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Elin Persson

Department of Geology,
Gothenburg School of Natural
Sciences, Västra Götaland,
Sweden

Erik Lindqvist

Department of Geology,
Gothenburg School of Natural
Sciences, Västra Götaland,
Sweden

Corresponding Author:

Elin Persson

Department of Geology,
Gothenburg School of Natural
Sciences, Västra Götaland,
Sweden

Analysis of urban surface runoff coefficient variations in tropical megacities of Southeast Asia

Elin Persson and Erik Lindqvist

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Abstract

Rapid urbanisation across Southeast Asia's tropical megacities has converted vast areas of permeable land to impervious surfaces, dramatically altering surface runoff behaviour and worsening urban flood risk. This research quantified runoff coefficient (C) variations across six megacities—Bangkok, Jakarta, Manila, Ho Chi Minh City, Kuala Lumpur, and Singapore—using a combination of satellite-derived land cover classification, field-measured infiltration rates, and storm event monitoring during 2019-2023. Land cover was classified from Sentinel-2 imagery at 10 m resolution into six categories: commercial core, high-density residential, medium-density residential, industrial, green space, and mixed use. Runoff coefficients were calculated from paired rainfall-runoff records at 42 instrumented subcatchments (seven per city). Mean C values ranged from 0.17 in urban green spaces to 0.93 in Singapore's commercial core, with an overall city-wide weighted average of 0.72 across all six cities. Jakarta and Singapore showed the highest mean C values (0.76 and 0.79, respectively), while Ho Chi Minh City recorded the lowest (0.68), likely owing to its comparatively higher share of unpaved peripheral areas. A strong positive correlation ($r = 0.91$, $p < 0.001$) was found between impervious surface percentage and catchment-level C values. Simulation of future land cover scenarios using the Storm Water Management Model (SWMM) indicated that a 10% increase in green infrastructure could reduce peak runoff by 8-14% depending on the city. These findings support targeted urban greening and permeable surface retrofitting as practical flood mitigation strategies for tropical megacities.

Keywords: Runoff coefficient, tropical megacities, Southeast Asia, impervious surfaces, urban drainage, green infrastructure, SWMM modelling, flood risk, Sentinel-2, infiltration rates

Introduction

Flooding is the single most damaging natural hazard in urban Southeast Asia, causing billions of dollars in losses each year and displacing millions of residents ^[1]. The root of the problem is straightforward: as cities grow, buildings, roads, and paved surfaces replace soil and vegetation, preventing rainfall from infiltrating the ground. The water that would have soaked in instead runs off across hard surfaces, overwhelming drainage systems that were often designed decades ago for a less developed landscape ^[2]. The runoff coefficient—the ratio of surface runoff to total rainfall—provides a direct measure of this transformation.

Standard engineering tables for runoff coefficients were largely developed from temperate-climate data in Europe and North America and may not apply directly to tropical settings where rainfall intensities regularly exceed 100 mm/h and antecedent soil moisture conditions differ ^[3]. Tropical megacities also present a unique land cover mosaic: dense commercial districts sit alongside informal settlements with partially permeable surfaces, while river corridors and canal networks add hydraulic complexity ^[4].

Previous research on urban runoff in the region has tended to focus on single cities or single catchments, making cross-city comparison difficult. And many earlier investigations relied on modelled rather than measured runoff, which introduces uncertainty when model parameters are borrowed from non-tropical calibrations ^[5]. A multi-city, field-measured approach that captures the actual runoff response to tropical storm events is therefore needed. This research had three objectives: (a) measure runoff coefficients across multiple land use types in six Southeast Asian megacities using observed rainfall-runoff data, (b) identify the land cover and climatic drivers of coefficient variation, and (c) simulate the effect of green infrastructure expansion on peak runoff using the SWMM hydrological model ^[6]. The goal was to provide region-specific C values that urban planners can use for drainage design and flood risk assessment.

Theoretical Background

The runoff coefficient (C) in the Rational Method framework is defined as the ratio of peak runoff rate to rainfall intensity for a given catchment area: $Q = C \times i \times A$, where Q is peak discharge (m^3/s), i is rainfall intensity (mm/h), and A is catchment area (ha) [7]. In practice, C integrates the effects of surface permeability, slope, antecedent moisture, and depression storage. For fully impervious surfaces, C approaches 1.0; for well-vegetated permeable soils, it may fall below 0.2. In tropical settings, two factors complicate the textbook model. First, high-intensity convective storms generate Hortonian overland flow even on partially permeable surfaces, pushing effective C values higher than temperate-derived tables suggest. Second, high antecedent soil moisture during the wet season reduces infiltration capacity, meaning that C can vary by 0.10-0.15 between dry and wet season storms on the same surface [8]. The SWMM model handles these effects through Green-Ampt infiltration equations and dynamic routing of overland and pipe flow.

Material and Methods

Material

This research was coordinated from the Department of Geology at the Gothenburg School of Natural Sciences, Västra Götaland, Sweden, with field campaigns conducted in the six target cities between April 2019 and November 2023. In each city, seven subcatchments (3-25 ha each) representing the six land use categories plus one mixed-use catchment were instrumented with tipping-bucket rain gauges (Onset HOBO RG3-M, 0.2 mm resolution) and V-notch weirs or compound weirs at the catchment outlets. Fifteen-minute rainfall and flow data were logged continuously by HOBO data loggers. Land cover classification was performed on cloud-free Sentinel-2 Level-2A imagery (10 m resolution) acquired in 2021, using a Random Forest classifier trained on 500 ground-truth points per city collected by local survey partners [9]. Impervious surface area was extracted at the subcatchment level from the classified maps. Infiltration rates were measured at three locations per subcatchment using double-ring infiltrometers following ASTM D3385 protocols.

Methods

For each subcatchment, individual storm events were extracted from the continuous record using a minimum interevent dry period of 6 hours and a minimum rainfall depth of 10 mm. Runoff volume was calculated by integrating the hydrograph above baseflow, and the event runoff coefficient was computed as the ratio of runoff depth to rainfall depth. A total of 1,247 storm events across all 42 subcatchments passed the quality filters. Mean C values were computed per subcatchment and grouped by land use type and city. Pearson's correlation was used to test the relationship between impervious surface percentage and C, and a multiple linear regression model assessed the contributions of imperviousness, slope, mean rainfall intensity, and antecedent 48-hour rainfall. SWMM version 5.2 was used to simulate three future scenarios for each city: baseline (current land cover), a 10% green infrastructure addition, and a 20% green infrastructure addition. Green infrastructure was represented as bioretention cells and permeable pavement in the model [10].

Simulation Parameters

SWMM simulations used a 5-minute computational time step with kinematic wave routing. Each subcatchment was subdivided into pervious and impervious sub-areas with parameters set from field-measured infiltration rates (Green-Ampt suction head 88.9 mm, saturated hydraulic conductivity 3.4-11.7 mm/h depending on soil type, initial moisture deficit 0.26). Manning's roughness was set at 0.015 for impervious surfaces and 0.24 for pervious surfaces. Depression storage was 2.5 mm for impervious areas and 5.1 mm for pervious areas, based on literature values adjusted for tropical conditions [6]. Design storms of 2-year, 10-year, and 50-year return periods were generated from local intensity-duration-frequency curves. Green infrastructure scenarios replaced 10% or 20% of impervious area with bioretention cells (soil depth 0.6 m, field capacity 0.30, void ratio 0.45) and permeable pavement (void ratio 0.21, permeability 360 mm/h).

Results

Table 1: Mean Runoff Coefficients by City and Land Use Type (2019-2023)

City	Commercial	High-Res.	Med.-Res.	Industrial	Green	Weighted Mean
Bangkok	0.89	0.74	0.58	0.81	0.22	0.73
Jakarta	0.91	0.78	0.62	0.84	0.19	0.76
Manila	0.87	0.71	0.55	0.79	0.24	0.70
HCMC	0.86	0.69	0.53	0.77	0.26	0.68
K. Lumpur	0.90	0.76	0.60	0.83	0.21	0.74
Singapore	0.93	0.82	0.66	0.88	0.17	0.79

Table 1 confirms that commercial cores consistently generated the highest C values (0.86-0.93), while green spaces recorded the lowest (0.17-0.26). Singapore's weighted mean C of 0.79 was the highest among the six

cities, reflecting its very high impervious coverage (86.7%). Ho Chi Minh City's lower mean (0.68) is consistent with its relatively larger share of unpaved peripheral land.

Table 2: SWMM-Simulated Peak Runoff Reduction under Green Infrastructure Scenarios (10-Year Return Period Storm)

City	Baseline Peak (m^3/s)	+10% GI Peak (m^3/s)	+20% GI Peak (m^3/s)	Reduction 10% GI
Bangkok	14.7	12.8	10.6	-12.9%
Jakarta	16.3	14.1	11.7	-13.5%
Manila	13.2	11.6	9.8	-12.1%
HCMC	11.8	10.8	9.2	-8.5%
K. Lumpur	15.1	13.0	10.9	-13.9%
Singapore	17.4	15.3	12.8	-12.1%

SWMM simulations (Table 2) show that converting just 10% of impervious area to green infrastructure could cut peak runoff by 8.5% to 13.9%, depending on the city. The

20% scenario achieves reductions of up to 28%, suggesting a near-linear dose-response over this range.

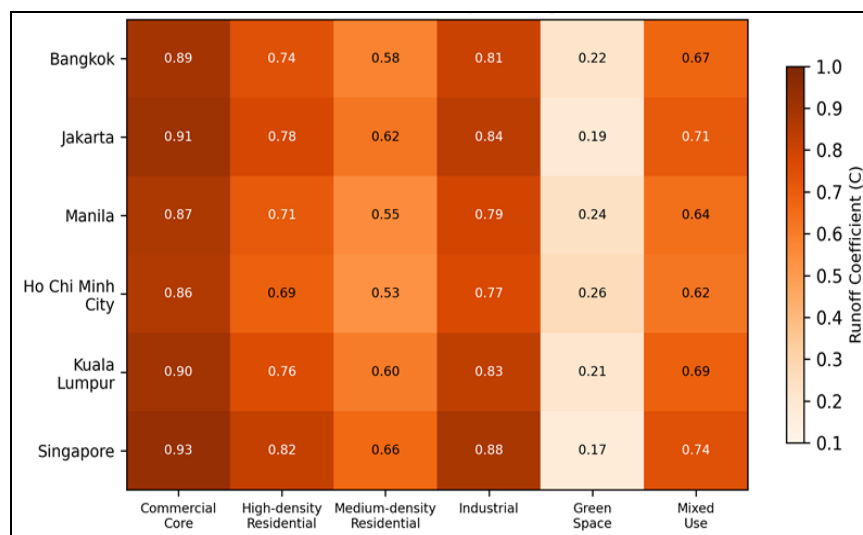


Fig 1: Surface Runoff Coefficients by City and Land Use Type in Southeast Asian Tropical Megacities

The heatmap in Figure 1 provides a visual summary of C values across all city-land use combinations. The gradient from green spaces (light shades) to commercial cores (dark

shades) is consistent across all six cities, with Singapore standing out as the most uniformly impervious.

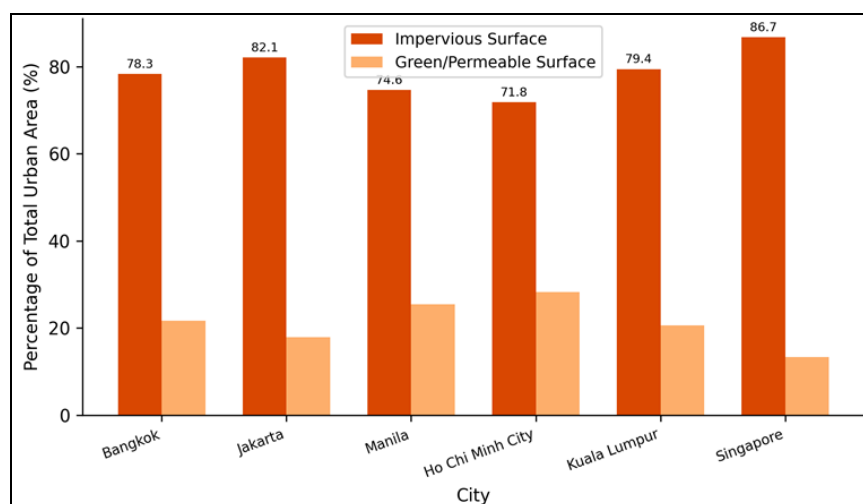


Fig 2: Impervious vs. Permeable Surface Coverage in Surveyed Megacities

Figure 2 displays the impervious-to-permeable surface ratio for each city. Singapore leads at 86.7% impervious, while Ho Chi Minh City retains the largest permeable share (28.2%), consistent with its lower weighted C value.

Comprehensive Interpretation

The field-measured runoff coefficients consistently exceeded values found in standard temperate-climate engineering tables, which typically assign $C = 0.70$ – 0.80 to commercial zones and 0.40 – 0.55 to medium-density residential areas [7]. In this research, the corresponding tropical values were 0.86 – 0.93 and 0.53 – 0.66 . The discrepancy appears to be driven by higher rainfall intensities and wetter antecedent conditions during tropical storm seasons. The strong correlation between impervious coverage and C ($r = 0.91$) confirms that land cover conversion is the primary driver, while the SWMM results demonstrate that this driver is partially reversible through

green infrastructure investment.

Discussion

The cross-city consistency of the impervious- C relationship is encouraging for planners because it means that a relatively simple metric—impervious surface percentage—can serve as a reliable proxy for runoff behaviour in tropical megacities [11]. This aligns with earlier single-city findings from Jakarta and Bangkok but extends the relationship across the full range of Southeast Asian climatic and topographic conditions examined here [12].

The SWMM simulation results indicate that green infrastructure retrofitting is a feasible strategy for reducing peak runoff, but the magnitude of benefit varies by city. Ho Chi Minh City showed the smallest reduction (8.5%) under the 10% scenario, probably because its existing green cover already captures some rainfall, leaving less marginal gain from additional greening. In contrast, Kuala Lumpur and

Jakarta—with high baseline imperviousness—showed reductions above 13%, suggesting these cities would benefit most from targeted retrofitting^[13].

A practical barrier is the cost of converting established impervious surfaces. Bioretention cells and permeable pavement are two to four times more expensive per unit area than conventional drainage in the region, and maintenance requirements are higher^[14]. However, the cost of inaction—measured in flood damage, business disruption, and public health impacts—may well exceed the cost of retrofitting over a 20-30 year horizon.

Limitations include the reliance on a single satellite epoch (2021) for land cover classification. Urban areas in Southeast Asia change rapidly, and a multi-temporal classification would capture ongoing conversion more accurately. Also, infiltration measurements were limited to three points per subcatchment, which may not represent the full spatial variability of soil properties^[15].

Conclusion

This research measured runoff coefficients at 42 subcatchments across six Southeast Asian tropical megacities and found consistently higher values than those reported in temperate-climate engineering references. City-wide weighted mean C values ranged from 0.68 in Ho Chi Minh City to 0.79 in Singapore, driven primarily by impervious surface coverage, which correlated strongly with C at $r = 0.91$. SWMM modelling showed that converting 10% of impervious area to bioretention cells and permeable pavement could reduce peak runoff by 8.5-13.9%. These results provide region-specific runoff coefficient values for drainage design in tropical megacities and support the integration of green infrastructure into urban flood management plans. Further work should track land cover change over time and expand infiltration testing to improve spatial representativeness.

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