comparative Modeling of Green Roof and Permeable Pavement Performance

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A B S T R A C T

Rapid urbanization and projected climate change impacts pose severe challenges to stormwater management in tropical megacities like Jakarta, Indonesia. Nature-Based Solutions (NBS) are critical for enhancing urban resilience, yet quantitative, context-specific performance data under future climate scenarios are scarce. This study provides a comprehensive, model-based comparative analysis of green roofs and permeable pavements for managing urban stormwater in Jakarta. An archetypal 1-hectare, medium-density urban catchment was developed in the Storm Water Management Model (SWMM). The model was rigorously calibrated and validated against published empirical data from analogous tropical regions (Nash-Sutcliffe Efficiency > 0.78). We evaluated the hydrological (runoff volume, peak flow) and water quality (TSS, TN) performance of green roofs and permeable pavements under partial and full implementation scenarios (25%, 50%, 75%, 100%) for current and two future climate scenarios (RCP4.5, RCP8.5 for 2050). Permeable pavements consistently demonstrated superior hydrological control, achieving up to 82% runoff volume reduction and 88% peak flow attenuation under full implementation for a 2-year baseline storm. Green roofs achieved 48% and 55%, respectively. Under an extreme 25-year storm in the RCP8.5 scenario, performance diminished but remained substantial, with permeable pavements (100% implementation) reducing runoff by 68%. Green roofs provided more consistent pollutant removal, particularly for total nitrogen (approx. 52% removal across scenarios), due to biological processes. In conclusion, both NBS technologies significantly enhance stormwater management capacity, though a clear trade-off exists between the superior hydrological control of permeable pavements and the balanced performance and co-benefits of green roofs. These findings provide a quantitative basis for integrating NBS into urban planning policy in Indonesia to foster climate-adaptive and resilient cities.

1. Introduction

The synergistic pressures of rapid, often unregulated, urbanization and the accelerating impacts of global climate change present a formidable challenge to urban water security worldwide. This challenge is particularly acute in the coastal megacities of Southeast Asia, such as Jakarta, Indonesia. The relentless expansion of impervious surfaces—roads, rooftops, and parking lots—has fundamentally altered the urban hydrological cycle. This disruption significantly reduces rainfall infiltration and evapotranspiration, leading to a dramatic increase in surface runoff volume and velocity. The consequences are severe: more frequent and devastating flash floods, degraded water quality in receiving water bodies due to the washoff of pollutants, and increased strain on aging, often inadequate, conventional "grey" drainage infrastructure[4]. The conventional approach, which prioritizes the rapid conveyance of stormwater away from urban centers via concrete channels and pipes, is increasingly recognized as unsustainable and ill-equipped to handle the projected increases in rainfall intensity and frequency associated with climate change. This has catalyzed a global paradigm shift towards more sustainable and resilient approaches, prominently featuring Nature-Based Solutions (NBS). NBS are interventions inspired and supported by nature, designed to address societal challenges while providing simultaneous environmental, social, and economic co-benefits. In the context of urban stormwater management, NBS, also known as Green Infrastructure or Low Impact Development (LID), encompasses a suite of technologies that aim to mimic pre-development hydrology by capturing, treating, infiltrating, and storing rainwater at its source.[1,2]

Among the most widely adopted and studied NBS technologies are green (vegetated) roofs and permeable pavements. Green roofs are multi-layered systems engineered to support vegetation on rooftops, which intercept rainfall, promote evapotranspiration, and delay runoff, while also offering significant co-benefits like mitigating the urban heat island effect, improving building energy efficiency, and enhancing urban biodiversity. Permeable pavements are specially designed porous surfaces that allow stormwater to pass through into an underlying aggregate storage layer, where it can be detained, infiltrated into the native subsoil, or slowly released into the drainage network, thereby drastically reducing surface runoff and filtering pollutants.[3,4]

While the efficacy of green roofs and permeable pavements is well-documented in temperate climates, a critical knowledge gap persists regarding their performance in tropical regions like Indonesia. The distinct climatic conditions—characterized by high-intensity, short-duration convective thunderstorms and pronounced wet and dry seasons—pose unique challenges and performance considerations for these systems. Furthermore, understanding the long-term resilience and effectiveness of these technologies under future climate change scenarios, which project a significant intensification of extreme rainfall events in the region, is paramount for sustainable urban planning. A direct, quantitative comparison of these two cornerstone NBS technologies is crucial for planners in Jakarta to make informed decisions about resource allocation, considering the different urban surfaces they treat (rooftops vs. ground surfaces) and their distinct suites of co-benefits.[5-7]

This study aims to address these critical gaps through a rigorous, model-based comparative assessment. The novelty of this research is threefold: (1) it provides a direct, quantitative comparison of the hydrological and water quality performance of green roofs and permeable pavements tailored to a tropical megacity context; (2) it systematically evaluates the performance of these systems under a range of implementation scenarios, from partial to full adoption; and (3) most critically, it assesses the resilience and operational effectiveness of these NBS under projected, high-intensity future climate change scenarios. The aim of this study is to quantify and compare the stormwater management performance of green roofs and permeable pavements in an Indonesian urban setting under current and future climate conditions, thereby providing a robust scientific basis for their strategic integration into urban development policies to enhance climate resilience.

2. Methods

To conduct a controlled and replicable comparative analysis, this study employed a virtual experimental approach using a hypothetical, archetypal urban catchment representative of medium-density residential areas in Jakarta. The 1-hectare (100x100 m) catchment was designed based on land-use typologies common to the city, consisting of 50% building rooftops, 30% roads and parking lots, and 20% managed green spaces (parks and lawns). This scale was selected as it represents a fundamental unit for micro-scale hydrological analysis, allowing for detailed process-based modeling of individual NBS technologies before results are considered for aggregation at larger sub-catchment scales. The catchment was assigned a uniform slope of 1%, a typical value for the flat coastal plain of Jakarta.

Table 1. NBS Engineering Design Characteristics

LAYER / COMPONENT	PARAMETER	GREEN ROOF	PERMEABLE PAVEMENT
Green Roof System Layers			
Vegetation Layer	Plant Type	Succulents, native grasses	N/A
	Height	100 mm	N/A
Growing Medium	Composition	Expanded shale, sand, compost	N/A
	Depth	150 mm	N/A
	Porosity	0.45	N/A
Filter Layer	Material	Geotextile fabric	Geotextile fabric
Drainage Layer	Material	Lightweight drainage mat	N/A
	Depth	25 mm	N/A
Permeable Pavement System Layers			
Pavement Surface	Material	N/A	Interlocking concrete pavers
	Porosity	N/A	0.20
Bedding Course	Material	N/A	Coarse sand (ASTM C33 No. 8)
	Depth	N/A	50 mm
Base & Sub-base Courses	Material	N/A	Crushed stone (ASTM D2940)
	Depth (each)	N/A	300 mm
	Porosity	N/A	0.40

The performance of the two NBS technologies was evaluated across a range of implementation coverages to assess the marginal benefits of increased adoption. A baseline "business-as-usual" scenario was established, representing the catchment with conventional impervious rooftops and asphalt pavements. Four intervention scenarios were then developed for each NBS type: 25%, 50%, 75%, and 100% implementation; (1) Green Roof (GR) Scenarios: The specified percentage of the total rooftop area (50% of the catchment) was converted to extensive green roofs. For example, in the GR-25 scenario, 25% of the rooftop area (or 12.5% of the total catchment area) was converted; (2) Permeable Pavement (PP) Scenarios: The specified percentage of the total road and parking lot area (30% of the catchment) was replaced with permeable interlocking concrete pavements. For example, in the PP-75 scenario, 75% of the paved area (or 22.5% of the total catchment area) was converted. The design specifications for the green roof and permeable pavement systems were based on established engineering design guidelines and typical material properties, as detailed in Table 1.

The study evaluated NBS performance under three climate scenarios. The baseline scenario was developed using a 20-year historical rainfall dataset

(2000-2020) from a meteorological station in Jakarta. Two future scenarios for the year 2050 were developed based on the Representative Concentration Pathways (RCPs) from the IPCC's Fifth Assessment Report: RCP4.5 (an intermediate emissions scenario) and RCP8.5 (a high emissions, "worst-case" scenario). Future rainfall time series were generated by downscaling projections from an ensemble of three General Circulation Models (GCMs) known for their robust performance in the Southeast Asia region: HadGEM2-ES, MPI-ESM-MR, and CNRM-CM5. The "delta change method" was employed for downscaling. This method is a widely accepted approach for climate impact assessments that adjusts the historical baseline series by applying the projected monthly mean changes from the GCMs, thereby preserving the observed local rainfall patterns (diurnal cycles, storm profiles) while incorporating the long-term climatic shift. From these continuous time series, synthetic design storm events with return periods of 2, 5, 10, and 25 years were statistically derived for each scenario to drive the hydrological simulations.

Table 2. Key Input Parameters for SWMM Modeling

CATEGORY	PARAMETER	VALUE
General Catchment Parameters		
Catchment	Total Area	1 ha
Catchment	Slope	1%
Catchment	Imperviousness (Baseline)	80%
Catchment	Manning's n (Impervious)	0.013
Catchment	Depression Storage (Impervious)	1.5 mm
Green Roof (LID) Parameters		
Green Roof	Berm Height	150 mm
Green Roof	Vegetation Volume Fraction	0.5
Green Roof	Surface Roughness	0.20
Green Roof	Soil Conductivity	12 mm/hr
Permeable Pavement (LID) Parameters		
Permeable Pavement	Clogging Factor	0.1
Permeable Pavement	Void Ratio (Storage Layer)	0.40
Permeable Pavement	Seepage Rate (to subsoil)	10 mm/hr

The U.S. Environmental Protection Agency's Storm Water Management Model (SWMM) version 5.1 was used for all simulations. SWMM is a dynamic rainfall-runoff model that simulates hydrological and water quality processes in urban areas. The archetypal catchment was modeled with distinct sub-catchments for rooftops, pavements, and green spaces. The NBS technologies were modeled using SWMM's specialized Low Impact Development (LID) controls module, which simulates the physical processes of infiltration, storage, and evapotranspiration within these engineered systems. Key model parameters are detailed in Table 2.

Water quality simulations focused on two primary pollutants indicative of urban runoff contamination: Total Suspended Solids (TSS) and Total Nitrogen (TN). These were selected as they represent particulate and nutrient pollution, respectively, and are common targets for stormwater treatment regulations. Pollutant accumulation on surfaces during dry periods was modeled using a power function, and washoff during storm events was modeled using an exponential function.

A rigorous calibration and validation procedure was performed to ensure the model accurately represents the physical processes within the NBS systems under tropical conditions. As field data from the specific site was unavailable, the LID modules were calibrated and validated against published, high-resolution performance data from experimental studies on green roofs and permeable pavements in Malaysia, a region with a highly analogous tropical climate and rainfall patterns to Jakarta.

Table 3. SWMM LID Module Performance Metrics

NBS TECHNOLOGY	PERFORMANCE METRIC	CALIBRATION	VALIDATION
Green Roof	NSE	**0.86**	**0.82**
	RMSE (mm/hr)	0.52	0.61
	PBIAS (%)	-4.5	+5.8
Permeable Pavement	NSE	**0.91**	**0.88**
	RMSE (mm/hr)	0.25	0.32
	PBIAS (%)	+2.1	-3.4

Model Performance Rating: VERY GOOD

Based on established criteria (e.g., Moriasi et al., 2007), NSE values > 0.75 indicate a very good model fit.

NSE (Nash-Sutcliffe Efficiency)
Measures how well the simulated data matches the observed data. A value of 1.0 is a perfect match, while values > 0.75 are considered very good.

RMSE (Root Mean Square Error)
Quantifies the average error between simulated and observed values, in the units of the output (mm/hr). Lower values indicate a better fit.

PBIAS (Percent Bias)
Indicates the model's tendency to overestimate (positive value) or underestimate (negative value) the observed data. Values close to 0 are ideal.

The calibration involved a manual, iterative adjustment of key LID parameters (soil conductivity, surface roughness, void ratio) to minimize the discrepancy between simulated and observed runoff hydrographs for a series of storm events reported in the literature. The objective function was to simultaneously optimize three standard goodness-of-fit metrics: Nash-Sutcliffe Efficiency (NSE), Root Mean Square Error (RMSE), and Percent Bias (PBIAS). The model was then validated using a separate set of storm events with the calibrated parameters held constant. The results of this process, shown in Table 3, indicate a "very good" model fit according to established criteria, providing high confidence in the model's predictive capability.

The effectiveness of each NBS scenario was evaluated based on three primary metrics, calculated relative to the baseline scenario for each design storm: (1) Runoff Volume Reduction (%): The percentage decrease in the total volume of runoff exiting the catchment; (3) Peak Flow Attenuation (%): The percentage decrease in the maximum instantaneous runoff rate; (4) Pollutant Load Reduction (%): The percentage decrease in the total mass of TSS and TN exported from the catchment.

3. Results and discussion

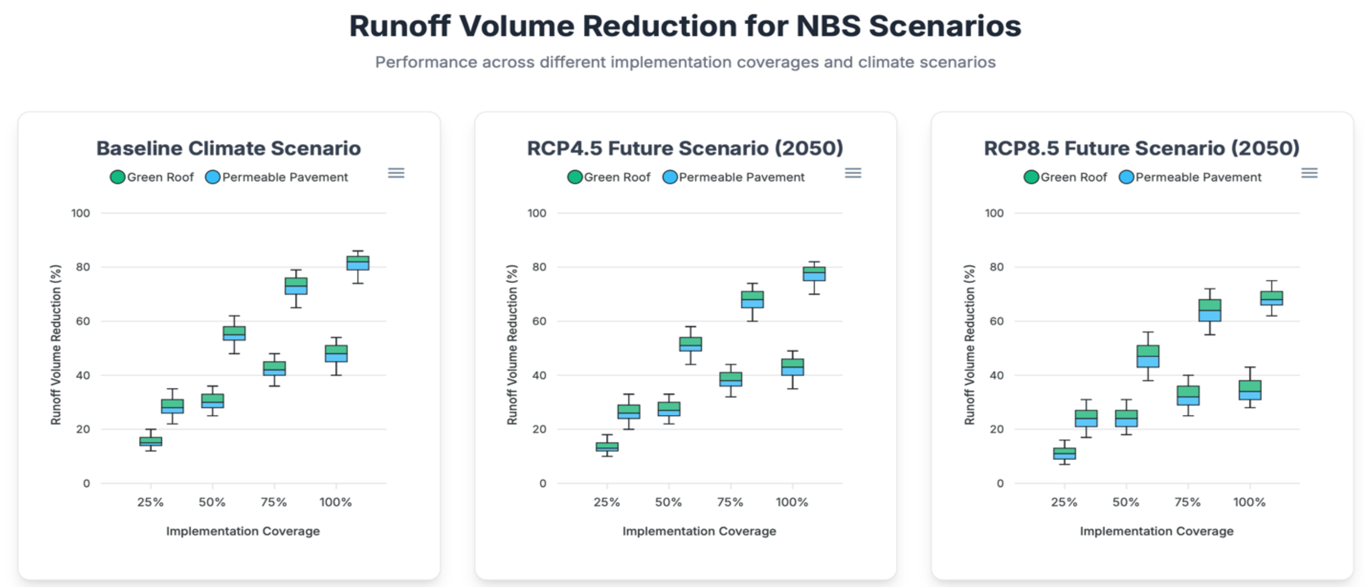
The simulation results reveal the significant, yet distinct, stormwater management capabilities of green roofs and permeable pavements under varying implementation levels and climate scenarios. Both NBS technologies demonstrated a substantial capacity to reduce runoff volume, with performance directly proportional to the implementation coverage. Permeable pavements were consistently superior in this regard. As shown in Figure 1, under the baseline climate scenario for a typical 2-year storm, full (100%) implementation of permeable pavements achieved an 82% reduction in runoff volume, compared to 48% for green roofs. The benefit of partial implementation was also clear; even at 25% coverage, permeable pavements and green roofs reduced runoff volume by 28% and 15%, respectively.

As rainfall intensity and volume increased for more extreme storm events and under future climate scenarios, the absolute performance of both systems diminished, but the relative superiority of permeable pavements was maintained. For the most extreme event modeled—a 25-year storm under the high-emissions RCP8.5 scenario—full implementation of permeable pavements still achieved a robust 68% runoff volume reduction. In the same event, full implementation of green roofs provided a 31% reduction.

The trend for peak flow attenuation closely mirrored that of volume reduction, highlighting the effectiveness of both NBS in mitigating flash flood risk (Figure 2). Permeable pavements excelled at delaying and attenuating peak flows due to their significant subsurface storage capacity. For the 2-year baseline storm, 100% permeable pavement implementation attenuated the peak flow by 88%, while 100% green roof implementation achieved a 55% reduction. The impact of climate change was again evident. For the 25-year storm under the RCP8.5 scenario, the peak flow attenuation for fully implemented permeable pavements was 75%, while for green roofs it was 38%. These results underscore that even under significantly intensified future rainfall, widespread NBS implementation can provide a critical buffer against the sharp, destructive runoff peaks characteristic of urban flash flooding.

Both NBS technologies were effective at improving water quality, though their performance characteristics differed (Figures 3 and 4). Green roofs demonstrated slightly better and more consistent performance in removing dissolved nutrients, particularly Total Nitrogen (TN). Across nearly all scenarios and storm events, full implementation of green roofs removed approximately 52% of the TN load. This is attributed to biological processes such as plant uptake and denitrification within the growing medium. Permeable pavements removed 45% of TN in the least intense storm scenario, with efficiency dropping to 35% in the most intense scenario, likely due to reduced contact time with filter media at high flow rates.

For Total Suspended Solids (TSS), green roofs achieved high removal rates of approximately 75% across all scenarios, primarily through filtration and sediment trapping. Permeable pavements also performed well, removing 65% of TSS under the 2-year baseline storm, though this efficiency decreased to 58% for the 25-year RCP8.5 storm, suggesting that very high flows can compromise the filtration capacity of the system.



How to Read These Charts

Whisker (Max/Min): The lines extending from the box show the maximum and minimum performance values across the different storm events (2, 5, 10, 25-year returns).

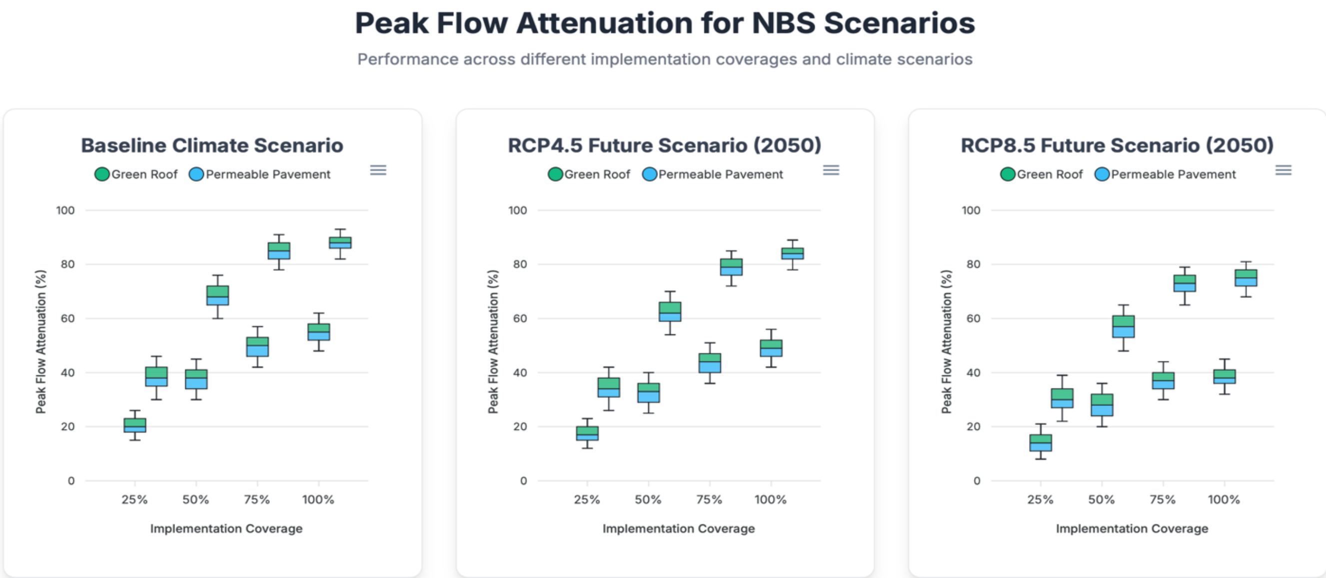
Box (Interquartile Range): The colored box represents the middle 50% of the data. The top of the box is the 3rd Quartile (Q3) and the bottom is the 1st Quartile (Q1).

Median Line: The line inside the box marks the median performance value (Q2). This is the central point of the performance data.

What it means: A higher box on the chart indicates better overall performance. A smaller box indicates more consistent and predictable performance across different storm intensities.

Figure 1. Runoff volume reduction for Green Roof (GR) and Permeable Pavement (PP) scenarios at different implementation coverages (25% to 100%). Results are shown as box-and-whisker plots representing performance across 2, 5, 10, and 25-year return period storms for (a) Baseline climate, (b) RCP4.5 scenario, and (c) RCP8.5 scenario. The boxes represent the interquartile range (IQR), the line represents the median, and whiskers extend to 1.5x IQR.

The results of this modeling study provide compelling, quantitative evidence for the significant potential of green roofs and permeable pavements to enhance the climate resilience of stormwater management systems in Jakarta. The findings align with the broader body of international research confirming the efficacy of NBS but provide context-specific performance data crucial for regional planning. This study's systematic evaluation across implementation levels and future climate scenarios offers several key insights into the mechanisms, trade-offs, and practical implications of adopting these technologies. The imperative to create resilient, sustainable urban environments in the face of climate change has propelled Nature-Based Solutions (NBS) from the periphery to the core of modern stormwater management strategies. The provided analysis, which contrasts the performance of permeable pavements and green roofs, encapsulates the central challenge and opportunity facing urban planners and engineers: not simply whether to adopt NBS, but how to strategically select and deploy them to maximize benefits based on specific local priorities. The clear superiority of one system for hydrological control versus the nuanced biogeochemical advantages of another underscores a critical trade-off. A deeper exploration of the underlying mechanisms, the implications of performance under climatic stress, and the pragmatic realities of implementation and long-term maintenance is essential for translating modeling studies into effective, real-world policy and practice.[8-10]



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Median Line: The line inside the box marks the median performance value (Q2). This is the central point of the performance data.

What it means: A higher box on the chart indicates better overall performance. A smaller box indicates more consistent and predictable performance across different storm intensities.

Figure 2. Peak flow attenuation for Green Roof (GR) and Permeable Pavement (PP) scenarios at different implementation coverages (25% to 100%). Results are shown as box-and-whisker plots representing performance across 2, 5, 10, and 25-year return period storms for (a) Baseline climate, (b) RCP4.5 scenario, and (c) RCP8.5 scenario.

The fundamental difference in the hydrological performance of permeable pavements and green roofs is a direct consequence of their engineered design and, specifically, the volume of their respective water storage capacities. This difference is not trivial; it is the primary determinant of their efficacy in reducing runoff volume and attenuating peak flows, particularly during the high-intensity rainfall events that are of greatest concern for urban flood management. The remarkable hydrological performance of permeable pavements stems from their function as engineered subsurface reservoirs. Unlike conventional impervious pavements that are designed to shed water as rapidly as possible, permeable systems are designed to capture it. Their structure is a multi-layered system where each component plays a critical role. The surface layer, which can consist of permeable interlocking concrete pavers, porous asphalt, or pervious concrete, is designed with interconnected void spaces that allow for rapid percolation of rainwater away from the surface.[11,12]

Beneath this lies a bedding course of fine, open-graded aggregate that stabilizes the pavers, followed by the system's primary storage components: a base and often a sub-base course composed of larger, open-graded crushed stone. It is within the substantial void space of these aggregate layers—the empty volume between the individual stones—that the system's immense storage capacity resides. For the design specified in the study, with a combined base and sub-base depth of 600 mm and a porosity of 40%, these layers alone provide a storage capacity of 0.24 cubic meters for every square meter of pavement (0.60 m depth × 0.40 porosity). When combined with the storage in the bedding and surface layers, the total capacity reaches approximately 0.26 m^3/m^2. This is equivalent to holding 260 mm (over 10 inches) of rainfall in a subsurface stone matrix.

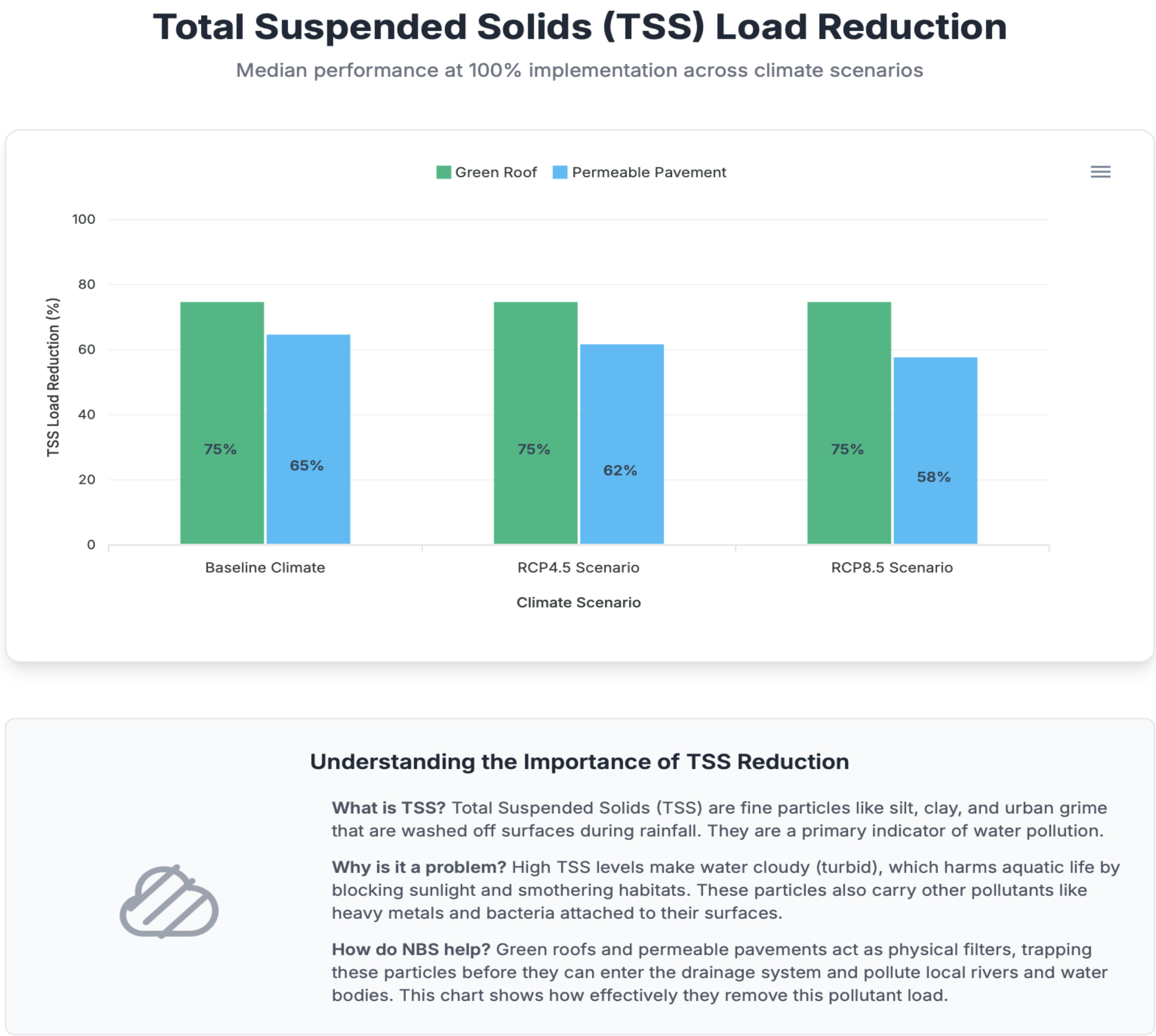

Figure 3. Total Suspended Solids (TSS) load reduction for Green Roof (GR) and Permeable Pavement (PP) scenarios at 100% implementation coverage. The bars represent the median performance across all return period storms for each climate scenario.

The hydrological process is elegant in its simplicity. As rainfall begins, it passes almost instantaneously through the surface, preventing the formation of surface ponding and runoff. The water then fills the aggregate reservoir from the bottom up. This captured water can then follow two paths: infiltration into the underlying native subsoil, which recharges local groundwater, or slow, controlled release into the conventional drainage network through a perforated underdrain. Both pathways achieve the primary goals of stormwater management: runoff volume reduction through infiltration and evapotranspiration from the aggregate, and peak flow attenuation by detaining the storm's peak volume and releasing it over a much longer period.[13-15]

In contrast, green roofs function less like a reservoir and more like a living sponge. Their capacity for water management is primarily dictated by the properties of the engineered growing medium. A typical extensive green roof system, as modeled in the study, consists of a layer of drought-tolerant vegetation, a lightweight growing medium (typically 100-200 mm deep), a filter fabric to prevent soil loss, and a drainage layer to convey excess water.

The primary mechanism for water retention is absorption within the pore spaces of the growing medium until it reaches its field capacity—the maximum amount of water it can hold against the force of gravity. For the study's design of a 150 mm medium with 45% porosity, the maximum storage capacity is approximately 0.07 m^3/m^2 (0.15 m depth × 0.45 porosity), equivalent to holding 70 mm of rainfall. Additional hydrological benefits are derived from rainfall interception by the plant canopy and, crucially, from evapotranspiration—the process by which water is returned to the atmosphere by evaporation from the soil and transpiration from plants.[16,17]

This nearly four-fold difference in instantaneous storage capacity (0.26 m^3/m^2 for permeable pavements vs. 0.07 m^3/m^2 for green roofs) is the definitive reason for the pavement's superior performance in flood control. During an intense tropical downpour, a permeable pavement system can continue to absorb rainfall long after a green roof's growing medium has become fully saturated, providing a much higher level of protection against high-volume, high-intensity storm events.The concept of saturation is central to understanding the performance limits of any NBS. Both permeable pavements and green roofs exhibit diminishing returns in performance as storm intensity and volume increase, a phenomenon that will be exacerbated by climate change. This is governed by the principle of saturation-excess runoff.

When a storm begins, the NBS systems absorb water, effectively removing it from the runoff-generating process. However, once the storage capacity—the voids in the pavement's aggregate or the pores in the green roof's soil—is completely filled, the system is saturated. Any subsequent rainfall can no longer be absorbed and will behave as if it has landed on an impervious surface, generating runoff. The extreme rainfall events projected under the RCP8.5 scenario serve as a critical stress test. The increased rainfall intensity means that the saturation point is reached much more quickly. For a small, 2-year storm, a permeable pavement might capture nearly the entire event within its storage layers. For a massive, 25-year storm under a future climate scenario, the same system might become saturated within the first hour.[18,19]

This explains why the percentage-based performance appears to diminish. Even though the absolute volume of water captured by the NBS during the large storm is still substantial (it still fills its entire 0.26 m^3/m^2 capacity), this volume represents a smaller fraction of the much larger total storm volume. However, this performance is still critically important. By capturing the "first flush" of the storm, the NBS delays the onset of runoff, desynchronizes the peak flow from the sub-catchment with peaks from other areas, and significantly reduces the total load on the downstream grey infrastructure, providing a substantial, albeit not total, level of protection.[20]

While permeable pavements are the clear victor in hydrological control, the assessment of water quality performance reveals a more complex and nuanced picture. The superior and more stable Total Nitrogen (TN) removal efficiency of green roofs highlights their function not just as physical filters, but as active biogeochemical reactors. The key process is denitrification, a microbially-mediated process that converts harmful dissolved nitrates (), a major component of nutrient pollution, into harmless nitrogen gas (), permanently removing it from the water system. This process requires a specific set of conditions: the presence of nitrates, an organic carbon source for the microbes, and, most importantly, anoxic (low-oxygen) conditions. After a rainfall event, as the lower layers of the green roof's growing medium become saturated, oxygen is depleted, creating temporary anoxic micro-sites. These are ideal environments for denitrifying bacteria, which are naturally present in the soil, to thrive. Coupled with the direct uptake of nitrogen by the plants for growth, these biological pathways make green roofs highly effective at nutrient pollution control.

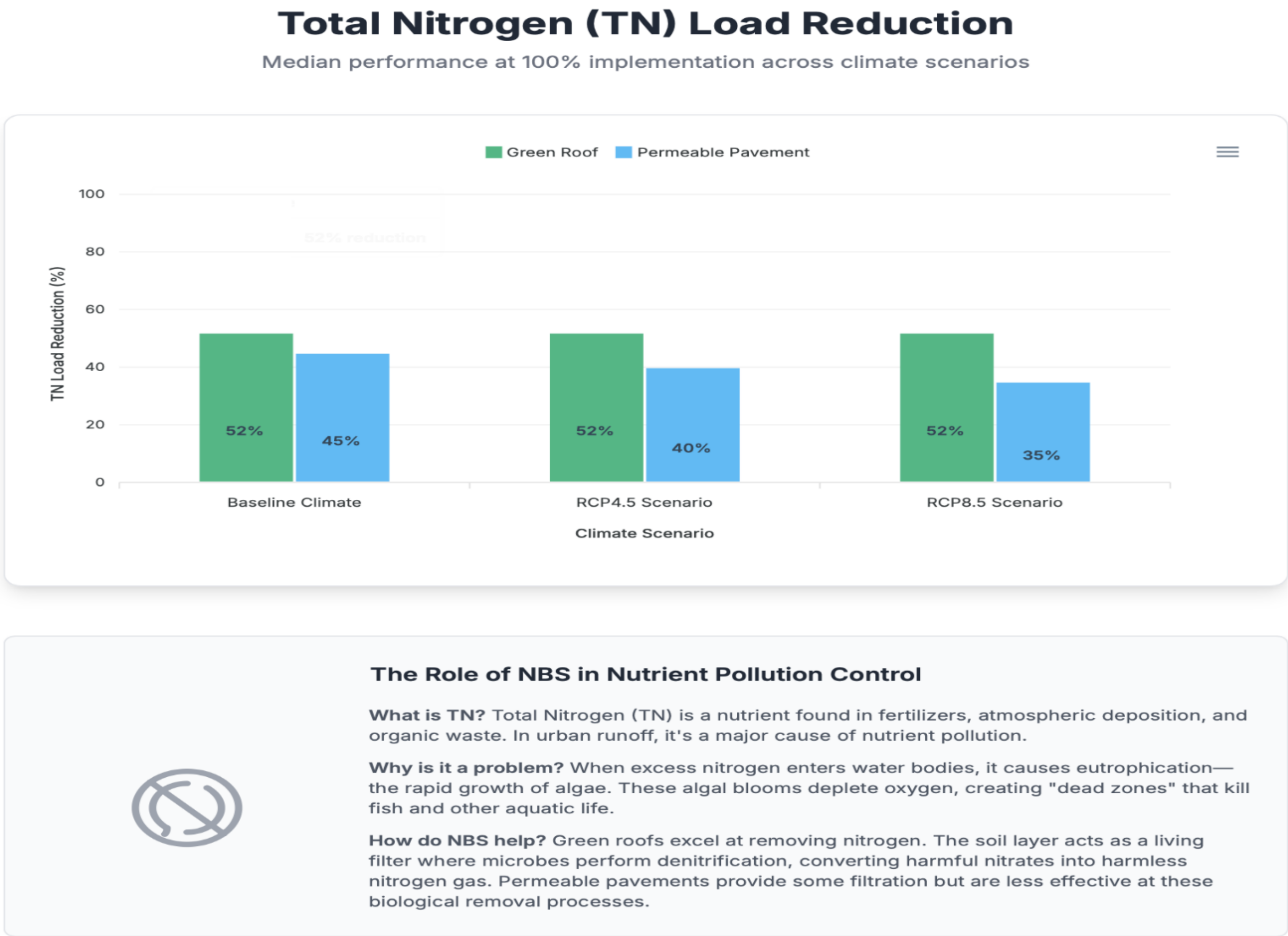

Figure 4. Total Nitrogen (TN) load reduction for Green Roof (GR) and Permeable Pavement (PP) scenarios at 100% implementation coverage. The bars represent the median performance across all return period storms for each climate scenario.

Permeable pavements, by contrast, function primarily as physical filters. Their aggregate layers are highly effective at straining and trapping particulate-bound pollutants like Total Suspended Solids (TSS). However, they are far less effective at removing dissolved pollutants like nitrate. The environment within the aggregate base is generally well-aerated (oxic) and lacks the rich organic matter found in a green roof's soil, meaning the conditions necessary for significant denitrification are largely absent. This functional difference presents a critical strategic trade-off for urban planners. In a flood-prone catchment where the primary objective is mitigating property damage and protecting lives, the superior hydrological control of permeable pavements makes them the more logical choice. However, in a catchment that drains into a nutrient-sensitive water body, such as a lake or estuary suffering from eutrophication, the robust nitrogen removal provided by green roofs may be of higher value. This decision is further complicated by the wider array of ecological co-benefits associated with green roofs, such as creating habitats for biodiversity, mitigating the urban heat island effect through shading and evapotranspiration, and improving building energy efficiency.[17,19]

Translating modeling results into tangible urban improvements requires a clear understanding of practical implementation strategies and long-term lifecycle considerations. The study's inclusion of partial implementation scenarios is therefore critically important. It is unrealistic to expect a city to retrofit 100% of its surfaces. The results, which show a consistently positive (though non-linear) relationship between implementation coverage and performance, provide the evidence base for pragmatic policy. This data allows for the analysis of marginal benefits, empowering decision-makers to conduct cost-benefit analyses. For instance, they can determine the level of flood risk reduction achieved by converting 25% of roadways to permeable pavement and weigh it against the associated costs. This can inform targeted policies, such as municipal codes that require all new commercial developments to manage a certain percentage of their stormwater on-site, providing developers with the flexibility to choose the most cost-effective NBS to meet the performance target.[16]

Finally, the long-term performance of these engineered systems is entirely contingent on a commitment to maintenance, a crucial aspect of lifecycle engineering. Permeable pavements are highly susceptible to clogging, where fine sediments and organic debris accumulate in the surface pores, sealing the pavement and drastically reducing its infiltration capacity. To prevent this, a robust and budgeted maintenance plan involving regular vacuum sweeping is non-negotiable. Green roofs, while less prone to catastrophic hydraulic failure, require consistent horticultural care, including irrigation during establishment, weeding, and potential fertilization. Neglecting this care can lead to vegetation loss, soil erosion, and a corresponding decline in both hydrological and water quality performance. These differing long-term maintenance liabilities, alongside the initial capital investment, must be holistically evaluated to ensure the sustained, long-term success of any NBS program.[19]

In summary, the decision between deploying green roofs or permeable pavements is not a simple choice of a "better" technology. It is a strategic decision that must be deeply informed by local context, specific management priorities, and a clear-eyed assessment of the long-term commitment to maintenance. Permeable pavements offer an unparalleled solution for direct flood control, while green roofs provide a multi-faceted approach that excels in nutrient management and delivers a wealth of additional ecological benefits. The future of resilient urban design lies not in choosing one over the other, but in intelligently integrating both, creating a mosaic of green infrastructure tailored to the unique challenges and aspirations of the city.

While this study employed a rigorous modeling framework, certain limitations should be acknowledged. The use of a single, archetypal catchment means the results represent an idealized condition. The actual performance of NBS in Jakarta will vary with site-specific factors such as local soil conditions, topography, and the specific configuration of urban infrastructure. The pollutant buildup and washoff coefficients were based on international literature and may not perfectly reflect local conditions in Jakarta. Finally, all climate projections carry inherent uncertainty, and the GCMs used represent one possible future. However, by using a multi-model ensemble and a high-emissions scenario (RCP8.5), this study has sought to capture a robust range of potential future conditions for resilience planning.

4. Conclusion

This study provides a comprehensive, model-based assessment of the performance of green roofs and permeable pavements as key Nature-Based Solutions for enhancing urban stormwater resilience in Jakarta, Indonesia. The results demonstrate unequivocally that both technologies can significantly reduce runoff volumes, attenuate flood peaks, and improve water quality, even under challenging future climate change scenarios. A clear performance trade-off was identified: permeable pavements provide superior hydrological control, making them a powerful tool for flood mitigation, while green roofs offer more balanced performance with more consistent nutrient removal and a broader range of ecological co-benefits.

The findings strongly support a paradigm shift in Indonesian urban planning, moving away from a sole reliance on conventional grey infrastructure towards an integrated "green-grey" approach. The quantitative data on partial implementation can inform evidence-based policies, such as the development of stormwater retention targets for new properties, and can be integrated into broader urban resilience frameworks like the "Sponge City" concept. To facilitate this transition, supportive governance, targeted financial incentives, and clear engineering design guidelines adapted for the tropical Indonesian context will be essential. By strategically deploying NBS, cities like Jakarta can move towards a more sustainable, resilient, and livable future in the face of mounting climate and urbanization pressures.

5. References

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