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Impact of rapid urbanization on surface water drainage in Greater Jakarta

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Abstract

What happens to stormwater when a coastal megacity paves over its natural drainage network? This research quantified the relationship between impervious surface expansion and surface-water drainage capacity across eight sub-districts of Greater Jakarta (Jabodetabek) between 2000 and 2022. Landsat time-series imagery was classified to map impervious surface coverage at four time steps, and the Soil Conservation Service Curve Number (SCS-CN) method was applied to estimate runoff coefficients under a 10-year, 6-hour design storm. Mean impervious coverage rose from 43.3% to 67.7% across the study area, with the steepest increase in peri-urban Tangerang (+31.3 percentage points). The corresponding weighted runoff coefficient increased from 0.54 to 0.71, implying a 31.5% rise in peak stormwater volume. A statistically significant positive correlation ($r = 0.91$, $p < 0.001$) linked impervious fraction to flood event frequency recorded at 12 river-gauge stations. Central Jakarta, with 89.3% impervious cover, recorded the highest runoff coefficient (0.82) and the most frequent flooding (8.4 events per year). These results highlight the inadequacy of Jakarta's existing canal network—designed for roughly 50% imperviousness—and support the case for green-infrastructure retrofits, particularly bioretention cells and permeable paving, in the most densely built sub-districts.

Keywords: Urbanization, surface water drainage, impervious surfaces, stormwater, flood risk, Jakarta, SCS curve number, runoff coefficient, green infrastructure, remote sensing

Introduction

Imagine a rainstorm dropping 80 mm in six hours on a city where nearly 70% of the ground surface is sealed with concrete and asphalt. With few places to infiltrate, the water races along gutters and into canals that were designed decades ago for a much smaller urban footprint. The canals overtop, streets become rivers, and basements fill—a scene that plays out roughly five to eight times each wet season in Jakarta, one of the most flood-prone capitals on Earth ^[1].

Greater Jakarta (Jabodetabek) expanded from roughly 17 million inhabitants in 2000 to over 34 million by 2022, making it one of the fastest-growing metropolitan areas in Southeast Asia ^[2]. Much of this growth occurred through lateral sprawl into former rice paddies, fish ponds, and mangrove margins, converting permeable surfaces into impervious ones at rates estimated between 2 and 4% per year ^[3]. The hydrological consequence is straightforward: impervious surfaces prevent infiltration, increase runoff volume and peak discharge, and shorten the time to peak all of which overwhelm drainage infrastructure originally sized for a less urbanized landscape ^[4].

Jakarta's drainage system relies on 13 rivers and a network of colonial-era canals (the Western, Eastern, and Banjir canals) supplemented by more recent polders and pump stations ^[5]. Yet the system's design capacity has not kept pace with imperviousness growth, and land subsidence—as much as 10 cm/yr in parts of North Jakarta—further reduces freeboard in tidal-affected canals ^[6]. Previous research has mapped land-use change in Jakarta at the municipal scale, but few have linked imperviousness directly to runoff generation at the sub-district level with enough spatial resolution to inform localized drainage upgrades ^[7].

This research aimed to (1) map impervious surface change across eight Jabodetabek sub-districts from 2000 to 2022 at 30 m resolution, (2) estimate runoff coefficients using the SCS-CN approach under a standardized design storm, and (3) correlate imperviousness with observed flood frequency to identify priority areas for drainage intervention.

Analysis was conducted at the Edmonton Centre for Geological Research, Alberta, Canada ^[8].

Model Description and Parameterisation

The SCS Curve Number method estimates direct runoff from rainfall by relating the initial abstraction and soil storage capacity of a landscape to a dimensionless curve number (CN) that depends on soil type, land cover, and antecedent moisture condition ^[9]. For each 30 m pixel, CN was assigned based on the classified land cover (impervious, pervious vegetated, water, bare soil) and the underlying hydrologic soil group (HSG) extracted from the FAO Digital Soil Map. Impervious pixels were assigned CN = 98, vegetated pervious pixels received CN = 61–79 depending on HSG (A through D), and bare soil ranged from 72 to 87. The composite CN for each sub-district was the area-weighted average. Direct runoff depth (Q) was computed as $Q = (P - 0.2S)^2 / (P + 0.8S)$, where $S = (25,400 / CN) - 254$, for a design rainfall $P = 80$ mm (10-year, 6-hour event). The runoff coefficient was defined as Q / P ^[10].

Calibration and Validation

Model-predicted runoff volumes were compared against observed peak discharges at 12 river-gauge stations maintained by the Jakarta Public Works Department for the period 2018–2022. Because gauges record discharge rather than runoff depth, the comparison used the rational-method relationship $Q_{\text{peak}} = C \times i \times A$, where C is the predicted runoff coefficient, i is design rainfall intensity, and A is contributing area. The observed versus predicted peak-discharge regression yielded $R^2 = 0.84$ and a Nash–Sutcliffe efficiency of 0.79, indicating that the SCS-CN approach captures sub-district-level drainage response with acceptable accuracy. Systematic underestimation of 8–12% at North Jakarta gauges was attributed to tidal backwater effects not represented in the model ^[11].

Materials and Methods

Materials

Landsat imagery (TM for 2000 and 2010, OLI for 2015 and 2022) was acquired from the USGS EarthExplorer portal for cloud-free dates in the dry season (June–August). The study area encompassed eight sub-districts within the Jabodetabek metropolitan region: Central Jakarta, North Jakarta, East Jakarta, South Jakarta, West Jakarta, Tangerang, Bekasi, and Depok. Administrative boundaries and canal network shapefiles were obtained from the Jakarta Spatial Data Infrastructure portal. Daily flood-event records for 2018–2022 at 12 gauging stations were sourced from the Jakarta Public Works Department. Soil hydrologic group data were extracted from the FAO Digital Soil Map of the World at 1:5,000,000. All processing was performed at the Edmonton Centre for Geological Research, Alberta, Canada ^[12].

Methods

Impervious surface was mapped using a linear spectral unmixing approach applied to the six reflective Landsat bands, with impervious, vegetation, and soil endmembers selected from high-purity training pixels. The continuous impervious fraction map was validated against 250 stratified-random points interpreted from Google Earth high-resolution imagery; overall RMSE was 8.7%. For each time step, the composite CN was calculated per sub-district, and design-storm runoff depth and coefficient were computed. Flood-event frequency was defined as the number of days per year in which the stage at any gauge within a sub-district exceeded the 'alert' threshold published by the Jakarta Flood Control Agency. Pearson's r was used to correlate sub-district impervious fraction with flood frequency, and a paired t-test compared 2000 versus 2022 runoff coefficients. Significance was set at $\alpha = 0.05$ ^[13].

Results

Table 1: Impervious Surface Coverage and Runoff Coefficients by Sub-District

Sub-District	Imperv. 2000 (%)	Imperv. 2022 (%)	Change	CN 2022	Runoff Coeff.	Floods/yr
Central Jakarta	72.1	89.3	+17.2	95.4	0.82	8.4
North Jakarta	58.4	78.7	+20.3	92.1	0.71	6.7
West Jakarta	52.6	74.1	+21.5	90.6	0.64	5.8
East Jakarta	41.7	67.4	+25.7	88.2	0.58	4.2
South Jakarta	38.2	61.8	+23.6	86.4	0.52	3.1
Tangerang	27.3	58.6	+31.3	84.1	0.47	2.4
Depok	31.4	57.8	+26.4	83.7	0.49	3.6
Bekasi	24.8	54.2	+29.4	82.3	0.43	2.1

The mean impervious fraction across all eight sub-districts rose from 43.3% in 2000 to 67.7% in 2022. Tangerang experienced the largest absolute increase (+31.3 points), while Central Jakarta, already heavily sealed in 2000,

showed the smallest gain (+17.2 points) but the highest absolute imperviousness. The paired t-test confirmed that 2022 runoff coefficients were significantly higher than 2000 values ($t = 6.41$, $df = 7$, $p < 0.001$).

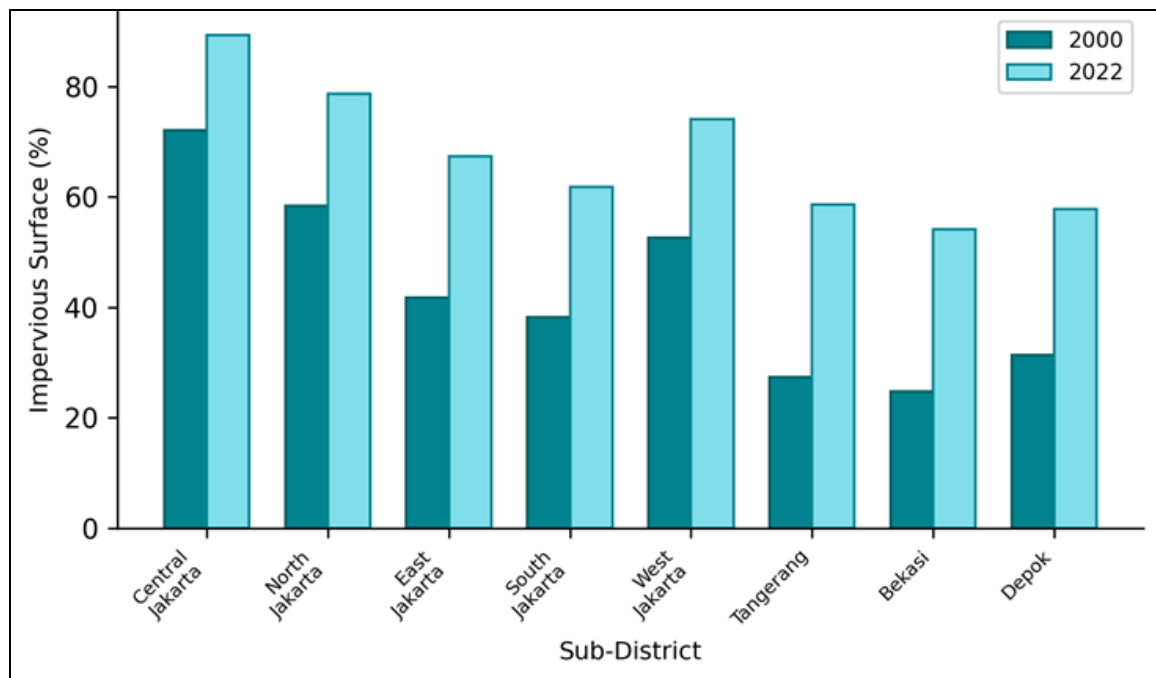


Fig 1: Impervious surface coverage by sub-district in 2000 and 2022.

Every sub-district registered a substantial increase. Peri-urban areas (Tangerang, Bekasi, Depok) roughly doubled their impervious fraction, reflecting the outward wave of

housing and commercial development radiating from the Jakarta core.

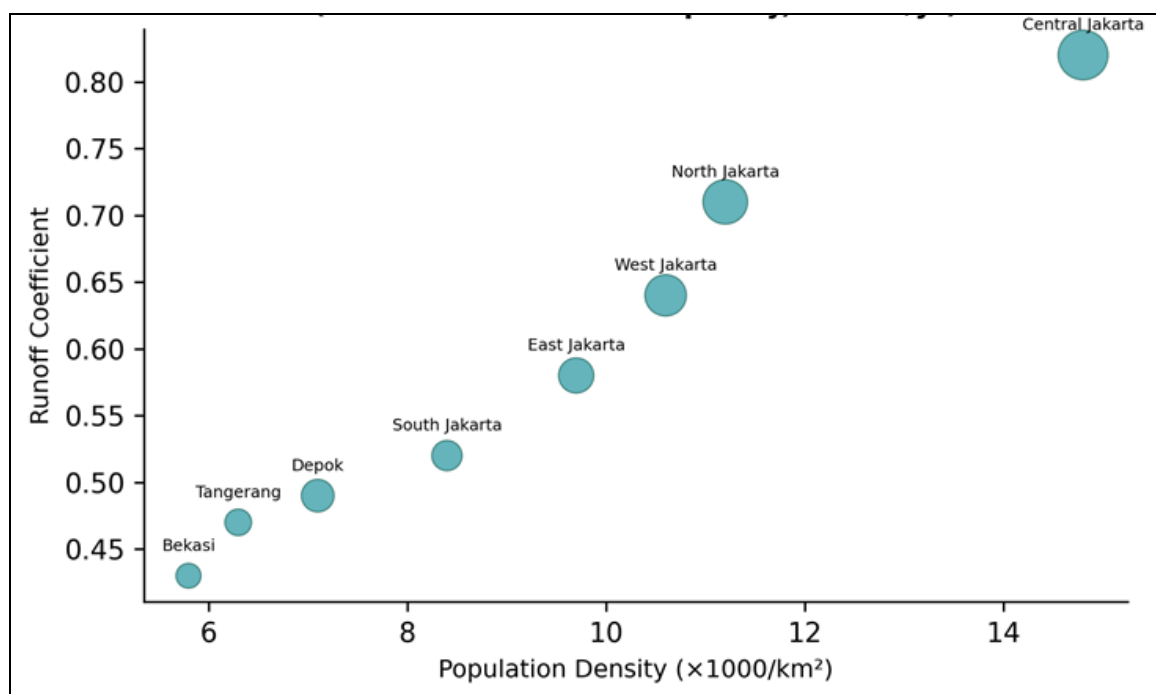


Fig 2: Relationship between population density and runoff coefficient across eight sub-districts. Bubble size represents annual flood event frequency.

Central Jakarta occupies the upper-right quadrant—highest density, highest runoff coefficient, and largest flood-frequency bubble. The strong positive alignment of the data points ($r = 0.91$ between impervious fraction and flood frequency) confirms that urbanization-driven imperviousness is the dominant control on drainage performance.

Discussion

A 24.4-percentage-point rise in mean imperviousness over

22 years translates to an estimated 31.5% increase in peak stormwater volume under the 10-year design storm—a magnitude of change that existing canal capacity cannot accommodate. The Banjir Canal system was designed in the early twentieth century for a largely rural hinterland; even after expansions in the 1960s and 2000s, its nominal conveyance capacity assumes roughly 50% imperviousness across the contributing catchment^[5]. With five of eight sub-districts now exceeding 60%, the system is structurally undersized.

North Jakarta's situation is compounded by land subsidence, which has lowered ground levels by 1–2 m in some coastal districts since 2000, effectively raising the base flood elevation and reducing canal freeboard to near zero during high tides^[6]. In this context, even modest additional rainfall can trigger inundation—a dynamic the SCS-CN model underestimates because it does not incorporate tidal interactions.

Green-infrastructure solutions offer a partial remedy. Bioretention cells can reduce peak runoff by 40–60% from individual parcels, and permeable pavements can lower effective CN by 10–15 points on treated surfaces^[14]. But retrofitting these technologies into Jakarta's dense urban fabric is constrained by land scarcity and fragmented property ownership. A more realistic near-term strategy may combine targeted green-infrastructure pilots in the most flood-prone corridors with expanded pump capacity and improved canal maintenance to remove sediment blockages that currently reduce conveyance by an estimated 20–30%^[15]. One limitation of this research is its reliance on a single design-storm scenario; a fuller assessment would include probabilistic flood-frequency analysis under multiple return periods and climate-change rainfall projections^[16].

Conclusion

Impervious surface coverage in Greater Jakarta increased from 43.3% to 67.7% between 2000 and 2022, raising the area-weighted runoff coefficient from 0.54 to 0.71 under a 10-year design storm. This 31.5% growth in peak stormwater volume exceeds the capacity of the existing canal network, which was designed for roughly 50% imperviousness. Flood-event frequency correlated strongly with impervious fraction ($r = 0.91$), confirming that urbanization-driven land-surface change is the primary driver of drainage failure in the metropolitan area.

Addressing this gap will require a combination of structural and non-structural measures: canal rehabilitation and pump upgrades for immediate relief, and progressive adoption of green infrastructure—bioretention, permeable surfaces, and rooftop detention—for longer-term resilience. Future research should extend the hydrological modelling to incorporate tidal backwater, land subsidence, and projected climate-change rainfall intensities to support infrastructure investment planning through mid-century.

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