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Assessing Permeable Pavements and Urban Layouts Designed to Absorb Stormwater and Mitigate Flood Risks

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Abstract—Urban flooding increasingly reflects the interaction of high imperviousness, short-duration intense rainfall, constrained drainage networks, and spatially concentrated runoff. Permeable pavements can transform roads, parking areas, sidewalks, and courtyards from runoff-generating surfaces into distributed storage and infiltration systems, but their effectiveness depends as much on urban layout, loading ratio, soil conditions, drainage configuration, maintenance, and storm magnitude as on pavement material. This paper develops a data-driven assessment of permeable pavements and spatial low-impact-development (LID) layouts using published field observations and recent city-scale modeling evidence. The evidence base includes monitored permeable-pavement installations in North Carolina, New Hampshire, Wisconsin, and northern Ohio, together with a 2026 optimized retrofit study of an older urban community that used EPA SWMM, observed 2024 rainfall events, and explicit placement of permeable pavements, rain gardens, and green roofs. Field studies show that properly designed permeable pavements can sharply reduce surface runoff and delay peaks; a monitored porous-asphalt system in New Hampshire reduced peak flow by approximately 90%, while broader Great Lakes evidence reports event-volume reductions ranging from about 13% to nearly 99% depending on site and design. In the 2026 urban-layout case, optimized LID deployment reduced stormwater runoff by roughly 59% and total suspended solids loads by about 79%; peak TSS concentrations during the 20-year design storm decreased from 132.22 to 45.72 mg/L, while observed 2024 storm events also showed substantial reductions. The study synthesizes these data into a spatial design framework emphasizing distributed source control, targeted treatment of low-lying convergence zones, preservation of exceedance pathways, maintenance access, and matching pavement area to contributing impervious area. Results indicate that flood mitigation is strongest when permeable pavement is treated not as an isolated material substitution but as a coordinated component of urban drainage morphology. The proposed framework provides practical guidance for civil engineers, planners, and municipalities seeking robust stormwater absorption and flood-risk reduction under current and future rainfall extremes.

Index Terms—permeable pavement, urban flooding, stormwater, low impact development, green infrastructure, SWMM, sponge city, infiltration, spatial layout, flood resilience.

I. INTRODUCTION

Urban drainage systems were historically designed to collect runoff quickly and convey it away from streets and buildings. That strategy performs well for frequent events when pipe capacity is adequate, but it can create a hydrologically efficient network that synchronizes runoff from roofs, roads, parking lots, and compacted landscapes. As urbanization increases effective impervious area, rainfall that once infiltrated or was detained in surface depressions is converted into rapid surface runoff. The resulting hydrographs are characterized by larger volumes, shorter lag times, and higher peaks, which increase the probability of surcharge, manhole overflow, street ponding, and downstream channel stress. Climate-driven shifts toward more intense short-duration rainfall compound the problem because many existing drainage networks cannot be economically enlarged at the same rate as flood risk grows.

Permeable pavement is a source-control measure that reverses part of this urbanization process. Instead of a hydraulically sealed surface, the pavement allows rainfall and, in some designs, runoff from adjacent impervious surfaces to pass through a porous wearing layer or through joints between units. Water is temporarily stored in an open-graded aggregate reservoir and is then removed by exfiltration into native soil, underdrain discharge, evaporation, or controlled overflow. Because the storage is located beneath a surface that would otherwise be impervious, permeable pavement is attractive in dense urban areas where land for ponds or large surface basins is scarce.

However, the phrase 'permeable pavement reduces flooding' is too general to be a reliable design rule. Field performance varies because the same pavement can behave very differently under different loading ratios, soil permeabilities, reservoir depths, underdrain elevations, antecedent moisture conditions, clogging states, maintenance practices, and storm intensities. The spatial position of a pavement system inside the urban drainage network also matters. A square meter of permeable pavement placed where runoff is generated may intercept water before it enters the pipe network; the same area located downstream may receive a larger contributing flow but can fill earlier or shift hydrograph timing in undesirable ways. Flood mitigation therefore depends on the combined material, hydraulic, and spatial design of the urban system.

This research paper addresses that systems perspective. Rather than presenting a laboratory-only evaluation of a single pavement mixture, it combines real field observations with recent spatial optimization evidence to examine how permeable pavement and urban layout jointly influence runoff volume, peak flow, waterlogging duration, and water quality. The paper uses published monitored cases as the empirical foundation and a recent urban-retrofit case as the primary spatial-layout example. This approach

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avoids inventing experimental data while still allowing a rigorous comparative assessment of design variables that are directly relevant to contemporary civil-engineering practice.

The central hypothesis is that permeable pavement delivers the most reliable flood-risk reduction when it is embedded in a distributed urban water-management layout: source areas are disconnected from directly connected impervious drainage; storage is sized to the contributing area and design storm; low-lying convergence zones receive targeted treatment; and larger exceedance flows are routed safely through streets, swales, open spaces, or oversized conveyance corridors. The paper evaluates that hypothesis through published hydrologic evidence, a spatial design framework, and engineering interpretation of recent SWMM-based case studies.

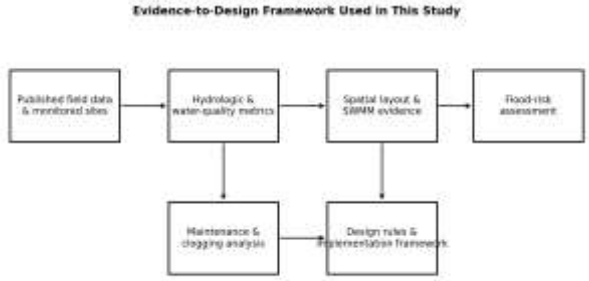


Fig. 1. Evidence-to-design framework adopted in this paper. Field observations are combined with hydrologic metrics, spatial-layout evidence, maintenance analysis, and flood-risk design rules.

II. OBJECTIVES AND RESEARCH CONTRIBUTIONS

The first objective is to quantify the practical stormwater benefits that have been observed at full-scale or pilot-scale permeable-pavement installations. Key outcomes include event runoff reduction, peak-flow attenuation, infiltration behavior, time-to-peak effects, and selected water-quality responses. Because reported performance spans a wide range, the analysis focuses not only on average values but also on the site characteristics responsible for high or low performance.

The second objective is to assess how spatial urban layout changes the value of permeable pavement. The paper considers distributed placement, treatment at runoff-source areas, targeted placement in low-lying subcatchments, and combinations of permeable pavement with rain gardens and green roofs. Recent spatial optimization studies show that the most effective layout is rarely a uniform percentage applied everywhere; location-specific matching is more robust because land use, topography, drainage bottlenecks, and storm intensity differ across the urban landscape.

The third objective is to convert the evidence into a design workflow that can be applied during new development or retrofit planning. The proposed workflow links site screening, infiltration testing, storage sizing, contributing-area ratios, SWMM representation, exceedance routing, maintenance planning, and performance verification. The resulting contribution is therefore both analytical and practical: it explains why permeable pavement works, where it is most useful, and how it should be coordinated with the surrounding street and drainage layout.

III. PERMEABLE PAVEMENT AS A STORMWATER SYSTEM

A. System Components and Flow Paths

A permeable-pavement system is best understood as a layered hydraulic structure rather than a porous surface alone. Typical configurations contain a permeable wearing course or pavers, a bedding or choker layer, an open-graded aggregate reservoir, a separation layer where required, and the native subgrade. An optional underdrain may be placed at the bottom of the reservoir or elevated above the base to create an internal water-storage zone. During rainfall, the surface transmits water into the reservoir. The reservoir attenuates the inflow hydrograph by temporarily storing water and releasing it by infiltration or drainage at a slower rate.

Three surface technologies dominate practice: porous asphalt, pervious concrete, and permeable interlocking concrete pavement (PICP). Pervious concrete and porous asphalt achieve permeability through connected voids in the material matrix, whereas PICP depends on openings or joints filled with clean aggregate. Grid systems, reinforced turf, and resin-bound permeable surfaces are also used. The hydraulic behavior of each system depends on both surface infiltration and the capacity of the deeper storage and soil layers; very high surface permeability does not prevent flooding if the reservoir is undersized or the subgrade and underdrain cannot release stored water between storms.

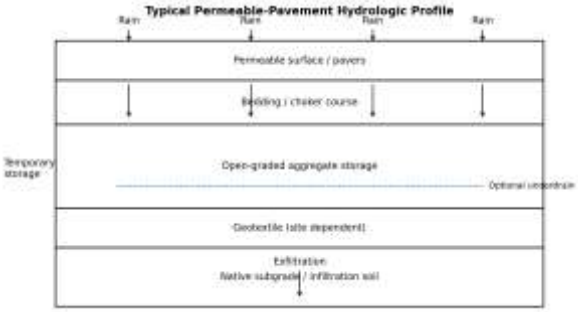


Fig. 2. Typical permeable-pavement section showing the surface, aggregate reservoir, optional underdrain, and exfiltration pathway.

B. Governing Hydrologic Relationships

At event scale, the storage layer can be represented by a continuity relationship in which the change in stored water equals inflow minus all loss and outflow pathways. A simplified form is

$$dS/dt = Q_in - Q_exf - Q_drain - Q_over - E$$

where S is water stored in the pavement profile, Q_in is direct rainfall plus routed inflow from contributing impervious surfaces, Q_exf is exfiltration to native soil, Q_drain is controlled underdrain discharge, Q_over is overflow or surface bypass, and E is evaporation. Flood mitigation is achieved when the system temporarily holds enough water to reduce and desynchronize Q_over and Q_drain relative to the baseline impervious runoff hydrograph.

For preliminary sizing, the net storage volume provided by an aggregate reservoir may be estimated from its plan area, thickness, and effective void ratio:

$$V_s = A_p d_s n_e$$

where V_s is effective storage volume, A_p is permeable-pavement area, d_s is storage-layer thickness, and n_e is drainable void ratio. For systems receiving runoff from adjacent impervious surfaces, the hydraulic loading ratio is especially important:

$$LR = A_c / A_p$$

where A_c is the connected contributing impervious area. A high LR can make efficient use of limited permeable surface, but it also increases sediment loading and raises the probability that storage is exhausted during high-intensity events. Great Lakes guidance summarized by the U.S. Geological Survey notes that loading ratio, drawdown rate, and underlying soil permeability are major controls on whether events are fully captured.

TABLE I. TYPICAL PERMEABLE-PAVEMENT SYSTEMS AND HYDROLOGIC ROLES

System	Primary inflow route	Main storage mechanism	Typical urban use	Key vulnerability
Porous asphalt	Through connected surface voids	Open-graded stone reservoir	Parking, local roads	Clogging by fines; binder aging
Pervious concrete	Through cementitious pore network	Stone reservoir + slab voids	Parking, sidewalks, plazas	Surface raveling; clogging; high pH leachate

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				early in life
PICP	Through aggregate-filled joints	Bedding and stone reservoir	Streets, parking, courtyards	Joint sediment accumulation
Grid pavement	Open cells / vegetated or aggregate fill	Cell voids + subbase	Overflow parking, low-speed areas	Vegetation wear or fill clogging

IV. LITERATURE REVIEW AND FIELD EVIDENCE

A. Long-Term and Multi-Site Hydrologic Performance

One of the foundational field studies is Brattebo and Booth's six-year evaluation of four commercial permeable-pavement systems. The installations remained structurally serviceable and infiltrated virtually all rainfall with very little surface runoff. Their work is important because it demonstrates that high infiltration can persist under real parking use when systems are properly constructed and maintained. It also established that permeable pavement can modify water quality, with infiltrated water showing lower copper and zinc concentrations than direct asphalt runoff and no detected motor oil in the infiltrated samples reported by the study.

Bean, Hunt, and Bidelspach subsequently surveyed surface infiltration at 40 permeable-pavement sites in several U.S. states. Their results showed that infiltration capacity is not a fixed material property: it reflects age, construction quality, sediment exposure, and maintenance condition. At 15 concrete-grid-paver sites, removal of the upper 13–19 mm of residual material significantly improved infiltration. This field evidence supports a maintenance-centered interpretation of long-term hydraulic reliability.

Collins, Hunt, and Hathaway monitored four permeable-pavement types and a conventional asphalt section in Kinston, North Carolina. The test parking lot included pervious concrete, two PICP surfaces with different open-area percentages, and concrete grid pavers, each with a crushed-stone base and underdrain over poorly drained soil. The permeable sections substantially reduced surface runoff volume and peak flow relative to asphalt. Differences among permeable systems were linked not only to surface type but also to underdrain elevation, storage volume, and the water-retention behavior of joint or fill media. This result is particularly relevant to urban layout design: subsurface configuration can compensate for unfavorable native soil if the reservoir and drainage details are engineered intentionally.

The University of New Hampshire Stormwater Center monitored porous asphalt in a cold climate from 2004 to 2008. The pavement remained functional despite frost penetration and subfreezing conditions. Reported mean infiltration capacity remained very high, and peak flow was reduced by approximately 90%, from a reference impervious-cover value of about 5.5 m3/s/km2 to about 0.58 m3/s/km2. The cold-climate study is valuable because it contradicts the assumption that permeable pavement is inherently unsuitable where freezing occurs; the reservoir's drainage condition and void structure can prevent the standing water that would otherwise cause freeze-related hydraulic failure.

A broad U.S. Geological Survey synthesis of Great Lakes green infrastructure reported that permeable-pavement sites initially captured and reduced stormwater at every installation reviewed. Across studies, stormwater-volume reduction ranged from roughly 13% to nearly 99%, and some installations completely captured as many as 80% of monitored storm events. The wide range reinforces the need for site-specific assessment. Four northern Ohio installations showed volume reductions around 16–32%, while the fraction of fully captured events varied from approximately 4% to 80%. Loading ratio, drawdown, storage details, rainfall characteristics, and maintenance were identified as major controls.

The Madison, Wisconsin, test facility provides additional evidence under intentionally high sediment loading. Three 500-ft2 test plots—porous asphalt, pervious concrete, and PICP—received runoff from an adjacent conventional asphalt parking area. The facility was designed to measure influent, underdrain discharge, and bypass. Sediment capture progressively reduced surface infiltration, increasing bypass over time, but maintenance partially restored hydraulic function. This demonstrates an important operational reality: permeable pavement may remain structurally intact while its flood-reduction performance degrades because of surface clogging.

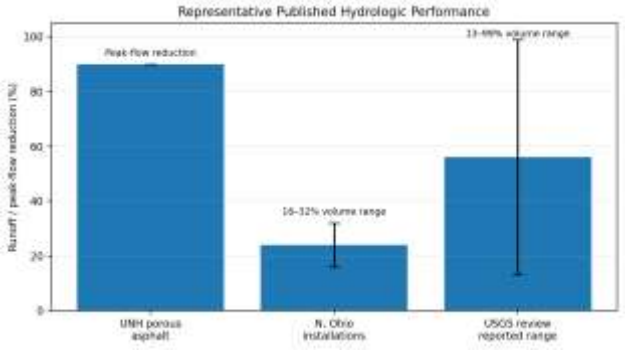


Fig. 3. Representative published hydrologic performance values. The Great Lakes value is shown as an approximate midpoint with the reported 13–99% range; northern Ohio installations reported about 16–32% event-volume reduction; the UNH porous-asphalt case reported about 90% peak-flow reduction.

TABLE II. REAL-WORLD EVIDENCE USED IN THIS PAPER

Study / location	Scale and period	Relevant measured or modeled outcome	Use in this paper
Brattebo & Booth, USA	4 commercial systems; 6 years	Virtually all rainfall infiltrated; long-term durability and water-quality observations	Long-term field benchmark
Kinston, North Carolina	4 permeable types + asphalt; 2006–2007	Large reductions in surface runoff and peak flow; design differences affected outflow	Material and reservoir comparison
UNH, New Hampshire	Porous asphalt; 2004–2008	~90% peak-flow reduction; cold-climate hydraulic resilience	Extreme climate benchmark
Madison, Wisconsin	3 × 500 ft² plots	Clogging reduced infiltration; maintenance restored part of function	Maintenance and sediment loading
Northern Ohio	4 parking-lot installations	~16–32% volume reductions; 4–80% of events fully captured	Loading ratio / drawdown evidence
Older community, China, 2026	7 subcatchments, 59 nodes; SWMM + observed 2024 storms	~59% runoff reduction; ~79% TSS-load reduction; optimized placement	Primary urban-layout case
White Oak Bayou, Houston	155 subcatchments; >500 SWMM configurations	LID siting performance controlled by storm, catchment, storage time scales	Spatial and temporal scaling interpretation

B. Water Quality and Pollutant Fate

Permeable pavements modify stormwater quality through filtration, sedimentation, sorption, precipitation, and biological processes in the surface and reservoir layers. Reported benefits are strongest for suspended solids, many metals, and petroleum hydrocarbons. The

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U.S. EPA review of green infrastructure cites field studies in which permeable systems reduced sediment-associated contaminants, and it notes microbial degradation of hydrocarbons within pavement profiles. Drake and coauthors reported that three partial-infiltration systems reduced total suspended solids by more than 80% and achieved substantial removal of several heavy metals compared with conventional asphalt.

Nutrient behavior is less uniformly positive. Aerated aggregate layers promote nitrification, so ammonium may decline while nitrate can increase. Concrete-based systems may raise pH, which can enhance precipitation of some metals and phosphorus but can also alter effluent chemistry. This variability is important when permeable pavement is used near sensitive groundwater or when infiltrated runoff contains road salts, nutrients, or dissolved contaminants. Flood-risk benefits should therefore be paired with source control and site screening rather than assuming that infiltration always improves all water-quality constituents.

For flood-resilient urban design, TSS is especially relevant because suspended sediment contributes to surface clogging. A layout that intentionally routes large dirty catchments onto a small permeable area may provide early hydraulic benefit but can accelerate clogging and shorten the maintenance interval. Sediment pretreatment, inlet design, periodic vacuuming, and avoiding winter sand application directly onto permeable surfaces are therefore part of the hydrologic design, not merely housekeeping measures.

C. Maintenance, Clogging, and Recovery

Clogging usually initiates near the pavement surface because coarse and fine particles accumulate at the runoff–pavement interface and within the upper pore network. The recent review by Singer and coauthors notes that clogging effects are concentrated largely within the upper 1.5–2.5 cm in many systems, which is why surface-focused maintenance can be effective. Vacuum sweeping, regenerative-air cleaning, pressure washing, or removal and replacement of joint aggregate are commonly used depending on pavement type.

The Madison test facility illustrates the mechanism clearly: as sediment capture increased, more water bypassed the permeable surfaces. Maintenance improved infiltration, but the degree of recovery differed among porous asphalt, PICP, and pervious concrete. From a flood-risk perspective, maintenance is therefore a design parameter. A municipality that cannot reliably access or clean a surface should apply conservative long-term infiltration values, lower contributing-area ratios, and provide safe overflow routes.

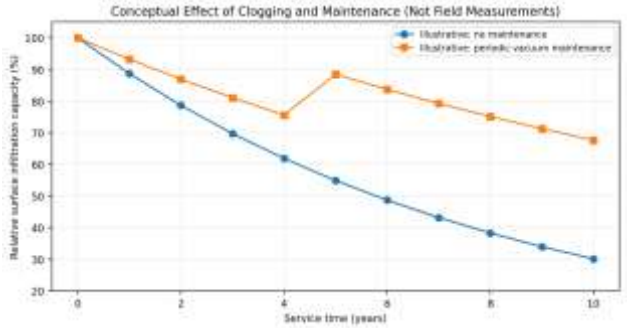


Fig. 7. Conceptual—not measured—illustration of how clogging can reduce infiltration capacity and how periodic maintenance can partially restore hydraulic function. Actual rates are site-specific.

V. URBAN LAYOUT AND DISTRIBUTED FLOOD CONTROL

A. Why Spatial Position Matters

At city scale, permeable pavement changes both runoff volume and hydrograph timing. If placed near runoff sources, it can disconnect impervious surfaces before water enters the pipe system. If concentrated downstream, it may intercept a large contributing area but can fill early and then pass through later runoff with limited attenuation. The relative timing of treated and untreated subcatchments can either decrease or increase coincidence of hydrograph peaks at the outlet. This is why spatial optimization studies sometimes report different preferred locations for the same total LID area.

A 2025 Water Resources Research study by Castro, Hung, and Sivapalan framed this behavior through three characteristic times: rainfall duration, catchment time of concentration, and LID storage time. Their White Oak Bayou case used a high-resolution SWMM representation with 155 subcatchments and more than 500 LID configurations. The analysis showed that peak-flow mitigation depends on interactions among storm size, catchment response, storage capacity, and spatial location rather than on LID area alone. This provides a process explanation for why simple 'percent green infrastructure' targets do not reliably predict flood reduction.

A practical layout should therefore combine distributed source treatment with targeted capacity at known bottlenecks or low points. Distributed elements reduce the amount of runoff entering the network and increase spatial desynchronization. Targeted elements protect areas where topography concentrates water or where pipe capacity is insufficient. A third layer—safe exceedance routing—recognizes that permeable pavement cannot economically absorb every extreme storm. Streets, parks, swales, and designated flow corridors should convey residual floodwater without directing it toward buildings or critical infrastructure.

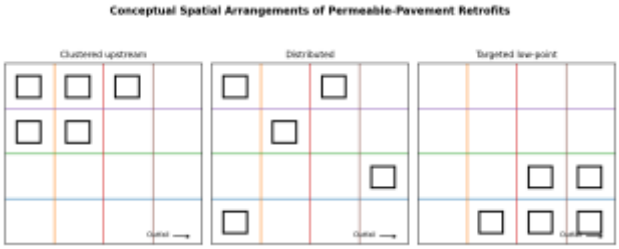


Fig. 4. Conceptual examples of clustered, distributed, and low-point-targeted permeable-pavement layouts. Squares represent permeable retrofits within a simplified street grid.

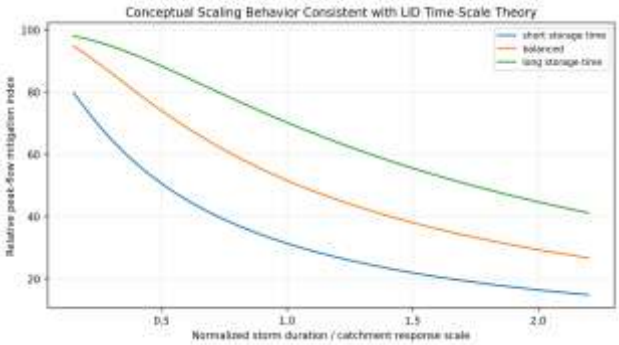


Fig. 9. Conceptual illustration of LID time-scale behavior. The plotted curves are explanatory rather than extracted from the White Oak Bayou study; they show why storage duration relative to storm and catchment response can change peak-flow benefit.

B. Layout Performance Metrics

For consistent comparison, four principal performance metrics are used in this paper. Event runoff reduction is

$$R_V = 100 (V_{base} - V_{LID}) / V_{base}$$

where V_base and V_LID are event runoff volumes for the baseline and LID cases. Peak-flow reduction is

$$R_Q = 100 (Qp_{base} - Qp_{LID}) / Qp_{base}$$

A water-quality load reduction for constituent j is

$$R_{M,j} = 100 (M_{base,j} - M_{LID,j}) / M_{base,j}$$

For urban flood analysis, these measures should be supplemented by node-flood volume, flood duration, maximum ponding depth, number of flooded nodes, and exposure of buildings or roads. A layout that achieves excellent total runoff reduction but leaves one critical underpass deeply flooded may not be acceptable. Multi-

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objective optimization is therefore more appropriate than a single runoff-volume objective.

TABLE III. SPATIAL LAYOUT STRATEGIES AND EXPECTED HYDROLOGIC EFFECTS

Layout strategy	Primary mechanism	Strength	Potential weakness
Uniform percentage	Applies similar PP fraction across subcatchments	Simple policy and costing	Ignores local topography and bottlenecks
Distributed source control	Intercepts runoff close to generation	Reduces connected imperviousness; desynchronizes flow	Requires many assets and maintenance points
Low-point targeted	Adds storage where runoff converges	Strong local waterlogging benefit	May receive high sediment and hydraulic loading
Downstream clustered	Large facility near outlet or trunk drainage	Easy access; centralized management	Can fill early; timing may reduce outlet benefit
Hybrid blue-green	PP combined with rain gardens/green roofs/storage	Multiple pathways and redundancy	Higher planning complexity

VI. DATA AND METHODOLOGY

A. Study Design and Data Provenance

This paper is a secondary-data research synthesis and engineering assessment. It does not claim that new field monitoring was performed by the author of this manuscript. Numerical values labeled as published results are taken from peer-reviewed papers or agency syntheses. Original figures in this manuscript are redrawings or comparative plots created from reported values, not copied proprietary figures. Conceptual figures and evidence-informed suitability scores are explicitly identified as conceptual. This distinction is essential for research integrity because it separates measured evidence from interpretation and design guidance.

The empirical evidence base was selected to cover diverse climatic and design contexts: temperate and cold-climate systems, poorly drained native soil with underdrains, multiple pavement types, long-term operation, high sediment loading, and city-scale spatial optimization. The 2026 older-community study was selected as the primary layout case because it resolves LID placement at subcatchment scale and evaluates runoff, flooding, and TSS under both a 20-year design storm and observed rainfall events from 7 May and 17 August 2024.

The White Oak Bayou study provides complementary watershed-scale evidence. Its baseline SWMM model used high-resolution terrain and land-cover data and represented 155 subcatchments. More than 500 model configurations were used to examine LID performance across storms and siting patterns. While its focus is broader than permeable pavement alone, the study is valuable for interpreting when distributed stormwater storage changes peak flow at a watershed outlet.

B. Comparative Assessment Procedure

The assessment proceeds in five stages. First, monitored pavement studies are summarized to establish realistic bounds on infiltration, runoff reduction, and maintenance sensitivity. Second, the 2026 urban-retrofit case is analyzed to quantify how optimized LID distribution changes runoff and water quality at community scale. Third, spatial effects are interpreted using the time-scale logic of the White Oak Bayou work. Fourth, performance is mapped to practical design variables: loading ratio, storage depth, underdrain configuration, native-soil infiltration, terrain position, and maintenance access. Finally, the findings are converted into a screening and design workflow for municipalities and consulting engineers.

Because the primary studies use different climates, event definitions, pavement areas, and monitoring methods, the paper does not pool all data into a single statistical meta-analysis. Instead, results are treated as bounded field evidence. Reported ranges are preserved and the reasons for variation are examined qualitatively. This approach is more defensible than computing a simple grand mean from non-comparable sites.

TABLE IV. CORE ASSESSMENT VARIABLES

Category	Variable	Engineering interpretation
Hydrology	Runoff-volume reduction	Amount of rainfall retained, infiltrated, or evaporated
Hydrology	Peak-flow reduction	Stress reduction on downstream pipes and channels
Hydrology	Time to peak / drawdown	Hydrograph desynchronization and readiness for next storm
Flooding	Node flood volume / duration	Local drainage-network failure and exposure
Water quality	TSS concentration and load	Sediment control and clogging relevance
Geometry	Loading ratio (Ac/Ap)	Hydraulic and sediment stress on the pavement
Subsurface	Storage depth / void ratio	Temporary detention capacity
Operations	Surface infiltration after aging	Long-term rather than initial performance
Spatial	Location relative to low points / network	Ability to treat source runoff or relieve bottlenecks

VII. CASE STUDY 1: 2026 OLDER-COMMUNITY LID LAYOUT OPTIMIZATION

The recent study by Zhang, Wu, Kong, and Zhu provides a useful example of how permeable pavement can be embedded within a broader urban layout rather than evaluated as an isolated parking-lot material. The study focused on an older urban community characterized by high imperviousness, drainage limitations, and waterlogging. Its SWMM representation comprised seven subcatchments, 59 nodes, 59 conduits, and one outfall. Land cover was divided into building roofs, green space, and impervious surfaces. The candidate LID practices were green roofs, rain gardens, and permeable pavements.

The optimization combined NSGA-II with SWMM to generate Pareto-optimal trade-offs among construction cost, runoff reduction, and TSS-load reduction. The selected solutions were then refined through an iterative exhaustive-search process to translate continuous theoretical LID areas into specific feasible retrofit locations. This refinement is particularly important for real urban design because available roofs, courtyards, green strips, and paved surfaces are discrete physical objects rather than continuous optimization variables.

Across the three final solutions, green roofs occupied about 70% of available roof area, rain gardens approximately 98–100% of available green space, and permeable pavements roughly 69–70% of suitable impervious area. The three solutions produced very similar hydrologic outcomes: stormwater runoff reductions of approximately 58.85–59.30% and TSS-load reductions of approximately 79.11–79.51%. The stability of these solutions indicates that a near-optimal spatial pattern can be robust even when exact percentages vary slightly.

The spatial result was not uniform. Permeable-pavement allocation shifted toward the western part of the southern sector, where topography created a low-lying runoff convergence area. This is a strong example of location-specific matching: the optimization placed more infiltration and storage where hydrologic need was greatest rather than distributing all practices evenly. The result supports the central argument of this paper that urban layout is a first-order design variable for flood mitigation.

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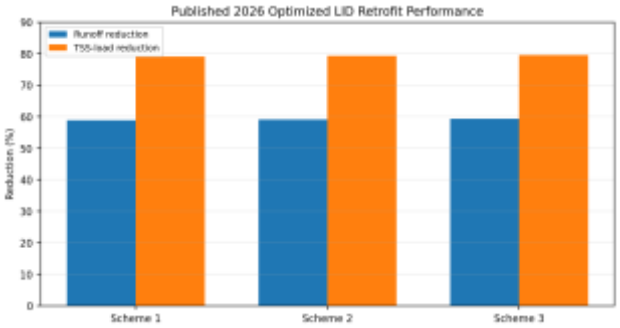


Fig. 5. Published performance range of the three optimized 2026 retrofit solutions. Values are based on the study's reported runoff- and TSS-load-reduction ranges.

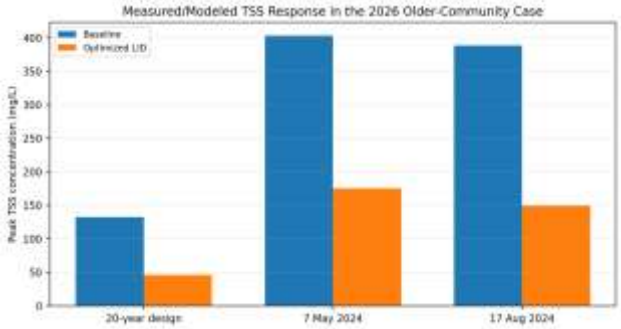


Fig. 6. Peak TSS concentration before and after optimized LID implementation in the 2026 urban-community case. The 20-year storm value uses the best reported scheme; the two 2024 events are reported observed-rainfall simulations.

TABLE V. KEY CHARACTERISTICS OF THE 2026 URBAN-LAYOUT CASE

Item	Reported value / description
Hydrologic model	EPA SWMM 5.2
Drainage representation	7 subcatchments, 59 nodes, 59 conduits, 1 outfall
LID practices	Green roofs, rain gardens, permeable pavements
Optimization	NSGA-II + AHP + iterative exhaustive spatial refinement
Green-roof coverage	~69.89–70.06% of available roof area
Rain-garden coverage	~97.93–100% of available green space
Permeable-pavement coverage	~69.28–70.00% of suitable impervious area
Runoff reduction	~58.85–59.30%
TSS-load reduction	~79.11–79.51%
Validation events	20-year design storm and observed 7 May / 17 Aug 2024 rainfall

TABLE VI. PUBLISHED TSS RESPONSE IN THE 2026 CASE

Rainfall case	Baseline peak TSS (mg/L)	Optimized peak TSS (mg/L)	Approx. reduction
20-year design storm	132.22	45.72	65.4%
7 May 2024 observed event	402.92	175.05	56.6%
17 Aug 2024 observed event	388.24	149.43	61.5%

A. Peak-Flow and Waterlogging Effects

The study reported peak-flow reductions exceeding 33% for the design storm and more than 47% during the observed rainfall events. At the node level, the pre-retrofit drainage system had many locations with waterlogging lasting more than one hour. After LID implementation, the majority of nodes shifted to flooding durations below 0.5 h, with only a small fraction retaining longer inundation. This demonstrates why outlet-only metrics are insufficient: a layout can be evaluated by how it redistributes and shortens local flood duration as well as by its total runoff reduction.

The mechanism is consistent with distributed-storage theory. Permeable pavement and other LID practices capture the early part of the event, reduce inflow to pipes, and lower the probability that multiple upstream subcatchments simultaneously exceed conduit capacity. Where the pavement is located near low points, it also acts as a local buffer that absorbs runoff before it accumulates as deep street ponding. During extreme or long-duration storms, the storage eventually approaches capacity, but the delayed and reduced inflow can still shorten the period during which downstream nodes remain surcharged.

B. Water-Quality Response

The 2026 case also modeled TSS. Under the 20-year design storm, the peak TSS concentration decreased from a baseline of 132.22 mg/L to 45.72 mg/L in the strongest of the three solutions, corresponding to a reduction of approximately 65.4%. For the observed 7 May 2024 event, peak concentration fell from 402.92 to 175.05 mg/L, and for the 17 August 2024 event from 388.24 to 149.43 mg/L. These results show that spatially distributed LID can simultaneously reduce hydraulic load and sediment-associated pollution.

From a permeable-pavement operations perspective, the TSS benefit also has a maintenance implication: particles removed from runoff do not disappear; a portion is retained within or near treatment media. Consequently, designs that achieve high TSS removal need planned sediment removal if long-term infiltration is to be preserved. High pollutant-capture performance and surface clogging are two sides of the same filtration process.

VIII. CASE STUDY 2: WHITE OAK BAYOU AND THE IMPORTANCE OF TIME-SCALE MATCHING

Castro, Hung, and Sivapalan used White Oak Bayou in Houston as a real-world watershed for a predictive LID planning framework. Terrain, land cover, hydrologic soil groups, and drainage geometry were used to build a detailed SWMM model. The watershed was divided into 155 subcatchments, and more than 500 combinations of LID siting and storm characteristics were evaluated. The study introduced a normalized efficiency framework based on rainfall duration, catchment response time, and LID storage time.

For permeable pavement, the practical interpretation is straightforward. If a storm fills the available pavement storage well before the watershed peak develops, then the pavement behaves increasingly like a pass-through system for the latter part of the event and offers less peak attenuation. If storage persists through the period when untreated subcatchments are peaking, the pavement can materially lower the combined outlet peak. The ideal spatial location therefore changes with storm duration, network travel time, and available storage.

This helps explain apparently conflicting statements in the literature about whether upstream, downstream, centralized, or distributed LID is best. There is no universally optimal position independent of the event and catchment. The more reliable planning rule is to match storage time and location to the runoff timing of the subcatchments being treated. For routine storms, widespread source control often maximizes volume capture. For larger storms, additional low-point storage, offline detention, and robust conveyance paths are needed.

IX. COMPARATIVE RESULTS AND ENGINEERING INTERPRETATION

A. What the Field Data Demonstrate Reliably

Across the field evidence, the strongest consistent finding is that permeable pavement can nearly eliminate surface runoff for many small and moderate events when the surface remains permeable and subsurface storage is not saturated. This has been observed under different pavement technologies and climates. The second consistent finding is that performance degrades as contributing area, storm magnitude, or sediment loading increases. The third is that reservoir and underdrain design can be as important as pavement type. An elevated underdrain, for example, creates

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additional temporary storage and increases retention even where native soil infiltration is limited.

Published values should therefore be interpreted as a performance envelope rather than a universal efficiency. A 90% peak reduction in the UNH porous-asphalt study is a credible monitored value for that system and hydrologic setting, but it should not be transferred directly to every urban street. Conversely, the 16–32% volume reductions reported at four northern Ohio installations should not be treated as an upper limit; those systems had specific loading ratios, soils, and drainage characteristics. The broad 13–99% range in the Great Lakes synthesis is precisely what would be expected when site design varies substantially.

The urban-layout evidence adds a fourth conclusion: flood risk is reduced most efficiently when LID area is located according to drainage function. The 2026 community study directed permeable pavement toward a low-lying runoff convergence zone and obtained roughly 59% runoff reduction at system scale. This does not mean that 70% permeable coverage is always required. It means that layout, land-use availability, and multi-practice integration can convert high LID coverage into coordinated drainage-system benefit.

B. Effect of Contributing-Area Ratio

The ratio of impervious contributing area to permeable-pavement area determines both hydraulic demand and sediment exposure. A very low ratio means the pavement mainly manages rainfall falling directly on itself; this is hydraulically reliable but may use valuable surface area inefficiently. A moderate ratio allows one permeable strip or parking bay to treat adjacent conventional pavement. A high ratio can overload storage and accelerate clogging, particularly where runoff carries road grit, soil, leaf litter, or construction sediment.

For conceptual design, engineers should therefore size both storage and treatment area. If the contributing impervious area is Ac and design rainfall depth is P, the gross inflow volume can be approximated as C P Ac, where C is an event runoff coefficient. The pavement reservoir plus infiltration during the storm must be large enough to absorb the desired portion of that volume. A useful screening inequality is

$$A_p\, d_s\, n_e + f_s\, A_p\, t_r \geq \eta\, C\, P\, A_c \quad (7)$$

where f_s is a conservative saturated exfiltration rate, t_r is storm duration, and η is the target capture fraction. The expression is intentionally simple and does not replace dynamic simulation, but it makes the trade-off explicit: higher loading ratio must be compensated by deeper storage, faster infiltration, longer available drawdown, or a lower capture target.

C. Soil and Underdrain Effects

Native soil does not determine whether permeable pavement is possible; it determines which configuration is appropriate. Highly permeable soil favors full infiltration and groundwater recharge. Slowly permeable or clayey soil may require an underdrain, but meaningful peak and volume reductions are still possible if the stone reservoir provides detention and the underdrain is throttled or elevated. Impermeable liners are appropriate where contaminated soils, karst concerns, high groundwater, or structural constraints make exfiltration undesirable; in those cases, the pavement functions primarily as a subsurface detention and filtration system.

This distinction is important for urban flood retrofits. A city should not map 'poor soil' as an automatic exclusion for all permeable pavement. Instead, it should map the appropriate hydraulic mode: infiltration, partial infiltration, lined detention, or no infiltration. The choice should be coordinated with groundwater protection and foundation setback requirements.

TABLE VII. DESIGN RESPONSE TO SITE CONDITIONS

Site condition	Recommended hydraulic configuration	Primary objective
High-permeability soil; deep groundwater	Full infiltration, no underdrain if feasible	Runoff-volume reduction and recharge
Moderate soil infiltration	Partial infiltration with elevated underdrain	Volume reduction + peak attenuation
Low-permeability clay	Deep reservoir + throttled underdrain	Detention and peak attenuation
Contaminated soil / groundwater constraint	Lined system with underdrain	Detention and filtration without recharge
High sediment load	Pretreatment + conservative loading ratio + frequent cleaning	Maintain infiltration and avoid bypass
Critical low point	Permeable pavement + overflow inlet + safe exceedance route	Local flood-depth reduction and resilience

X. DESIGNING THE URBAN LAYOUT FOR FLOOD MITIGATION

A. Source Control and Disconnection

The first layout principle is to reduce directly connected impervious area. Rooftops, sidewalks, parking aisles, and local streets often discharge into curb-and-gutter systems that rapidly connect rainfall to trunk drainage. Permeable parking bays, curb extensions, and porous sidewalks can interrupt these connections. Even when the pavement does not retain all water, the travel pathway changes from rapid surface conveyance to temporary subsurface storage and slower release.

Source control is particularly effective for frequent storms because storage is empty at the start of many events and rainfall depths are small enough to be captured fully. Benefits include lower runoff frequency, reduced first-flush pollutant loads, and decreased frequency of small pipe surcharges. These routine-event benefits accumulate over the year even if extreme design storms exceed the capacity of individual LID units.

B. Targeting Topographic Low Points and Bottlenecks

The second principle is strategic reinforcement of low-lying and hydraulically constrained locations. The 2026 case explicitly shifted permeable pavement toward a depression where runoff converged. Similar logic can be applied using digital elevation models, observed flood complaints, CCTV inspection, hydraulic grade-line modeling, or 2D surface-flow results. Low-point treatments should have generous overflow capacity because they receive runoff from larger areas and are therefore more likely to be exceeded during intense storms.

Targeted low-point pavement should not be designed as the sole emergency drainage solution. Instead, it should reduce the depth and duration of ponding while an overflow inlet, swale, or surface corridor safely conveys excess water. The system then follows a 'retain what is practical, route what exceeds capacity' philosophy.

C. Distributed versus Clustered Placement

Distributed placement increases the probability that runoff is intercepted before synchronization in the pipe network, but it increases the number of assets that require inspection and maintenance. Clustered placement simplifies operations and can exploit deeper shared storage, but it may be hydraulically overloaded and may not protect upstream nuisance-flood locations. A hybrid approach is often best: distributed permeable pavement for ordinary runoff, plus strategically larger storage or bioretention at convergence points.

The correct balance should be tested dynamically. SWMM can represent pavement surface storage, pavement layers, reservoir storage, exfiltration, and underdrains. For highly flood-prone sites, 1D sewer modeling should be coupled with 2D surface routing or a model that can represent street inundation. This is necessary because the benefit of permeable pavement is ultimately measured by changes in depth, duration, velocity, and exposure—not only by runoff at a single outfall.

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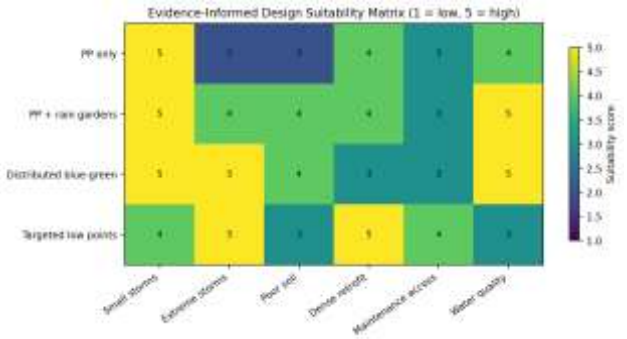


Fig. 8. Evidence-informed suitability matrix for common layout strategies. Scores are engineering synthesis values, not measured performance data.

TABLE VIII. LAYOUT DECISION MATRIX FOR PRACTICE

Planning question	Preferred response when answer is "yes"
Is nuisance flooding concentrated at identifiable low points?	Add targeted permeable storage plus safe overflow routing.
Are many small impervious surfaces directly connected to drains?	Use distributed pavement strips/bays to disconnect sources.
Is native soil infiltration poor?	Use underdrained or lined detention-style permeable pavement.
Is sediment loading high?	Reduce loading ratio; add pretreatment and accessible vacuum-cleaning zones.
Is extreme-storm protection required?	Combine PP with larger detention, open-space storage, and exceedance corridors.
Is maintenance capacity limited?	Use fewer accessible assets, conservative infiltration assumptions, robust overflow.

XI. CLIMATE RESILIENCE AND EXTREME STORMS

Permeable pavement is often criticized because any finite storage can be overwhelmed. That criticism is correct but incomplete: all drainage infrastructure has a finite design capacity. The question is whether the pavement reduces consequences across a useful range of storms and fails safely when its capacity is exceeded. For frequent and moderate events, well-designed permeable pavement can capture large fractions of runoff. For rare extreme events, its residual storage at the start of the storm, continued infiltration, and delayed drainage still reduce the rate at which water reaches the sewer system, although the percentage reduction generally declines as rainfall depth and intensity increase.

Climate resilience therefore requires a hierarchy of controls. Level 1 is source absorption through permeable surfaces, green roofs, and soils. Level 2 is distributed detention in pavement reservoirs, rain gardens, and underground storage. Level 3 is controlled conveyance through streets, drains, and channels. Level 4 is floodable open space or regional storage for exceptional events. A resilient urban layout does not expect one level to perform the function of all four.

Future rainfall uncertainty should be addressed through stress testing rather than a single design event. At minimum, simulations should include frequent water-quality storms, the local drainage-design return period, a larger exceedance event, and sensitivity cases with reduced infiltration to represent clogging. If the development is critical, nonstationary rainfall allowances or climate-adjusted intensity-duration-frequency curves should also be considered where authoritative local projections are available.

XII. MAINTENANCE AND LIFE-CYCLE PERFORMANCE

The hydraulic life of permeable pavement depends on preventing fine sediment from sealing the surface. Construction-phase protection is especially important because a new pavement can be damaged before it is commissioned if bare-soil runoff is allowed to cross it. Upgradient landscaping should be stabilized, stockpiles should be isolated, and conventional winter sand should be avoided where possible. Maintenance plans should specify inspection frequency, acceptable infiltration thresholds, vacuum equipment, joint-material replacement procedures, and responsibility for record keeping.

A useful maintenance program is performance based. Rather than cleaning only on a fixed calendar, agencies can combine scheduled preventive cleaning with periodic infiltration testing. Locations near tree pits, construction access, intersections, or high-sediment drainage paths may need more frequent attention. Where one pavement strip receives runoff from conventional asphalt, the boundary between surfaces is often a critical deposition zone and should be designed for easy cleaning.

Life-cycle assessment should also include underdrain inspection. A surface can remain permeable while a clogged outlet or saturated reservoir causes slow drawdown. Observation wells installed in the storage layer provide a simple method to verify whether water levels return to baseline between storms. Persistently high water levels indicate restricted exfiltration, underdrain blockage, groundwater interaction, or insufficient storage release.

TABLE IX. OPERATION AND MAINTENANCE PLAN

Asset / observation	Suggested action	Hydrologic reason
Surface sediment / joint clogging	Vacuum sweep or regenerative-air cleaning	Restores entry capacity and reduces bypass
Low measured infiltration	Targeted deep cleaning; replace joint aggregate if necessary	Recovers surface hydraulic conductivity
Standing water after storm	Check underdrain and observation well	Identifies reservoir drawdown failure
Upgradient bare soil / construction	Install sediment controls immediately	Prevents irreversible early-life clogging
Winter maintenance	Prefer low-sediment deicing strategy	Avoids sand-driven pore blockage
Overflow inlet	Remove debris and verify grate capacity	Ensures safe exceedance routing

XIII. ECONOMIC AND URBAN-PLANNING CONSIDERATIONS

Permeable pavement can be more expensive per square meter than conventional pavement, but direct unit-cost comparisons are incomplete because the system may replace or reduce other stormwater infrastructure. In constrained redevelopment sites, subsurface storage beneath parking or streets can avoid land acquisition for surface detention. Reduced pipe sizes, fewer inlets, lower detention volume, and compliance with stormwater regulations can partially offset pavement cost. The economic analysis should therefore compare complete drainage systems rather than surface materials alone.

The 2026 older-community study explicitly treated construction cost as an optimization objective and still selected substantial permeable-pavement coverage because runoff and pollution benefits justified distributed retrofits within the modeled trade space. This type of multi-objective planning is preferable to either minimizing cost without performance constraints or maximizing hydrologic benefit without considering implementability.

Urban-design co-benefits can further strengthen the business case. Permeable pavement can support traffic calming, parking-lane differentiation, plaza design, pedestrian comfort, and tree-root-zone water supply when correctly detailed. However, structural loading, accessibility, utility trenches, snow operations, and emergency vehicle routes must remain part of the design. A pavement that cannot meet structural or operational needs should not be selected merely for hydrologic benefit.

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XIV. PRACTICAL DESIGN WORKFLOW



Fig. 10. Recommended planning-to-operations workflow for permeable-pavement and urban-layout flood mitigation.

Step 1—Map hydrologic function. Delineate impervious surfaces, drainage inlets, subcatchments, major flow paths, depressed areas, and buildings at risk. Include observed flood complaints and high-water marks where available. The objective is to understand where runoff is produced, how quickly it reaches the network, and where it accumulates.

Step 2—Screen constraints. Test or estimate native-soil infiltration, groundwater depth, contamination risk, utility conflicts, pavement loading, frost conditions, and setbacks. Classify candidate areas as full-infiltration, partial-infiltration, lined, or unsuitable.

Step 3—Size storage and loading. Select permeable surface area, reservoir depth, void ratio, underdrain elevation, and contributing-area ratio. Use conservative long-term infiltration values rather than laboratory-clean values. Check inter-event drawdown so that storage is available for successive storms.

Step 4—Optimize spatial layout. Compare uniform, distributed, and targeted arrangements using SWMM or equivalent. Evaluate runoff volume, peak flow, node flooding, and where relevant water quality and groundwater impacts. If critical flood depths are important, couple sewer modeling with surface routing.

Step 5—Design exceedance pathways. Identify where water goes after pavement storage is full. Provide overflow inlets and surface routes that protect buildings, transport corridors, and emergency access. Confirm that the retrofit does not transfer risk downstream or to neighboring properties.

Step 6—Design maintenance and verification. Specify cleaning methods, access, monitoring points, infiltration tests, inspection intervals, and acceptance criteria. Post-construction testing should verify that the as-built system infiltrates and drains at rates consistent with design assumptions.

XV. DISCUSSION

A. Why Permeable Pavement Should Be Evaluated as Infrastructure, Not Material

A recurring error in permeable-pavement discussions is to compare only surface infiltration rates or compressive strength. Flood performance is a system property. A high-infiltration surface over a shallow saturated base can produce poor stormwater control, while a moderately permeable surface over a deep reservoir with well-designed underdrain control can substantially attenuate runoff. Similarly, a technically excellent pavement placed where it receives little runoff may have less flood benefit than a carefully sized system at a convergence zone.

The field literature supports this systems view. The Kinston study found hydrologic differences associated with storage and underdrain configuration. Northern Ohio observations linked full-event capture to loading ratio and drawdown. Madison demonstrated time-dependent deterioration from sediment loading. The 2026 urban case showed that moving permeable pavement to a low-lying sector improved spatial fit. Together, these findings argue against one-size-fits-all specifications based solely on pavement product type.

B. Interpreting Large Reported Performance Ranges

The 13–99% runoff-volume reduction range reported in the Great Lakes synthesis may appear too wide to be useful, but the range is informative because it quantifies the sensitivity of green infrastructure to context. High performance is associated with favorable storage-to-loading relationships, permeable native soils, adequate drawdown, and smaller events. Lower performance is expected when the pavement receives a large impervious drainage area, is installed over slowly draining soil without sufficient storage, or is partially clogged.

Design practice should therefore use ranges and scenario testing. A prudent model may include clean/initial, expected long-term, and degraded infiltration scenarios. If the drainage system remains safe under the degraded scenario, confidence in resilience is higher. If the design fails as soon as infiltration falls modestly, the system is maintenance-sensitive and requires either more storage, less contributing area, or stronger overflow infrastructure.

C. Permeable Pavement within a Treatment Train

The strongest layouts often combine permeable pavement with other controls. Green roofs reduce rooftop runoff before it reaches ground level. Rain gardens provide soil and vegetation processes that can complement the rapid hydraulic intake of permeable pavement. Tree trenches add evapotranspiration and root-zone storage. Offline detention or floodable parks provide capacity for larger storms. The 2026 optimization selected all three major LID types rather than relying solely on pavement, illustrating the value of complementary pathways.

Treatment-train design is also beneficial for maintenance. A vegetated strip or sediment forebay upstream of permeable pavement can reduce fine-particle loading. Conversely, pavement can spread and slow runoff before it enters a bioretention system. The sequence should be chosen based on space, contamination risk, maintenance access, and desired hydraulic response.

TABLE X. SYNTHESIZED DESIGN RECOMMENDATIONS

Issue	Recommendation	Evidence basis
Small / frequent storms	Prioritize distributed source-control PP	High event capture reported across many field sites
Large contributing area	Increase storage, lower LR, or add pretreatment	Northern Ohio loading-ratio findings; clogging evidence
Poor soil	Use partial infiltration / elevated underdrain	Kinston and other underdrained field systems
Cold climate	Design drainable base; avoid standing water	UNH multi-year cold-climate performance
Urban low point	Target PP plus reliable overflow	2026 spatial optimization and flood-duration results
Long-term reliability	Model degraded infiltration and maintain surface	Madison/Bean maintenance findings
Extreme storms	Integrate PP with conveyance and larger storage	Time-scale and exceedance logic from watershed modeling

XVI. LIMITATIONS

The principal limitation of this paper is that it synthesizes heterogeneous published case studies rather than reporting a new controlled field experiment at one location. The evidence spans different climates, pavement types, contributing-area ratios, soils, event definitions, and monitoring methods. Direct averaging of all performance values would therefore be misleading. The paper instead uses ranges and identifies the design variables responsible for differences.

The 2026 urban-layout case is model based, although it incorporates observed rainfall events and a calibrated/validated SWMM framework. Its optimized LID percentages should not be transferred directly to another city without local modeling. Similarly, the White Oak Bayou scaling study examines broader LID storage behavior and not only permeable pavement. Its

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contribution here is process interpretation rather than a universal pavement-specific performance factor.

Water-quality discussion emphasizes TSS and widely reported pollutants, but groundwater impacts can be site specific. Infiltration beneath high-traffic or contaminated areas may require pretreatment or lining. Cost data are also jurisdiction dependent and were not normalized across countries. Finally, long-term climate and maintenance uncertainty can materially change performance; future research should combine continuous monitoring, 2D flood modeling, deterioration models, and life-cycle cost analysis.

XVII. FUTURE RESEARCH DIRECTIONS

Future research should focus on long-duration monitoring that links hydraulic decline to measured sediment mass, land use, cleaning frequency, and changes in reservoir drawdown. Standardized datasets would improve transferability among cities. Digital inspection using street imagery, embedded moisture sensors, and low-cost water-level loggers could help agencies identify clogging or slow drainage before surface flooding becomes visible.

Spatial optimization should increasingly include failure and maintenance states. Most LID optimization assumes design infiltration remains constant. A more realistic framework would assign probability distributions to surface conductivity, underdrain performance, and antecedent saturation, then optimize layouts for expected service over decades rather than for a single clean-system simulation.

There is also a need for stronger integration between pavement engineering and urban flood modeling. Structural design determines layer thickness, material gradation, and compaction, all of which influence hydraulic storage and conductivity. Conversely, hydrologic requirements can affect base depth and underdrain location. Co-designing structural and hydraulic performance would reduce the risk of specifications that are excellent in one discipline but weak in the other.

TABLE XI. PRIORITY RESEARCH NEEDS

Research area	Priority question
Long-term field performance	How quickly does infiltration decline under specific sediment loads and maintenance regimes?
Urban layout	Which spatial patterns remain effective across multiple storm intensities and failure states?
Climate adaptation	How should storage and overflow capacity change under nonstationary rainfall?
Groundwater protection	When should infiltrating pavement be lined or pretreated?
Digital monitoring	Can low-cost sensing predict clogging and maintenance need?
Life-cycle economics	When do avoided pipes/detention and flood damages offset added pavement cost?

XVIII. CONCLUSIONS

Permeable pavement is a mature but strongly context-dependent stormwater technology. Real field monitoring shows that it can sharply reduce surface runoff and peak flow when the surface remains permeable and subsurface storage is matched to hydraulic loading. The New Hampshire porous-asphalt case reported approximately 90% peak-flow reduction, while broader Great Lakes evidence shows volume reductions ranging from about 13% to nearly 99%. Such variation is not contradictory; it reflects differences in loading ratio, storage, soil permeability, underdrain design, maintenance condition, and rainfall.

Urban layout is as important as pavement material. A square meter of permeable pavement has different flood-mitigation value depending on whether it disconnects a runoff source, relieves a low point, receives excessive contributing area, or alters hydrograph timing near the catchment outlet. Recent watershed-scale research demonstrates that storm duration, catchment response time, storage time, and spatial location jointly control peak-flow reduction.

The 2026 older-community case provides a strong contemporary example of layout-based design. An optimized combination of permeable pavement, rain gardens, and green roofs reduced runoff by about 59% and TSS loads by about 79%, while directing permeable pavement toward a low-lying convergence zone. The study also showed reduced long-duration node flooding and lower peak TSS concentrations during both a 20-year design storm and observed 2024 rainfall events.

For practice, permeable pavement should be designed as part of a hierarchical stormwater system: distributed source absorption for frequent events, targeted storage at bottlenecks and low points, larger detention or blue-green infrastructure for major storms, and safe exceedance routing for events that surpass design capacity. Long-term performance requires explicit sediment management, infiltration testing, underdrain inspection, and conservative modeling of degraded conditions.

The central conclusion is that permeable pavement does not mitigate urban flooding merely because it is porous. It mitigates flooding when its surface, reservoir, soil interface, drainage controls, contributing area, spatial location, maintenance program, and overflow pathways are coordinated as one system. Cities that apply this systems approach can use pavement areas that already exist—streets, parking, plazas, and walkways—as active components of flood-resilient urban infrastructure.

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