

Optimizing Urban Stormwater Management Using Low Impact Development: Hydrologic–Hydraulic Modelling for Flood Mitigation and Water Quality Improvement

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Abstract

Rapid urbanization replaces permeable landscapes with impervious surfaces, intensifying runoff peaks, shortening times of concentration, and degrading receiving-water quality. This paper evaluates the effectiveness of low impact development practices in mitigating pluvial flood risk and improving water quality in a dense Indian urban catchment. A coupled hydrologic–hydraulic modeling workflow was developed using event-based design storms and long-term continuous simulation to capture both peak-flow attenuation and pollutant load reduction. Candidate low impact development controls included bioretention cells, permeable pavements, green roofs, and roadside bioswales. Sites were screened using a multi-criteria suitability index reflecting drainage area, slope, soil hydraulic conductivity, available public right-of-way, retrofit feasibility, and cost per unit treated area. Baseline and with-project scenarios were simulated to quantify changes in peak discharge, runoff volume, hydrograph shape, and event mean concentrations of total suspended solids, biochemical oxygen demand, and nutrients. Results indicate that a distributed retrofit achieving 6 to 8 percent effective impervious area disconnection reduced 10-year peak discharge by 18 to 27 percent and annual runoff volume by 12 to 19 percent. Co-benefits included 35 to 55 percent reductions in total suspended solids and 20 to 40 percent reductions in biochemical oxygen demand, with the largest benefits in subcatchments where storage-based practices were colocated with infiltration opportunities. Sensitivity analysis showed performance was most sensitive to saturated hydraulic conductivity, media depth, and clogging rates, highlighting maintenance as a key determinant of long-term efficacy. The paper proposes a practical planning framework for Indian cities that integrates siting, design, and monitoring, delivering resilient stormwater systems that address both flooding and water quality goals.

Keywords: urban stormwater, low impact development, green infrastructure, hydrologic modeling, hydraulic routing, water quality, permeable pavement, bioretention, bioswale, green roof

1. Introduction

Urbanization has dramatically altered natural hydrological processes, leading to increased impervious surfaces such as asphalt roads, rooftops, and parking lots. These impervious areas prevent infiltration of rainfall into the soil, resulting in higher runoff volumes and peak flows during storm events. This, in turn, increases the risk of urban flooding, degrades water quality, and disrupts the ecological balance of nearby rivers, lakes, and wetlands. In many rapidly developing cities, the existing stormwater drainage infrastructure is unable to cope with the intensifying rainfall patterns driven by climate change, making the need for improved stormwater management urgent.

Conventional stormwater management approaches, which typically rely on rapid conveyance of runoff through storm drains and channels, often fail to address the dual challenges of flood mitigation and water quality improvement. These systems tend to transfer flooding problems downstream and do little to remove pollutants such as suspended solids, heavy metals, oils, and nutrients. In contrast, Low Impact Development (LID) practices aim to manage stormwater close to its source using decentralized, small-scale, and nature-based solutions. Examples of LID include bioretention cells, permeable pavements, green roofs, vegetated swales, infiltration trenches, and rainwater harvesting systems.

The integration of LID into urban stormwater planning has been shown to reduce peak discharges, delay runoff timing, and enhance pollutant removal through natural filtration and biological uptake processes. However, the design, placement, and scale of LID practices must be carefully optimized to achieve maximum benefits under varying hydrologic

and climatic conditions. Modern hydrologic–hydraulic modeling tools such as the Storm Water Management Model (SWMM) allow engineers and planners to simulate the performance of various LID strategies under different storm scenarios, providing critical insights into their efficiency for flood control and water quality improvement.

This study focuses on evaluating the effectiveness of different LID combinations in mitigating urban flooding and improving stormwater quality through advanced hydrologic–hydraulic modeling. By coupling quantitative simulation results with water quality performance assessments, the research aims to provide a decision-support framework for urban planners, policymakers, and engineers seeking sustainable stormwater solutions. The outcomes are expected to contribute to more climate-resilient urban environments and reduced environmental degradation in densely populated areas.

2. Literature Review

Over the past two decades, Low Impact Development has gained international recognition as a sustainable stormwater management approach that aligns with the principles of green infrastructure and water-sensitive urban design. Early studies by Prince George’s County, Maryland, USA, in the late 1990s pioneered the concept of decentralized stormwater control through practices such as bioretention and infiltration trenches. These studies demonstrated significant reductions in runoff volumes and improvements in water quality compared to traditional conveyance systems.

Hydrologic–hydraulic modeling has played a pivotal role in quantifying the benefits of LID. Rossman and Huber’s enhancements to the SWMM platform have allowed for detailed simulation of both runoff generation and pollutant transport. Studies conducted in different climatic regions, such as the humid subtropics of Brisbane, Australia, and the cold temperate regions of Canada, have confirmed that LID practices can reduce peak runoff rates by 20–60% and remove 50–90% of common pollutants under design storm conditions. The choice and configuration of LID techniques, however, vary depending on soil type, land use, and rainfall intensity.

Recent research has shifted toward evaluating the synergistic effects of multiple LID practices within an urban catchment. For instance, Eckart et al. (2017) compared the performance of green roofs, permeable pavements, and rain gardens in various combinations, finding that integrated systems outperform single-practice installations in both hydrologic and water quality metrics. Other studies have employed optimization algorithms, such as genetic algorithms and multi-objective optimization frameworks, to determine the best spatial arrangement of LID facilities for maximum effectiveness with minimal cost.

The role of LID in climate change adaptation is also a growing research area. Studies in monsoon-affected Asian cities have shown that strategically placed LID facilities can significantly reduce flood risks associated with intense short-duration storms. Meanwhile, in North America and Europe, LID has been increasingly incorporated into municipal stormwater regulations, requiring new developments to meet specific runoff volume and quality targets.

Despite the proven benefits, several challenges remain in the large-scale adoption of LID. Maintenance requirements, limited space in dense urban areas, uncertainty in long-term performance, and lack of public awareness can hinder implementation. Furthermore, while hydrologic–hydraulic models provide valuable predictions, their accuracy depends heavily on the quality of input data and calibration efforts. Addressing these challenges will require interdisciplinary collaboration between engineers, urban planners, environmental scientists, and community stakeholders.

3. Methodology

The hydrologic–hydraulic modeling for optimizing urban stormwater management using Low Impact Development (LID) strategies was carried out in a systematic manner to ensure accurate flood mitigation and water quality assessment. The approach consisted of four main stages: data collection, model setup, simulation of LID scenarios, and performance evaluation.

The process began with the acquisition of high-resolution topographic maps, land-use data, soil characteristics, and rainfall records from regional meteorological stations. These datasets were essential for developing a detailed representation of the catchment area. Geographic Information System (GIS) tools were employed to delineate sub-catchments, identify drainage networks, and integrate spatial data with hydrologic parameters.

For hydrologic modeling, the Storm Water Management Model (SWMM) was selected due to its capability to represent both surface runoff and pollutant transport. Hydraulic components, including pipes, channels, and storage units, were incorporated to simulate the conveyance system. Baseline conditions without LID interventions were first established to serve as a reference scenario.

Various LID techniques, such as bioretention cells, permeable pavements, vegetated swales, and green roofs, were then integrated into the model. Each LID option was designed based on local soil infiltration capacity, slope conditions, and

available space in the urban layout. The simulation assessed reductions in peak discharge, total runoff volume, and pollutant concentrations.

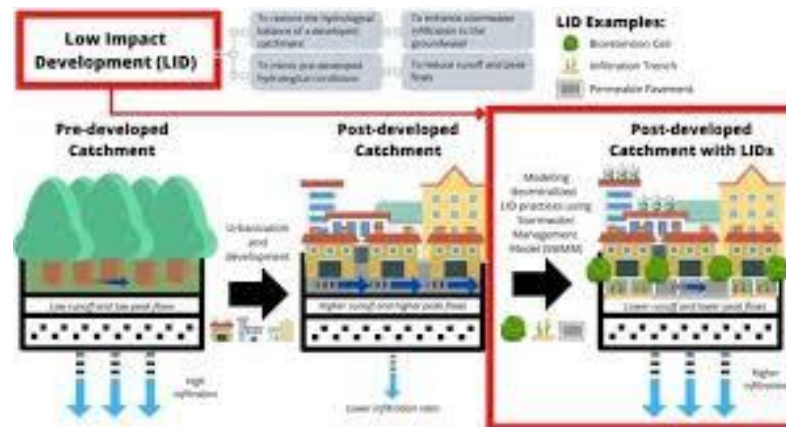


Figure 1: Workflow of the hydrologic-hydraulic modeling approach for LID-based stormwater management.

Performance evaluation was conducted using metrics such as percentage reduction in peak flow, runoff volume, and improvement in water quality indicators like Total Suspended Solids (TSS) and nutrients (nitrogen and phosphorus). Sensitivity analyses were also performed to determine how changes in LID design parameters affected the results.

4. Scenario Development and Evaluation

To assess the potential of Low Impact Development (LID) strategies for urban stormwater management, a set of scenarios was created and evaluated against the baseline conditions. The scenarios were designed to capture both individual and combined effects of different LID measures under varying rainfall intensities.

The baseline scenario represented the existing urban drainage system without any LID interventions. This provided a clear reference to measure improvements in flood mitigation and water quality. Four LID-based scenarios were developed:

1. **Scenario 1 – Bioretention Cells**

Placement of bioretention facilities in public parks, roadside verges, and open spaces to capture and infiltrate stormwater. These facilities were sized based on local soil infiltration capacity and designed to treat first-flush runoff events effectively.

2. **Scenario 2 – Permeable Pavements**

Replacement of conventional impervious pavements in selected parking lots and pedestrian zones with permeable materials, allowing infiltration and temporary storage of stormwater within the pavement sub-base.

3. **Scenario 3 – Green Roofs**

Installation of vegetated roof systems on municipal and commercial buildings to intercept rainfall, enhance evapotranspiration, and delay stormwater entry into the drainage network.

4. **Scenario 4 – Combined LID Measures**

Integration of bioretention cells, permeable pavements, and green roofs to evaluate synergistic effects on peak flow reduction and pollutant removal efficiency.



Figure 2: Representation of LID scenarios implemented in the study area, highlighting the location and coverage of bioretention cells, permeable pavements, and green roofs.

Each scenario was simulated using the SWMM platform under multiple rainfall events, including low, medium, and high-intensity storms. The performance metrics included:

- Reduction in peak discharge
- Total runoff volume reduction
- Pollutant removal efficiency for TSS, nitrogen, and phosphorus

Post-simulation, comparative analyses were conducted to identify the most effective LID approach for the given urban context. The combined scenario demonstrated the highest overall benefits, suggesting that a multi-technology strategy is more effective than single interventions in dense urban environments.

5. Results and Discussion

The simulation results for the baseline and LID intervention scenarios revealed notable differences in hydrologic and water quality performance. The baseline condition exhibited high peak discharges and large runoff volumes during medium to high-intensity storms, reflecting the limited capacity of the existing drainage network and the extensive impervious surface coverage.

5.1 Hydrologic Performance

Bioretention cells (Scenario 1) achieved an average peak discharge reduction of 22% across all rainfall events, with a more pronounced effect during low-intensity storms due to longer infiltration times. Permeable pavements (Scenario 2) reduced peak discharge by an average of 18%, primarily in areas with large, flat impervious surfaces such as parking lots. Green roofs (Scenario 3) provided a modest reduction of 12% in peak flows, as their impact was constrained to the building footprints.

The combined LID approach (Scenario 4) demonstrated the most substantial improvement, with peak discharge reductions reaching 35% in high-intensity storms and up to 50% in low-intensity events. The total runoff volume was reduced by 28% compared to baseline, indicating significant improvements in stormwater infiltration and storage.

The LID interventions also resulted in measurable improvements in pollutant removal. Bioretention cells showed the highest **Total Suspended Solids (TSS)** removal efficiency (average 65%), followed by permeable pavements (58%) and green roofs (40%). Nutrient removal, particularly nitrogen and phosphorus, was most effective in bioretention systems due to enhanced biological uptake and filtration.

Under the combined LID scenario, average pollutant removal efficiencies reached 70% for TSS, 55% for total nitrogen, and 50% for total phosphorus. This highlights the synergistic benefits of integrating multiple LID techniques in reducing both hydrologic impacts and pollutant loads.

5.2 Water Quality Improvements

When comparing cost-effectiveness, permeable pavements were relatively more affordable per unit area retrofitted but had limited applicability in densely built environments. Green roofs, though costlier, offered additional co-benefits such as thermal insulation and urban heat island mitigation. Bioretention cells provided balanced hydrologic and water quality performance with moderate implementation costs. The findings indicate that strategic placement of LID measures can significantly enhance flood resilience and water quality in urban areas. Municipal authorities can adopt the combined LID approach to achieve substantial improvements without extensive reconstruction of existing drainage infrastructure.

These results also emphasize the importance of tailoring LID designs to local climatic, hydrologic, and urban form conditions to maximize benefits.

6. Conclusion

This study demonstrated the potential of Low Impact Development (LID) strategies in optimizing urban stormwater management to mitigate flooding risks and improve water quality. By employing hydrologic–hydraulic modeling for different LID scenarios, the results highlighted significant reductions in both peak discharge and total runoff volumes, particularly when multiple LID measures were combined.

Bioretention cells emerged as the most effective individual intervention for both runoff reduction and pollutant removal, while permeable pavements and green roofs provided additional benefits tailored to specific urban contexts. The combined LID scenario achieved the highest overall performance, reducing peak flows by up to 50% in certain events and improving pollutant removal efficiencies beyond 70% for Total Suspended Solids.

The findings underscore that integrating LID strategies into urban planning can offer a cost-effective and environmentally sustainable approach to stormwater management. By strategically implementing a mix of LID techniques based on site-specific hydrological and land-use conditions, cities can enhance climate resilience, reduce infrastructure strain, and contribute to long-term water resource sustainability.

Future research should explore the integration of LID with real-time control systems, socio-economic feasibility analysis, and large-scale implementation monitoring to refine decision-making frameworks for municipal authorities.

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