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Nature-Based Solutions for Integrated Stormwater Management and Urban Water Quality Improvements

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ABSTRACT

Urbanization replaces permeable soil and vegetation with roofs, roads, and compacted surfaces, increasing runoff, peak discharge, and pollutant transport. This review evaluates nature-based solutions (NbS) for integrated stormwater quantity control and urban water-quality improvement. Evidence from green roofs, bioretention, swales, permeable pavements, urban trees, ponds, and constructed wetlands is synthesized with emphasis on hydraulic mechanisms, pollutant pathways, design variables, climate resilience, monitoring, and lifecycle delivery. Green roofs retain about 62% of event rainfall on average, while well-designed biofilters, pavements, and wetlands often achieve high suspended-solids removal and moderate nutrient and metal attenuation. Performance depends on storage, media conductivity and chemistry, internal water storage, vegetation, antecedent moisture, residence time, loading, and maintenance rather than the NbS label alone. The strongest outcomes arise from treatment trains combining source retention, conveyance filtration, infiltration, and end-of-pipe polishing. Key constraints include dissolved nutrient export, clogging, winter or monsoon variability, land competition, and fragmented financing. A risk-based framework is proposed in which NbS are sized for hydraulic and pollutant-load targets, connected to safe grey-drainage exceedance routes, and verified through standardized event and continuous monitoring.

KEYWORDS: *Nature-Based Solutions (NbS); Urban Stormwater; Green Infrastructure; Bioretention; Permeable Pavement; Constructed Wetlands; Pollutant Load Reduction; Climate Resilience; Water-Sensitive Urban Design.*

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INTRODUCTION

Conventional urban drainage rapidly conveys rainfall away from streets and buildings, but this reduces infiltration and evapotranspiration, increases downstream peaks, and transfers untreated pollutants to receiving waters. Runoff mobilizes sediment, tire- and brake-wear metals, hydrocarbons, nutrients, litter, microorganisms, and microplastics accumulated during dry periods. First-flush runoff may contain a disproportionate pollutant mass, especially from traffic surfaces [16]. Aging pipes and combined sewers increase overflow risk during intense rainfall. The U.S. Environmental Protection Agency therefore promotes green infrastructure that captures, infiltrates, and filters runoff near its source [3].

Nature-based solutions protect, restore, manage, or create ecosystems while addressing societal challenges and supporting biodiversity and human well-being [1]. In stormwater practice, NbS overlap with low-impact development, sustainable drainage systems, water-sensitive urban design, green infrastructure, sponge-city measures, and stormwater control measures [2]. Their common purpose is to restore interception, storage, infiltration, evapotranspiration, detention, and reuse through green roofs, rain gardens, bioretention, swales, trees, permeable pavements, ponds, and constructed wetlands. These systems can also reduce heat, improve habitat and streetscapes, and support circular non-potable water use [4]-[6].

Performance is highly conditional. Green roofs may retain most rainfall from a small event but little after substrate saturation. Bioretention can remove particulate phosphorus yet leach dissolved phosphorus from compost-rich media. Permeable pavement can lose infiltration through clogging, while wetlands require adequate residence time, land, and sediment and vegetation management. NbS must therefore be designed as hydraulic and treatment unit processes with defined contributing area, storage, media, underdrain, overflow, vegetation, bypass, and maintenance requirements [6], [12].

Urban programs often assess runoff reduction, pollutant removal, co-benefits, and cost separately. This review integrates these dimensions and examines how distributed measures can form treatment trains across parcel, street, neighborhood, and catchment scales. The objective is not complete replacement of grey drainage, but a hybrid system in which frequent storms are retained and treated, larger events are safely detained and conveyed, and receiving-water objectives remain achievable under future rainfall uncertainty.

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LITERATURE REVIEW

Stormwater research has moved from terminology and demonstration projects toward quantitative synthesis, design optimization, and system integration. Fletcher et al. [2] showed that LID, SuDS, WSUD, BMPs, and green infrastructure arose from different regional histories but increasingly converge on source control and hydrologic restoration. Recent reviews place these practices within NbS, adding multifunctionality, ecosystem integrity, participation, and adaptive management [1], [4]. A review of 187 publications found green roofs, permeable pavements, bioretention, and constructed wetlands to be the dominant measures studied for runoff and climate adaptation [4].

Hydrologic evidence is strongest for green roofs and bioretention. A synthesis of 2,375 green-roof observations from 21 countries reported mean event retention of 62%, with rainfall, substrate depth, vegetation, season, and climate explaining variability [7]. A systematic review of 114 bioretention studies reported generally strong performance but substantial variation caused by media, ponding depth, underdrains, internal water storage, vegetation, and antecedent moisture [8]. Recent review evidence likewise identifies media amendments, storage zones, and plant selection as decisive design controls [17].

Water-quality evidence consistently separates particulate from dissolved pollutants. Sedimentation and filtration reliably remove suspended solids and particle-bound metals, whereas dissolved nitrogen and phosphorus require sorption, precipitation, plant uptake, and microbial transformation. Pervious concrete combines filtration, sorption, precipitation, and biological activity, but alkaline leachate and desorption require attention [10]. Constructed wetlands add settling, complexation, nitrification, denitrification, and biodegradation, making them effective polishing systems when hydraulic loading and residence time are controlled [11]. Green roofs may retain or export nutrients depending on substrate and fertilizer use [6].
Catchment studies emphasize location, monitoring, economics, and governance. Soil, vegetation, dimensions, connectivity, and catchment position affect both runoff and treatment [12]. Water-quality models remain less transferable than hydraulic models because buildup, wash-off, transformation, and first flush are site-specific [13]. Continuous monitoring is constrained by fouling, intermittent flow, calibration, and surrogate sensor uncertainty [14]. Smart control can improve storage use, but adoption is limited by interoperability, operational capacity, and finance [15]. Economic assessments should rank NbS against local objectives

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and account for long-term funding rather than relying on uncertain single-value monetization [18], [20].

RESEARCH GAP

Despite substantial evidence for individual practices, five gaps limit reliable design and scaling of integrated stormwater NbS:

- **Hydrology-quality separation:** Many studies report runoff retention without simultaneous pollutant loads. Concentration-only assessment may overstate or understate benefit when outflow volume changes; load-based indicators are needed.
- **Insufficient treatment-train evidence:** Most field studies examine isolated assets. Fewer quantify cumulative performance when source, conveyance, infiltration, detention, and polishing controls are hydraulically connected.
- **Climate and aging uncertainty:** Short monitoring periods rarely capture clogging, vegetation succession, media exhaustion, drought, freezing conditions, or rainfall intensification over multi-decadal asset lives.
- **Weak standardization:** Differences in event definition, bypass accounting, sampling frequency, antecedent dry period, and reporting units hinder comparison and model transfer [14], [19].
- **Implementation disconnect:** Design guidance often omits land constraints, maintenance responsibility, equity, public acceptance, lifecycle cost, and stable financing, although these factors determine whether performance persists [18], [20].
- This review addresses these gaps through a framework linking unit processes, load-based indicators, treatment-train configuration, climate robustness, monitoring, and implementation responsibility.

OBJECTIVES

The review has four research objectives:

- **Objective 1- Technical synthesis:** Compare the hydraulic and water-quality mechanisms of major stormwater NbS and identify the design variables that govern performance.
- **Objective 2- Quantitative interpretation:** Synthesize representative ranges for runoff, peak flow, suspended solids, nutrients, and metal attenuation while distinguishing concentration reduction from mass-load reduction.

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- **Objective 3- Integrated system design:** Develop a treatment-train framework that connects parcel, street, neighborhood, and receiving-water controls with grey drainage exceedance pathways.
- **Objective 4- Practical guidance:** Evaluate monitoring, maintenance, lifecycle cost, governance, and climate uncertainty to define research and implementation priorities for municipalities and engineers.

METHODOLOGY

This study applies a critical integrative review rather than a pooled meta-analysis. Peer-reviewed reviews, field studies, modeling papers, and authoritative standards published mainly during 2015-2026 were prioritized, with foundational earlier work retained. Searches combined terms for NbS, green infrastructure, stormwater, bioretention, green roofs, permeable pavement, wetlands, pollutant removal, monitoring, cost, and climate resilience. Evidence was classified by intervention, spatial scale, climate, hydraulic configuration, pollutant, monitoring method, and implementation context.

Hydrologic performance was interpreted using event retention, runoff coefficient, peak reduction, lag time, and drawdown. Event water balance was expressed as $P = Qout + I + ET + \Delta S$, where P is precipitation plus run-on, Qout is overflow or underdrain discharge, I is infiltration, ET is evapotranspiration, and ΔS is storage change. Water quality was assessed through event mean concentration, influent and effluent mass, and load-removal efficiency, $\eta L = (Lin - Lout)/Lin \times 100$. Load-based metrics were preferred because strong volume reduction can lower total export even when effluent concentration changes little.

Reported values were harmonized into representative ranges and midpoints for comparison; they are evidence-informed syntheses rather than results from one calibrated catchment. Field monitoring and systematic reviews received greater weight than short laboratory tests. Findings were translated into a treatment-train concept and decision matrix covering footprint, hydraulic role, target pollutants, failure modes, maintenance, and co-benefits. The IUCN Global Standard provided a governance lens for societal challenge, biodiversity, trade-offs, and adaptive monitoring [1].

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RESULTS AND FINDINGS

Integrated Hydrologic Control

Evidence supports sequential placement of storage and treatment from source to outlet. Green roofs and capture systems intercept roof runoff; bioretention and swales treat road runoff and first flush; permeable pavement converts suitable hardscape into subsurface storage and infiltration; and ponds or wetlands provide final detention and polishing. Figure 1 summarizes this treatment-train logic.

The train reduces connected impervious area and increases effective storage. Green roofs perform best for frequent small-to-medium events; the 62% global mean retention is a benchmark, not a universal design value [7]. Bioretention typically combines surface ponding, engineered media, and, where soils are restrictive, an underdrain with internal water storage. Permeable pavement provides aggregate storage but requires pretreatment and vacuum sweeping. Wetlands and ponds provide less source control but attenuate downstream peaks and pollutant pulses [11].

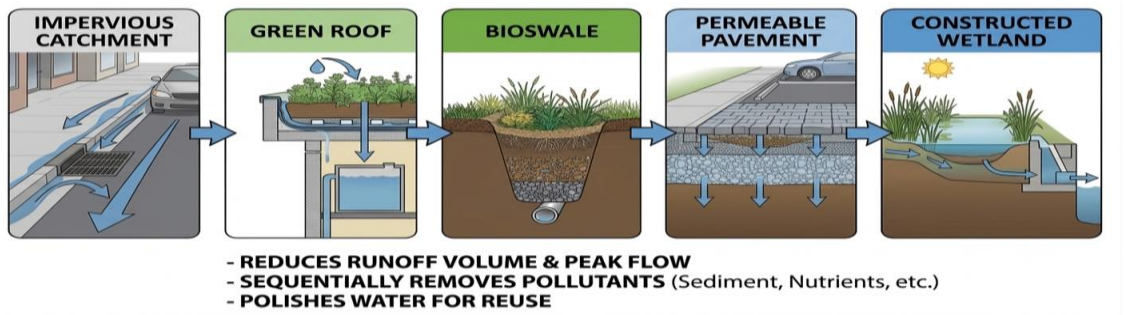


Figure 1: Integrated urban stormwater NbS treatment train linking source retention, conveyance - scale filtration, infiltration, and end-of-pipe polishing

Table 1: Engineering Functions and Design Controls of Major Stormwater Nature-Based Solutions

NbS type	Primary hydraulic process	Dominant treatment mechanisms	Critical design controls	Typical failure mode
Green roof	Interception, substrate storage, ET	Filtration; limited sorption and uptake	Substrate depth, drainage layer, vegetation, roof loading, climate	Saturation during long storms; nutrient export

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Bioretention / rain garden	Ponding, filtration, infiltration, delayed underdrain flow	Sedimentation, filtration, sorption, precipitation, nitrification-denitrification, uptake	Media gradation, Ksat, ponding depth, IWS zone, vegetation, run-on ratio	Clogging, short-circuiting, media nutrient leaching
Vegetated swale	Conveyance slowing and shallow infiltration	Settling, filtration, adsorption, biological uptake	Longitudinal slope, check dams, vegetation density, residence time	Erosion, channelization, bypass at high flow
Permeable pavement	Surface infiltration and subbase detention	Filtration, sorption, precipitation, biodegradation	Surface type, subbase void ratio, geotextile, soil infiltration, overflow	Sediment clogging, frost or structural distress
Pond / constructed wetland	Detention, sedimentation, controlled release	Settling, sorption, microbial transformation, plant uptake, photolysis	Residence time, depth zones, forebay, vegetation, outlet control	Sediment accumulation, invasive plants, stagnant zones

Urban Water-Quality Improvement

Particulate pollutants are removed more consistently than dissolved pollutants. Sedimentation, straining, and filtration often produce high total suspended solids and particle-bound metal removal. Dissolved phosphorus depends on media sorption capacity and can be exported by nutrient-rich organic amendments. Nitrogen behavior reflects filtration, ammonification, nitrification, denitrification, plant uptake, and carbon availability; an anoxic internal water storage zone can improve nitrate removal when drawdown remains acceptable [8], [17]. Wetlands provide additional residence time and redox gradients, but excessive hydraulic loading causes short-circuiting [11].

Permeable pavement treats runoff through surface interception and base-course storage, but performance changes as pores clog. Pervious concrete may sorb or precipitate metals and phosphorus, while high-pH leachate and eventual media saturation require verification [10]. Green roofs primarily reduce pollutant loads by reducing runoff volume, yet substrate and

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fertilizer can release nutrients [6]. Accordingly, inflow, treated discharge, and bypass loads should be monitored separately; concentration-only reporting can misrepresent benefit. Table 2 presents representative ranges for preliminary comparison, not guaranteed design values.

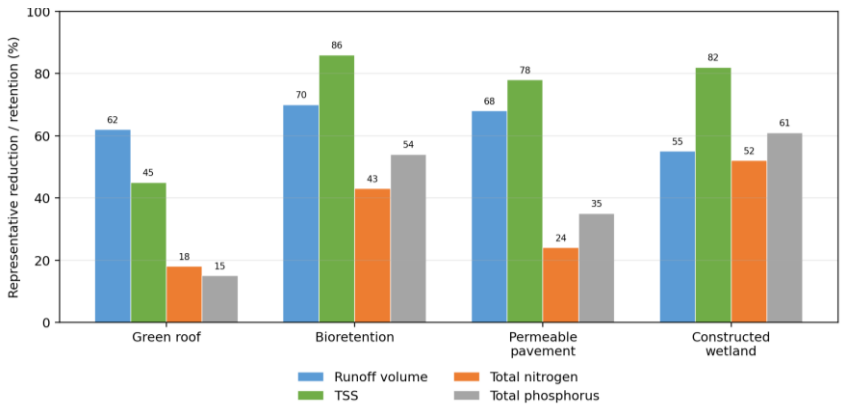


Figure 2: Representative reduction or retention for major NbS types. Values are evidence-informed midpoints synthesized from published reviews and are not site-specific design guarantees

Table 2: Representative Hydrologic and Pollutant-Load Performance Ranges Reported for Urban Stormwater NbS

NbS type	Runoff volume reduction	Peak-flow reduction	TSS load reduction	TN load reduction	TP load reduction	Key uncertainty
Green roof	40-80% per event; global mean ~62%	20-70%	Variable; generally secondary	0-30%; possible export	0-25%; possible export	Antecedent moisture and storm duration
Bioretention	50-90% where infiltration is feasible	40-85%	70-95%	25-65%	30-75%	Media chemistry, IWS zone, bypass
Permeable pavement	60-95% surface-runoff reduction	30-70%	60-90%	10-45%	20-55%	Clogging, subgrade soil, maintenance

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Constructed wetland	20-70% depending on storage and release	30-80%	65-95%	30-75%	35-80%	Residence time, season, short-circuiting

Catchment Integration and Climate Robustness

At catchment scale, spatial arrangement matters as much as total NbS area. Controls close to runoff sources intercept pollutants before mixing, while downstream ponds or wetlands buffer residual loads. Modeling should represent contributing area, routing, infiltration limits, underdrains, bypass, and temporal pollutant processes [13]. Distributed measures are generally most effective for frequent events; extreme-event resilience still requires detention, protected overland flow paths, and adequate pipe capacity.

Climate robustness requires explicit exceedance design. NbS should manage frequent water-quality storms and contribute to larger-event attenuation without being credited beyond tested capacity. Design rainfall should incorporate future intensity change, and infiltration requires screening for groundwater, contaminated soils, foundations, and utilities. Drought-tolerant vegetation, erosion-resistant inlets, sediment forebays, and maintainable overflow structures are especially important in monsoon climates. Smart outlets can pre-release storage before forecasts, but controls need fail-safe states and clear operators [15].

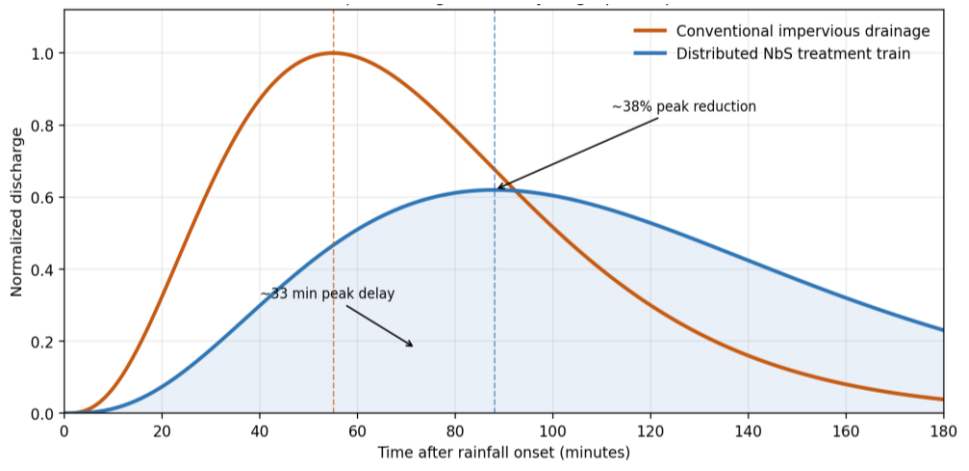


Figure 3: Conceptual normalized hydrograph showing peak attenuation and delay produced by a distributed NbS treatment train; illustrative rather than site-calibrated

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Implementation, Monitoring, and Lifecycle Performance

Long-term benefit depends on maintenance and measurable service levels. Monitoring should include rainfall, inflow and outflow volume, bypass, drawdown, infiltration decline, sediment depth, vegetation condition, and event-based pollutant loads. Continuous turbidity, conductivity, temperature, or water-level sensors can support diagnostics, but require calibration, fouling control, and quality assurance [14], [19]. Maintenance should be triggered by function, such as unacceptable drawdown or sediment accumulation, rather than appearance alone.

Lifecycle assessment should separate capital cost, routine maintenance, rehabilitation, land opportunity cost, and avoided grey-infrastructure expenditure. Co-benefits are important but uncertain monetization should not conceal hydraulic performance. Cost-effectiveness is strongest when NbS are embedded in road, park, housing, campus, or lake-renewal projects and when asset ownership and maintenance funding are assigned before construction [18], [20]. Table 3 links context, preferred measures, failure risks, and monitoring indicators.

Table 3: Context-Specific Selection and Performance Management Matrix

Decision context	Preferred NbS combination	Primary design target	Required monitoring	Major implementation risk
Dense commercial core	Blue-green roofs + curb bioretention + controlled underground storage	Peak reduction and combined-sewer overflow control	Water level, controlled outlet, overflow frequency	Limited space; complex ownership
Residential streets	Rain gardens + tree trenches + permeable parking lanes	Frequent-event retention and TSS/metals removal	Infiltration rate, drawdown, sediment and vegetation	Utility conflicts; inconsistent maintenance
Industrial / traffic catchment	Pretreatment forebay + lined bioretention + wetland polishing	Sediment, metals, hydrocarbons and spill containment	Influent/effluent loads, sediment chemistry, bypass	Contaminated infiltration and media disposal

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New urban district	Distributed source controls + swales + floodable park + reuse storage	Water balance restoration, flood resilience and reuse	Catchment flow, storage utilization, reuse demand	Performance assumptions not verified after build-out
Low-permeability or high groundwater site	Lined biofiltration + underdrain + detention wetland	Water-quality treatment without uncontrolled infiltration	Underdrain flow, groundwater separation, outlet quality	Standing water and insufficient drawdown

DISCUSSION

The central engineering conclusion is that NbS performance is governed by process design and hydraulic connectivity, not terminology. A green feature becomes stormwater infrastructure only when its contributing area, capture, storage, media, drainage, overflow, and maintenance are specified. Engineered assets can still be NbS when ecological processes and biodiversity are integral rather than decorative [1]. Municipal reporting should therefore measure captured runoff and pollutant loads, not merely green area.

Treatment trains offset single-practice weaknesses. Green roofs reduce roof runoff but do little for road metals; bioretention treats roadway runoff but may bypass in extreme rain; permeable pavement adds distributed storage but clogs; and wetlands polish residual loads but need land. Sequential systems let source measures reduce volume, pretreatment protect media, biofiltration remove particles and support transformation, and wetlands provide final residence time. Grey pipes and protected overland routes remain essential where infiltration is unsafe or design capacity is exceeded.

Water-quality assessment should prioritize loads and receiving-water outcomes. A 50% concentration reduction is not necessarily a 50% load reduction when outflow volume changes, and apparent negative concentration removal may still accompany net load reduction after retention. Monitoring must quantify inflow, treated outflow, and bypass. Dissolved nutrients should be reported separately from particulate fractions, and seasonal analysis should capture evapotranspiration, biological activity, deicing salts, and temperature effects.

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Design should be adaptive. Media amendments require pollutant-specific selection and leaching tests. Internal water storage may improve denitrification but must preserve drawdown. Plants should tolerate inundation, drought, pollutant exposure, and realistic maintenance. Inspections, infiltration testing, and sensor trends should trigger intervention before visible failure. Forecast-based control can reserve storage or extend wetland residence time, but must be fail-safe and governed by accountable operators [15].

For rapidly urbanizing Indian cities, NbS should be integrated with road renewal, lake restoration, campuses, housing layouts, and urban missions rather than isolated demonstrations. Monsoon intensity and long dry periods require robust pretreatment, erosion protection, safe overflow, sediment removal, drought-tolerant planting, and elimination of sewage cross-connections. Local monitoring is essential because temperate-climate performance values cannot be transferred directly.

LIMITATIONS

This review is limited by heterogeneity in climate, scale, event definition, inflow quality, and monitoring duration; reported ranges guide preliminary design but do not replace local modeling and pilots. The integrative method does not calculate pooled effect sizes or publication bias. Many studies lack long-term evidence on clogging, media exhaustion, pollutant remobilization, vegetation succession, microplastics, and disposal. Economic results are location-specific and often omit land, transaction costs, biodiversity, health benefits, and climate uncertainty. The figures therefore communicate mechanisms and representative performance, not guaranteed outcomes.

FUTURE SCOPE

Future research should prioritize:

- Standardized long-term observatories: Multi-climate networks using common event definitions, bypass accounting, QA/QC, and open hydraulic and pollutant-load datasets.
- Reactive and circular media: Low-leaching biochar, iron, aluminum, or recycled mineral amendments with defined regeneration and safe end-of-life pathways.
- Emerging contaminants: Treatment-train fate of microplastics, tire-wear particles, PFAS, pathogens, and resistance genes, including remobilization in extreme events.

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- Digital twins and adaptive control: Rainfall nowcasting, distributed sensors, water-quality surrogates, and real-time outlets optimized for storage and ecological objectives.
- Equity and finance: Distribution of flood, heat, amenity, and water-quality benefits, supported by financing that covers inspection and renewal [20].

CONCLUSION

Nature-based solutions can improve urban stormwater management when designed as connected hydraulic and treatment processes. Evidence supports event retention, peak attenuation, suspended-solids removal, and reduction of particle-bound metals. Nutrient performance is more variable because it depends on media chemistry, redox conditions, plants, microbes, residence time, and maintenance. Green roofs provide source retention; bioretention and swales filter road runoff; permeable pavements reduce connected impervious area and add storage; and ponds or wetlands provide downstream detention and polishing.

The most defensible strategy is a hybrid treatment train. Distributed NbS should capture and treat frequent storms, while grey drainage and protected overflow routes manage exceedance. Design requires pollutant-load targets, bypass accounting, climate-adjusted rainfall, safe infiltration screening, and lifecycle maintenance. Standardized monitoring must detect clogging, leaching, short-circuiting, and vegetation failure. Properly delivered systems can provide cleaner waters, reduced sewer overflow, recharge, non-potable supply, cooling, biodiversity, and better public space. Reliable scaling will depend on long-term local datasets, validated criteria, accountable ownership, and durable finance.

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