NDMI Research

Seminar Presentation

Mitigating Climate-Driven Urban Flood Responses:

A Laboratory-Based Physical Modelling Approach

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Background

Intensifying Rainfall Extremes

Climate change is driving more frequent and intense storm events that exceed historical design capacities.

Urban Vulnerability

Cities are highly susceptible to surface flooding due to extensive impervious surfaces during storm events.

Need for Process Understanding

Effective mitigation strategies require a detailed, process-level understanding of complex rainfall–runoff interactions, which laboratory models can provide visually and reliably.

※ Laboratory-based physical modelling provides a controlled environment to isolate key variables and also validate numerical models.

Research Gap

Little consideration of the urban drainage system in physical modelling approaches, to replicate complex rainfall-runoff interactions accurately in current urban flood mitigation studies.

Isolated Drainage Elements

Most experiments focus on individual components (inlets, manholes, roofs) rather than the integrated urban network system.

Simplified Runoff Generation

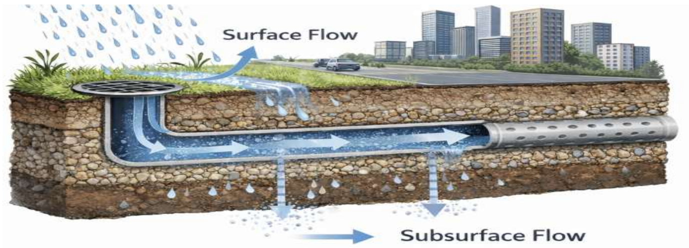
Surface runoff is often simulated via boundary inflow conditions, instead of realistic, direct rainfall application over the entire catchment.

Uncertainties from numerical models

Numerical models (SWMM, etc.) are frequently used without sufficient high-quality experimental data for calibration and validation.

Limited System Representation

There is limited attention to the reproduction of the dual drainage mechanism (surface + subsurface) under controlled rainfall conditions.



Developing an integrated physical modelling system that applies realistic rainfall and reproduces both surface and subsurface processes.

Three-Layer Physical Modelling Concept

Layer 1: Rainfall Simulator

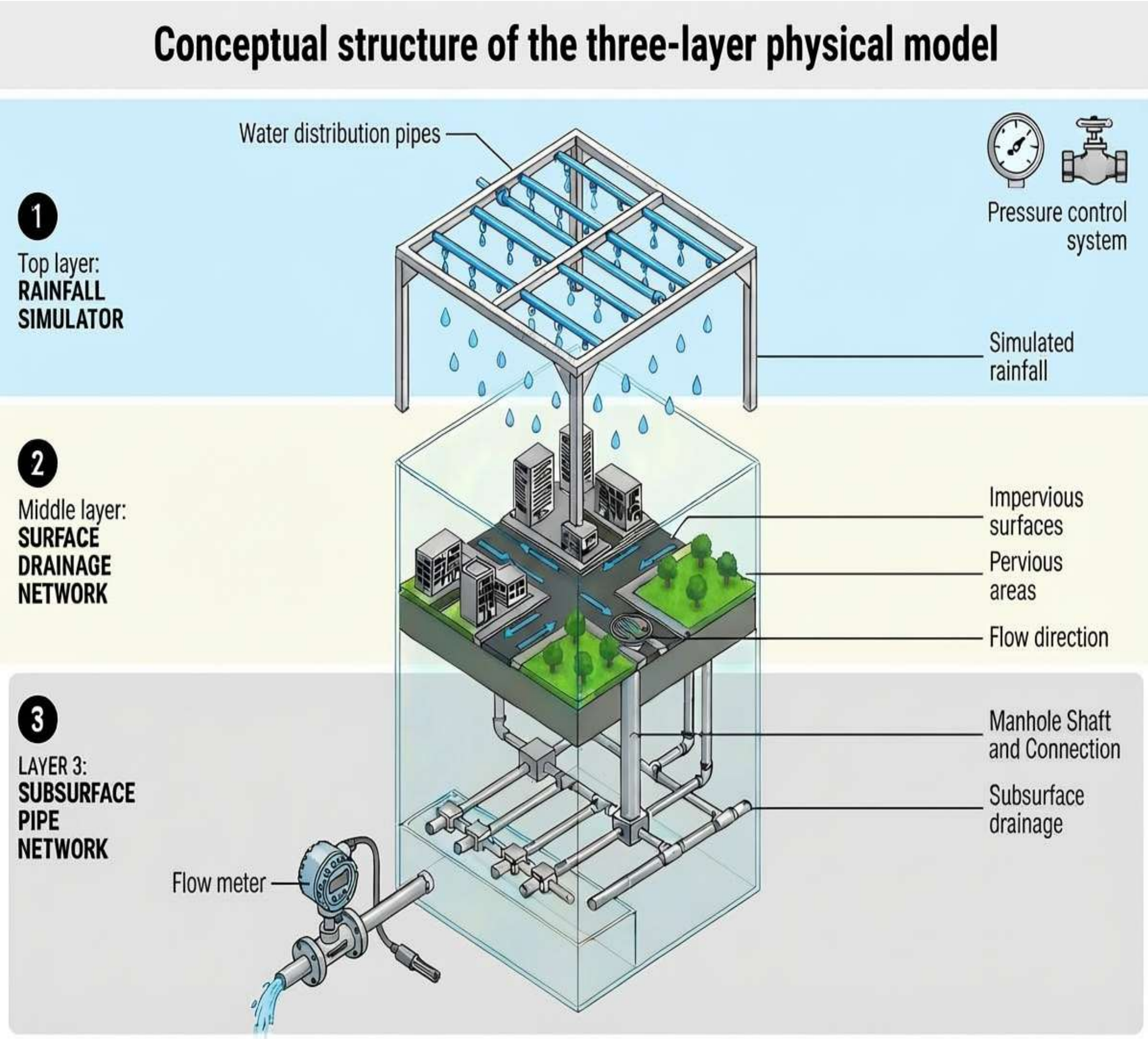
Large-scale facility (30m × 30m) with pressurized oscillating nozzles providing controlled intensity and spatial uniformity.

Layer 2: Surface Drainage Network

Physical Catchment Model (7m × 5m, 1:70 scale) representing impervious basins, road networks, and building structures.

Layer 3: Subsurface Pipe Network

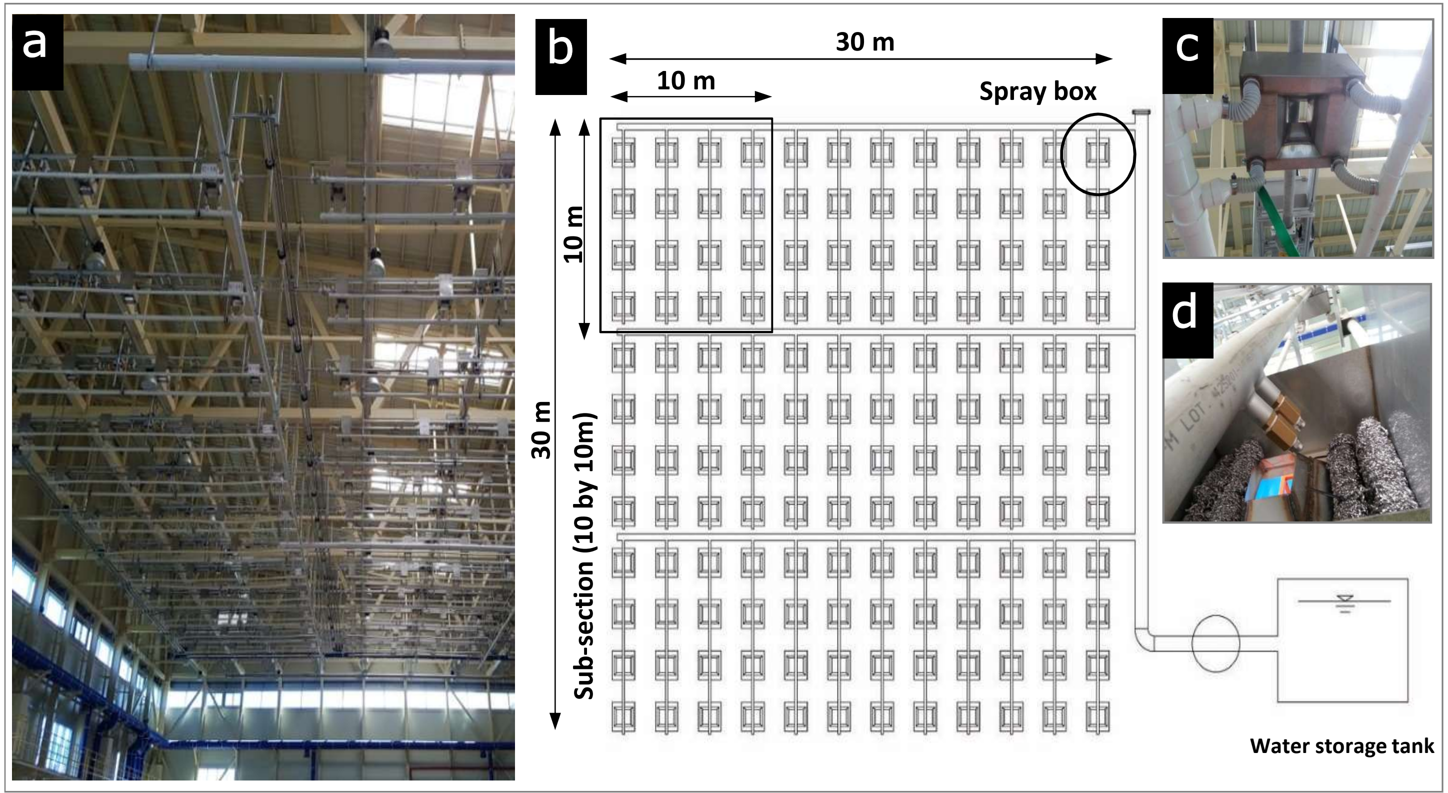
Network of drainage inlets connected to main rainwater pipes (2.5% slope, various sizes of PVC pipes) replicating the dual drainage system.



Integrated reproduction of urban rainfall–runoff processes via analog 'similarity of process' approach (Hooke, 1968; Green, 2014).

Rainfall Simulator Performance

Layer 1: Rainfall Simulator



(a) general view (b) nozzle configuration (c) spray box of a nozzle (d) oscillating nozzles

Figure. National Disaster Management Research Institute Rainfall Simulator (NDMI RS)

Rainfall Intensity Range

20 – 80 mm/h

Uniformity Coefficient (*CuC*)

78.6 – 84.0 %

Uniformity of simulated rainfall (Christiansen uniformity coefficient)

$$CuC = \left(1 - \frac{\sum_{i=1}^{n} |x_i - \bar{x}|}{n\bar{x}}\right) \times 100\ (\%)$$

n : number of the depth measurements

x_i : measured depth

$\bar{x}$: mean depth of x_i

Suitable for controlled rainfall–runoff experiments with high spatial homogeneity.

Physical Catchment Model (PCM)

Layer 2: Surface Drainage Network

Scale & Dimensions

7m × 5m hypothetical urban area (around 1:70 horizontal scale, representing 171,500m²) with 7 distinct sub-catchments.

Road Network

Three road widths (0.3m, 0.15m, 0.085m) with 3.5% slope. Permeable pavement (35% permeability).

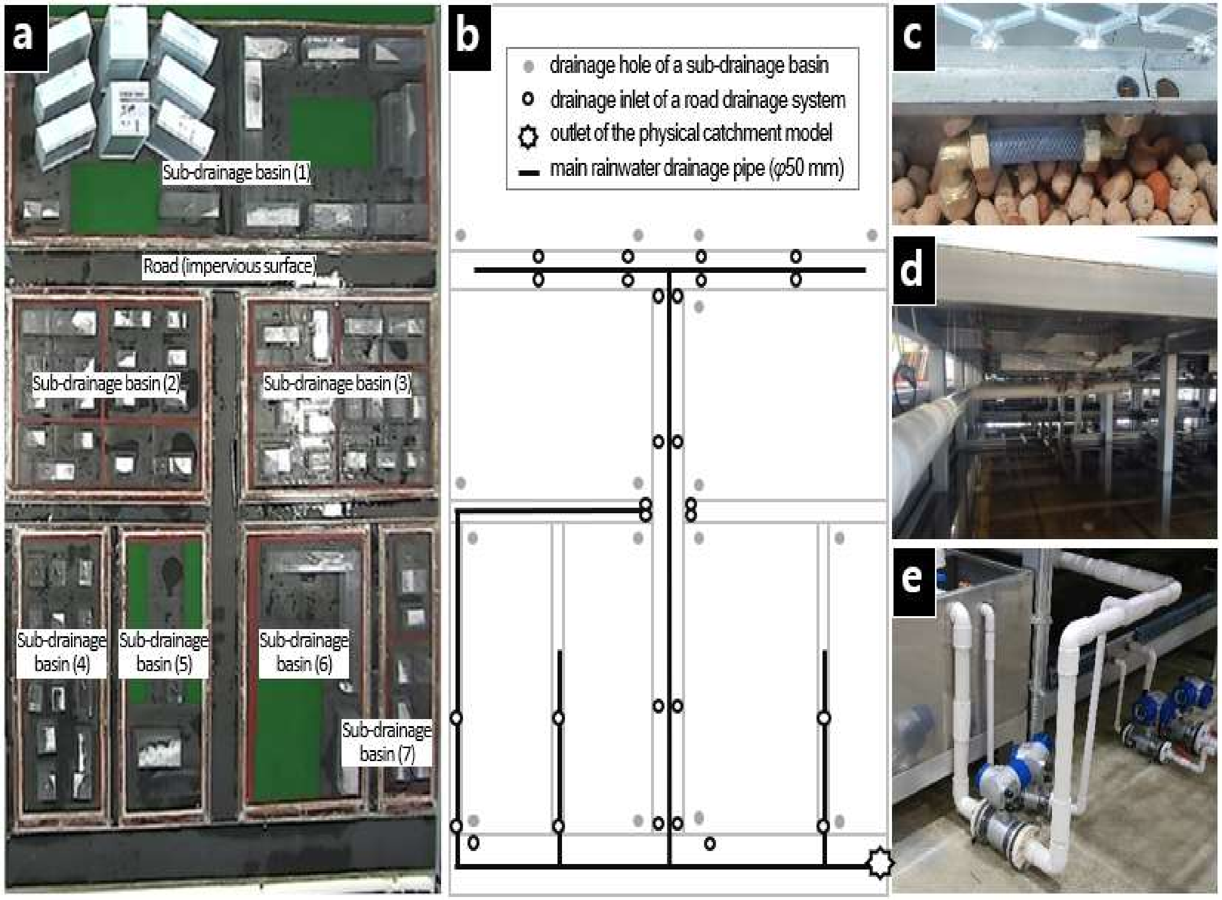
Building Structures

90 building units featuring rooftop detention storage (20mm storage depth) covering 6.3m² total rooftop area in model scale.

Layer 3: Subsurface Drainage Network

Dual Drainage System

Surface runoff enters via 16mm inlets connected to subsurface 50mm PVC main pipes (2.5% slope), monitored by electromagnetic flowmeters.



(a) aerial photograph of the physical model

(b) subsurface rainwater piping diagram

(c) rubber hose used to connect a drainage hole and a rainwater pipe

(d) PVC pipe used for the main rainwater drainage network

(e) electromagnetic flowmeters installed in an inverted siphon structure

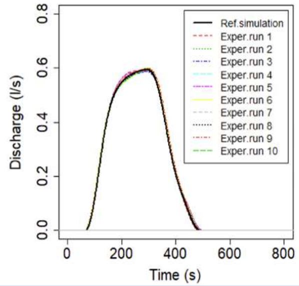
Figure. Physical catchment and drainage system (surface + subsurface)

PCM Validation: Reproducibility & SWMM

Experimental Reproducibility

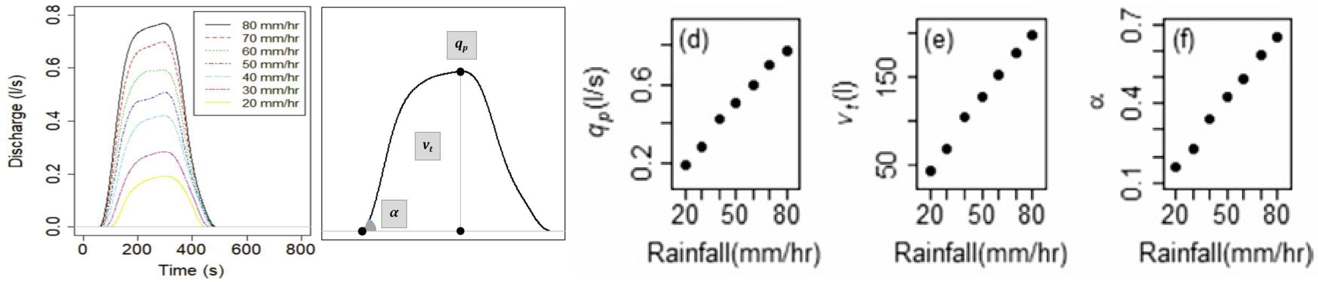
Excellent Repeatability

11 repeated runs: Consistent hydrographs at 60 mm/hr
Metrics: $NSE \approx 1.0$, $NSE_{ln} > 0.99$, $|\%bias| < 3\%$
Excellent repeatability and minimal variability.



Sensitivity to Intensity

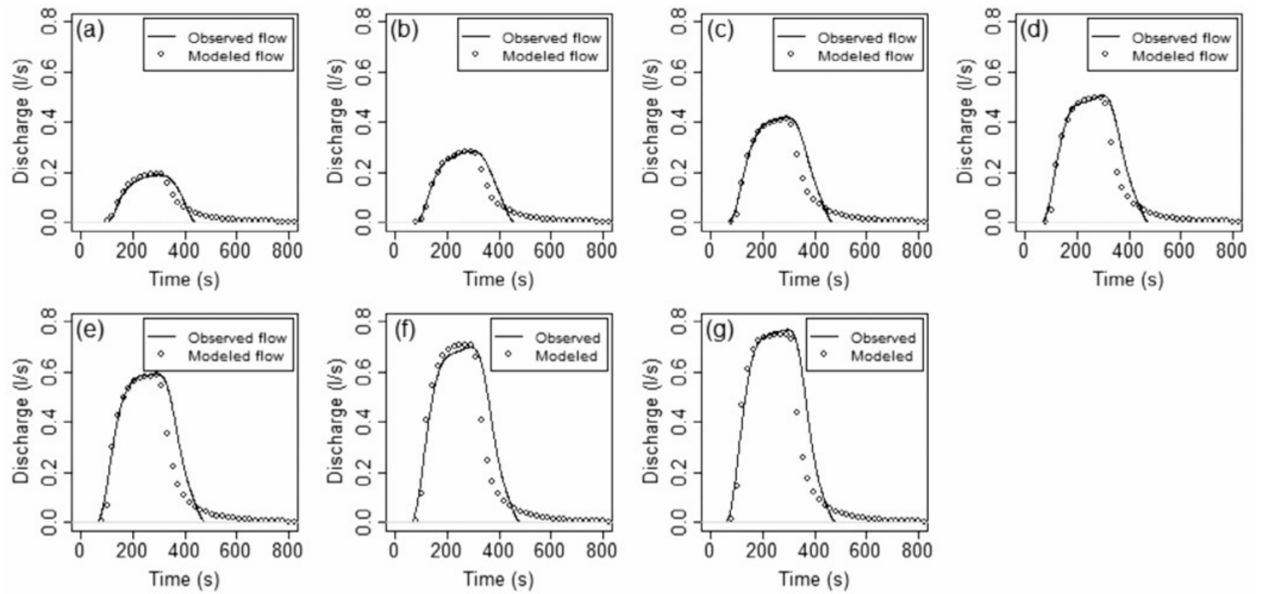
Tests from 20-80 mm/h showed logical increases in peak discharge (q_p), total volume (v_t), and rising limb slope (α) with intensity.



Numerical Comparison

SWMM Comparison

Strong agreement with numerical model simulations (Mean $NSE = 0.96$, $NSE_{ln} = 0.88$, $\%bias = 3.04$, respectively).



Confirms high reliability of the physical model.

Stormwater Management Scenarios

Rooftop Detention Storage

Total Area: 6.3 m^2

90 buildings, 20 mm storage depth

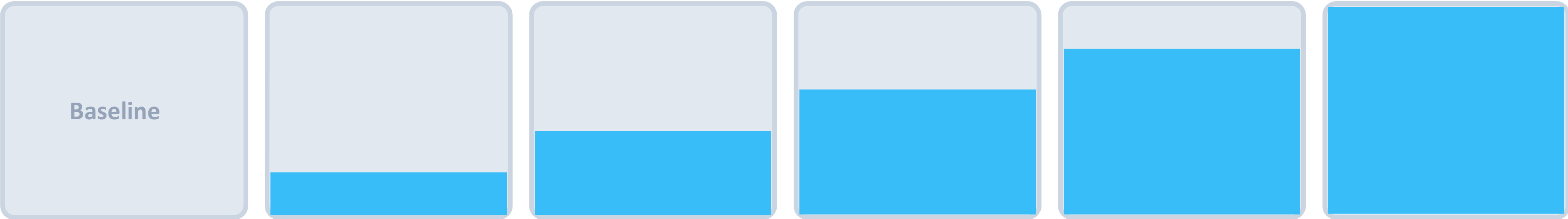
Permeable Road Pavement

Total Area: 5.5 m^2

35% permeability (via perforated rubber plates)

Experimental Coverage Levels

Rainfall Intensity: 60 mm/h represents approx. a 30-year return-period design event in Korea.



Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6
0% Coverage	20% Coverage	40% Coverage	60% Coverage	80% Coverage	100% Coverage

Six distinct scenarios tested: 0% (baseline), 20%, 40%, 60%, 80%, and 100% facility coverage distributed across the PCM (PCM area: 35 m^2).

Figure. Experimental scenarios and spatial allocation of facilities (0–100% coverage)

This scenario-based approach allowed systematic evaluation of facility performance under controlled conditions.

Empirical Relationships of Runoff Reduction

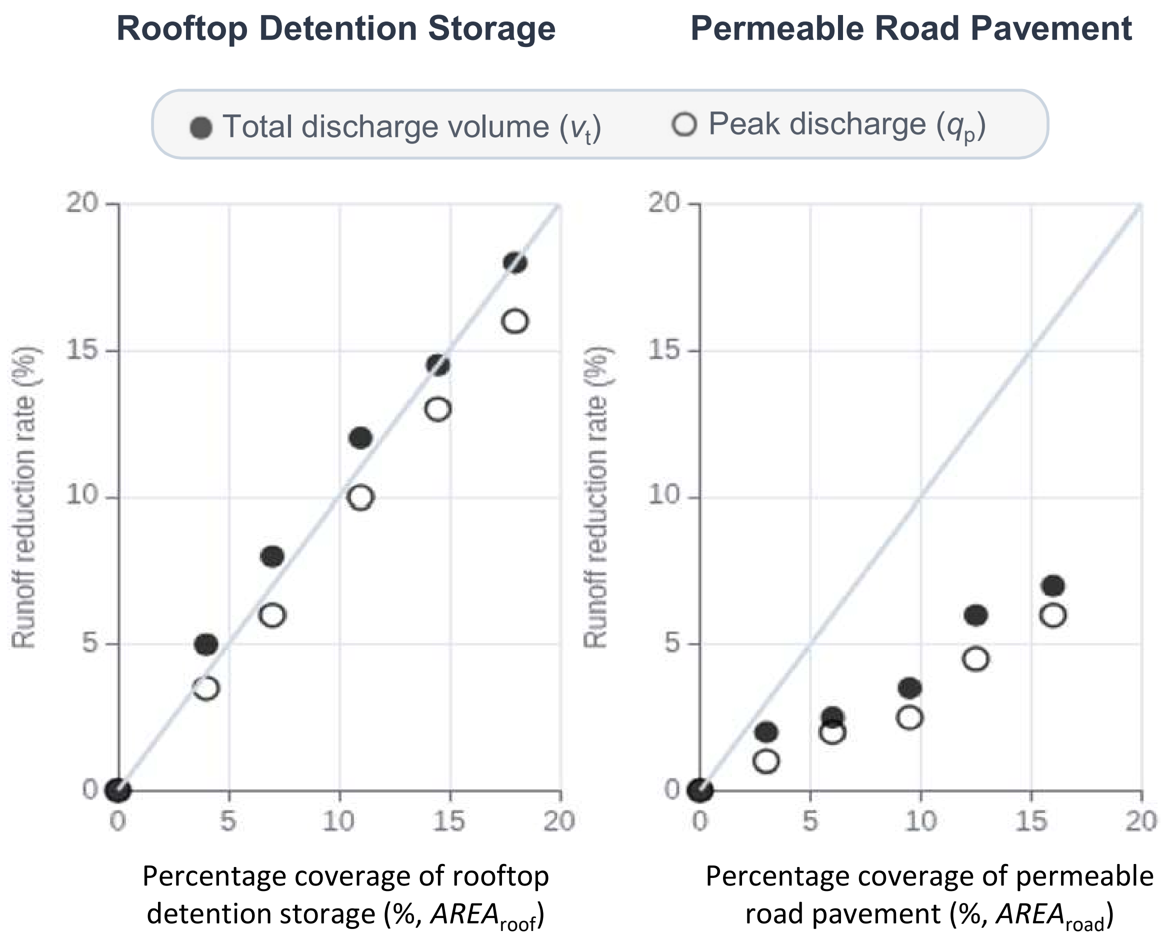


Figure. Runoff reduction rate (%) against facility coverage: (a) Rooftop detention vs (b) Permeable pavement (Gray line represents 1:1 ratio)

Linear Reduction

Runoff reduction in both peak discharge and total runoff volume increases linearly with facility coverage for rooftops and roads.

Comparative Efficiency

Rooftop detention storage is approximately **3 times more effective** than permeable pavement for runoff reduction at similar coverage levels.

Design Guidance

Empirical relationships derived for facility design:

Rooftop Detention:

$q_{p.rate} = 0.085 + 0.907 \cdot AREA_{roof}$ — $R^2 = 0.99$

$v_{t.rate} = 0.939 + 0.970 \cdot AREA_{roof}$ — $R^2 = 0.99$

Permeable Pavement:

$q_{p.rate} = -0.181 + 0.361 \cdot AREA_{road}$ — $R^2 = 0.96$

$v_{t.rate} = -0.001 + 0.435 \cdot AREA_{road}$ — $R^2 = 0.96$

Implication for Climate Adaptation

Evidence-Based Mitigation Support for Urban Flood Management

Provides quantitative support for urban flood mitigation strategies and enables preliminary design of stormwater facilities based on physical evidence.

Data Scarcity Solution

Particularly useful in regions where detailed observational data are limited, fragmented, or difficult to obtain from real-world events.

Strategy Testing

Supports rapid testing of multiple mitigation strategies (e.g., varying coverage of detention storage) under controlled, repeatable conditions.

Model Calibration Integration

Physical model results serve as high-quality validation datasets to inform and calibrate numerical models (like SWMM) for broader local applications.

Climate Adaptation Cycle

- Bridging theory & practice
- Reducing implementation risk

Conclusions

01 System Development

Successfully developed and validated a three-layer laboratory physical modeling environment capable of simulating integrated urban rainfall-runoff processes.

02 Reliable Reproduction

The system demonstrates high repeatability and accuracy (NSE ≈ 1.0) in reproducing hydrologic responses under controlled storm conditions.

03 Quantitative Design Criteria

Established intuitive, linear relationships between facility coverage and runoff reduction rates, enabling evidence-based facility sizing.

04 Climate Resilience Support

Provides a vital tool for testing climate adaptation strategies where observational data is limited or numerical models require physical calibration.