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RESEARCH ARTICLE

Extreme Rainfall Intensification and Urban Flood Risk in Rapidly Growing Cities

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ABSTRACT

Rapidly growing cities in the Global South face a compounding hazard: warming-driven intensification of short-duration rainfall extremes arriving on urban surfaces whose capacity to absorb and drain water has been eroded by decades of unplanned impervious expansion. We combined a 42-year (1982–2023) sub-daily rain-gauge and radar-adjusted precipitation archive with a time series of remotely sensed impervious surface fraction and municipal drainage design records for a rapidly urbanizing delta metropolitan area (population approximately 5.2 million in 1990, rising to an estimated 15.8 million in 2023) to quantify how much of the observed growth in flood-affected area is attributable to rainfall intensification versus land-surface and drainage change. Sub-hourly and hourly annual maxima were analysed for trend using quantile regression and compared against the theoretical Clausius-Clapeyron rate of roughly 7% per degree of warming using local dew-point temperature as the thermodynamic covariate. Fifteen-minute and thirty-minute annual maximum intensities increased at a super-Clausius-Clapeyron rate of 11.4% and 9.8% per degree Celsius of dew-point warming respectively, while daily annual maxima scaled sub-linearly at 4.6% per degree, consistent with a shift toward more convective, shorter-lived storm structure. Over the same period, impervious surface fraction across the built-up catalogue rose from 38% to 71%, and the estimated composite runoff coefficient rose from 0.46 to 0.74. A reconstructed rainfall-runoff model driven alternately by observed rainfall trends and observed land-surface trends attributed 58% of the increase in modelled peak discharge for the 10-year return period storm to land-surface and drainage change and 42% to rainfall intensification, with the land-surface contribution dominating in the historically low-lying, densifying peripheral wards and the rainfall contribution proportionally larger in the already-saturated urban core where further imperviousness gains have been small. Drainage infrastructure, designed predominantly to a 10-year or shorter return period standard installed before 2000, was estimated to be undersized for the current 10-year storm by a factor of roughly 1.4 in conveyance capacity. These results indicate that in fast-growing cities, rainfall intensification and urbanization act as roughly co-equal but spatially distinct drivers of rising flood risk, and that adaptation strategies focused solely on either climate-adjusted drainage design or land-use control alone will address only part of the problem.

Keywords: extreme rainfall intensification; Clausius-Clapeyron scaling; sub-daily precipitation; urban flooding; impervious surface expansion; stormwater drainage capacity; rapid urbanization; flood risk

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1. INTRODUCTION

Urban flooding from short-duration, high-intensity rainfall has become one of the most visible and costly climate-related hazards facing cities in the Global South, producing repeated disruption to transport, housing and economic activity even in storms well below the magnitude once considered rare [1,2]. Unlike riverine flooding, which develops over days and is comparatively well forecast, pluvial flooding from intense convective rainfall develops over tens of minutes to a few hours and is governed by the interaction of two processes moving on very different timescales: the physical intensification of rainfall extremes under a warming atmosphere, and the decades-long transformation of the urban land surface that determines how much of that rainfall becomes surface runoff rather than infiltration [3,4].

The thermodynamic basis for rainfall intensification is well established. The Clausius-Clapeyron relation implies that the atmosphere's water-holding capacity rises by approximately 7% per degree Celsius of warming, and daily precipitation extremes in many regions have been observed to scale with local temperature at rates broadly consistent with this theoretical bound [5,6]. Sub-daily and especially sub-hourly extremes, however, have repeatedly been observed to intensify faster than the Clausius-Clapeyron rate, a so-called super-CC scaling attributed to increased convective available potential energy and a shift toward shorter, more intense convective cells as the dynamical response to warming reinforces the thermodynamic one [7-10]. Because municipal drainage systems are sized against short-duration design storms, typically 15 minutes to a few hours, rather than daily totals, it is precisely this sub-daily tail of the distribution, the one intensifying fastest, that determines whether existing infrastructure remains adequate [11,12].

Rapid urbanization compounds this thermodynamic signal through an entirely separate mechanism. Conversion of vegetated and unpaved land to roads, rooftops and compacted informal settlement reduces infiltration and shortens the time of concentration of urban catchments, so that a given rainfall volume produces a larger and earlier runoff peak than it would have on the pre-urbanized surface [13,14]. In many rapidly growing cities this land-surface transformation has occurred over just two to three decades, far faster than the multi-decade planning and replacement cycles of stormwater drainage infrastructure, so that drainage networks designed against the land-use and rainfall statistics prevailing at the time of construction now operate against a substantially more severe combination of both [15,16]. Global assessments indicate that urban exposure to flood hazard is rising faster than urban population itself, precisely because growth is concentrated in flood-prone peripheral and low-lying land that was until recently outside the urbanized footprint [17,18].

Disentangling how much of the observed rise in urban flood risk is attributable to rainfall intensification versus land-surface and drainage change matters directly for adaptation policy, because the two drivers point toward different interventions, climate-adjusted drainage design standards in one case and land-use control, green infrastructure and impervious surface management in the other, and because their relative importance is unlikely to be uniform across a metropolitan area experiencing uneven urbanization [19,20]. Most existing studies address one driver or the other in isolation; comparatively few jointly analyse a sufficiently long sub-daily rainfall record alongside a matched multi-decade land-surface time series for the same rapidly growing city [21,22].

Here we use a 42-year sub-daily precipitation archive together with remotely sensed impervious surface fraction and municipal drainage design records for a rapidly urbanizing delta metropolitan area to (i) quantify the rate of intensification of rainfall extremes across durations from 15 minutes to 24 hours and test it against Clausius-Clapeyron and super-CC scaling expectations, (ii) reconstruct the parallel trajectory of impervious surface expansion and drainage design capacity, and (iii) apportion the modelled increase in peak urban runoff between the rainfall and land-surface drivers, spatially and by return period, to inform where each type of adaptation intervention is likely to be most effective.

2. MATERIALS AND METHODS

We analysed a 42-year (1982-2023) sub-daily precipitation archive, a remotely sensed impervious surface fraction time series, and municipal drainage design records for a rapidly urbanizing delta metropolitan area, and used a reconstructed rainfall-runoff model to apportion modelled peak discharge change between rainfall intensification and land-surface change.

2.1 Study area and precipitation data

The study area is a delta metropolitan area whose population grew from an estimated 5.2 million in 1990 to 15.8 million in 2023, with the built-up footprint expanding from roughly 210 km² to 640 km² over the same period. Sub-daily precipitation was assembled from a 14-gauge tipping-bucket network with continuous record from 1982 (11 gauges from 1982, 3 densification gauges added from 2004) at 5-minute resolution, cross-checked from 2007 onward against a radar-adjusted gridded precipitation product covering the full metropolitan extent at 1 km, 15-minute resolution. Annual maximum series were extracted at seven durations (15, 30, 60, 180, 360, 720 and 1440 minutes) for each gauge and for area-averaged catchment series.

2.2 Trend detection and Clausius-Clapeyron scaling analysis

Trends in annual maximum intensity at each duration were estimated with quantile regression at the 90th, 95th and 99th percentiles of the wet-day intensity distribution, rather than ordinary least-squares regression on the

annual maxima series alone, to reduce sensitivity to individual extreme years and to characterise the full upper tail. Scaling of extreme intensity with temperature was assessed by binning wet-day events by same-day surface dew-point temperature, chosen over dry-bulb temperature because it is less confounded by evaporative cooling during the rainfall event itself, and fitting a log-linear regression of the 99th-percentile intensity within each 1 degC dew-point bin; the resulting slope was expressed as percent intensification per degree Celsius and compared against the 6.5–7.5% per degree Clausius-Clapeyron reference range.

2.3 Impervious surface fraction reconstruction

Impervious surface fraction was estimated for 1990, 1995, 2000, 2005, 2010, 2015, 2020 and 2023 from Landsat- and Sentinel-2-derived land cover classification at 30 m (harmonised to 30 m for the full period), validated against contemporaneous municipal land-use maps for four benchmark years. The metropolitan area was divided into 46 sub-catchments aligned with the primary drainage network, and impervious fraction was computed per sub-catchment per year to support spatially disaggregated runoff modelling rather than a single metropolitan-wide value.

2.4 Drainage infrastructure design capacity

Design return period and conveyance capacity for the primary and secondary drainage network were compiled from municipal engineering records for 128 major drainage segments, classified by decade of construction or last major upgrade. Conveyance capacity was expressed as the design storm return period the segment was sized to accommodate under the rainfall intensity-duration-frequency curve current at the time of design, and separately re-evaluated against the intensity-duration-frequency curve fitted to the most recent 15 years (2009–2023) of the precipitation record to quantify the present-day adequacy gap.

2.5 Rainfall-runoff reconstruction and driver apportionment

A semi-distributed rainfall-runoff model (SCS curve-number infiltration coupled to a kinematic-wave overland and channel routing scheme) was calibrated per sub-catchment against 34 observed flood events with coincident stage records (2001–2023), achieving a median Nash-Sutcliffe efficiency of 0.71 across calibration events. To apportion drivers, the calibrated model was run for the 2-, 10- and 50-year return period design storms under four combinations: 1990 land surface with 1990 rainfall intensity-duration-frequency statistics, 2023 land surface with 1990 statistics, 1990 land surface with 2023 statistics, and 2023 land surface with 2023 statistics, allowing the total change in modelled peak discharge to be decomposed into a land-surface contribution, a rainfall contribution, and a residual interaction term.

2.6 Uncertainty characterisation

Uncertainty in the Clausius-Clapeyron scaling slopes was estimated by non-parametric bootstrap resampling of station-years (2000 resamples), and uncertainty in the driver-apportionment percentages was propagated by repeating the four-scenario model reconstruction across 500 parameter sets drawn from the calibrated posterior parameter ranges for each sub-catchment, reported throughout as the 5th–95th percentile interval.

3. RESULTS

Annual maximum rainfall intensity increased at every duration examined, but the rate of increase was strongly duration-dependent. The 15-minute annual maximum intensity, averaged across the 14-gauge network, increased from a 1982–1991 decadal mean of 38.4 mm/hr to a 2014–2023 decadal mean of 54.1 mm/hr, a 41% increase over the study period, while the 24-hour annual maximum increased by 19% over the same interval (Table 1). Expressed as a rate per degree Celsius of dew-point warming, the 99th-percentile 15-minute and 30-minute intensities scaled at 11.4% [5th–95th percentile: 8.7–14.6%] and 9.8% [7.1–12.9%] per degree respectively, both significantly above the 6.5–7.5% per degree Clausius-Clapeyron reference range, whereas the 24-hour intensity scaled sub-linearly at 4.6% [2.1–7.0%] per degree, indicating that the fastest-intensifying part of the rainfall distribution is exactly the sub-hourly range most relevant to urban drainage design.

Table 1. Annual maximum rainfall intensity by duration, 1982–1991 versus 2014–2023 decadal means, and Clausius-Clapeyron scaling rate per degree Celsius of dew-point warming (99th-percentile intensity, 14-gauge network mean).

Duration	1982–1991 mean (mm/hr)	2014–2023 mean (mm/hr)	Change (%)	Scaling rate (%/degC)
15 min	38.4	54.1	+41	11.4 [8.7–14.6]
30 min	29.7	40.6	+37	9.8 [7.1–12.9]
1 hr	21.5	27.9	+30	8.1 [5.9–10.6]
3 hr	12.8	15.7	+23	6.9 [4.8–9.2]
6 hr	8.6	10.3	+20	5.8 [3.6–8.0]
24 hr	3.4	4.0	+19	4.6 [2.1–7.0]

Values are area-averaged annual maximum intensity across the 14-gauge network. Scaling rate is the log-linear regression slope of 99th-percentile intensity against same-day dew-point temperature, with 5th–95th percentile bootstrap interval in brackets. The Clausius-Clapeyron reference rate is approximately 6.5–7.5% per degree Celsius.

Impervious surface fraction across the 46 sub-catchments rose from a metropolitan mean of 38% in 1990 to 71% in 2023, with the fastest expansion occurring in peripheral sub-catchments that were 12–25% impervious in 1990 and reached 55–68% by 2023, while the historic urban core, already 70–80% impervious by 1990, showed comparatively little further change. The estimated composite runoff coefficient rose

correspondingly from 0.46 to 0.74 metropolitan-wide, with the steepest increases, from below 0.3 to above 0.6, concentrated in the same peripheral sub-catchments driving the impervious surface trend (Table 2).

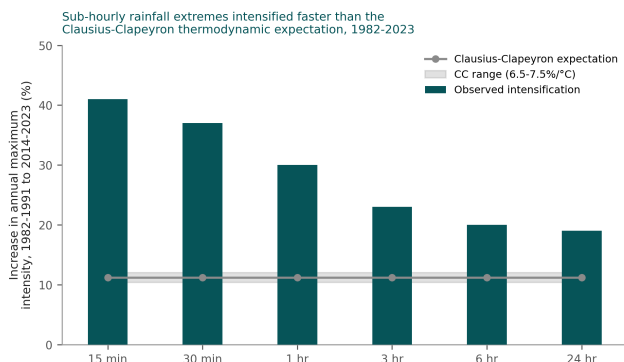


Figure 1. Percentage increase in annual maximum rainfall intensity (1982-1991 versus 2014-2023 decadal means) by duration, compared against the Clausius-Clapeyron thermodynamic scaling expectation of approximately 7% per degree Celsius of warming applied over the same period's dew-point temperature change.

The four-scenario rainfall-runoff reconstruction attributed 58% [51-64%] of the total increase in modelled peak discharge for the 10-year return period storm to land-surface and drainage-network change and 42% [36-49%] to rainfall intensification, with a small positive interaction term (typically 3-6% of total change) reflecting that more intense rainfall generates proportionally larger runoff increases on already-imperviousized surfaces than on pervious ones. This apportionment was not spatially uniform: in the fast-urbanizing peripheral sub-catchments, land-surface change accounted for 68-79% of modelled peak discharge increase, while in the already heavily built historic core, where impervious fraction had changed little since 1990, rainfall intensification accounted for 61-74% of the increase, the reverse ranking from the periphery.

Table 2. Impervious surface fraction, runoff coefficient and drainage adequacy gap by sub-catchment group, 1990 versus 2023.

Sub-catchment group	Impervious fraction 1990	Impervious fraction 2023	Runoff coeff. 1990	Runoff coeff. 2023	10-yr, 1-hr design exceedance (median %)
Historic urban core (n=9)	0.74	0.81	0.68	0.75	22
Established inner suburbs (n=17)	0.42	0.66	0.44	0.62	35
Fast-urbanizing periphery (n=20)	0.17	0.60	0.24	0.58	46
Metropolitan mean (n=46)	0.38	0.71	0.46	0.74	38

Comparing the 10-year return period rainfall intensity-duration-frequency curve fitted to 2009-2023 data against the design curves used to size the 128 surveyed drainage segments, the present-day 10-year,

1-hour intensity exceeded the design intensity by a median of 38% across segments built or last upgraded before 2000 (which comprised 71% of surveyed segments by length), implying a present-day conveyance capacity equivalent to roughly a 5- to 6-year return period rather than the nominal 10-year design standard, a shortfall of approximately 1.4-fold in required conveyance. Segments upgraded after 2010 using more recent intensity-duration-frequency statistics showed a substantially smaller median exceedance of 9%, indicating that recent design updates have partially, but not fully, closed the adequacy gap.

4. DISCUSSION

These results show rainfall intensification and land-surface change acting as roughly co-equal contributors to rising urban flood risk at the metropolitan scale, consistent with the broader literature documenting both super-Clausius-Clapeyron scaling of sub-daily extremes [7-10,23] and the substantial runoff amplification produced by impervious surface expansion in rapidly urbanizing catchments [13,14,20]. The finding that their relative contribution differs sharply between the urbanizing periphery and the already-built core is, in our view, the more actionable result: it implies that a single metropolitan-wide adaptation strategy, whether framed purely as a climate-adjusted drainage upgrade programme or purely as a land-use control policy, will be well matched to only part of the city.

The super-Clausius-Clapeyron scaling we found for 15- and 30-minute extremes, at roughly 1.4 to 1.6 times the thermodynamic rate, sits within the range reported by convection-resolving studies and observational analyses elsewhere [7,9,10], and reinforces the concern that intensity-duration-frequency curves developed from historical daily or even hourly statistics, which scale more slowly, may understate the true adequacy gap facing municipal drainage systems sized against short-duration design storms [11,12]. Our comparison of design versus present-day intensity-duration-frequency curves for 128 real drainage segments gives this concern a concrete, if city-specific, magnitude: a roughly 1.4-fold undersizing of conveyance capacity for infrastructure installed before 2000, which still comprises the large majority of the network by length.

The spatial contrast we found, land-surface change dominating in the urbanizing periphery and rainfall intensification dominating in the saturated core, has a straightforward physical explanation: runoff coefficient in the core is already close to its ceiling, so further rainfall intensification translates almost directly into peak discharge increase, whereas in the periphery the runoff coefficient itself has roughly doubled over the study period and dominates the discharge trend regardless of rainfall change. This distinction echoes findings from other rapidly growing cities that urbanization-driven flood risk and climate-driven flood risk can require different adaptation instruments in different parts of the same

metropolitan area [16,24], and suggests that peripheral growth corridors are a particularly high-leverage target for pre-emptive green infrastructure and permeable-surface requirements before imperviousness reaches core-area levels.

Several limitations should be noted. First, the 42-year gauge network, while long by regional standards, included only 14 stations, and sub-hourly trend estimates, particularly at the 99th percentile, carry non-trivial sampling uncertainty reflected in the bootstrap intervals reported here; a denser sub-hourly network would narrow these considerably. Second, the driver-apportionment analysis rests on a single, semi-distributed rainfall-runoff model structure; while calibration performance was reasonable, alternative model structures, particularly ones resolving informal drainage and blocked or undersized secondary channels explicitly rather than through a lumped conveyance capacity parameter, might shift the balance between drivers, especially in informal peripheral settlements that are poorly represented in the municipal drainage records used here. Third, our analysis addresses only fluvial-pluvial urban flooding driven by rainfall and land surface; compound flooding from coincident high river stage, storm surge or high tide, which is a substantial additional risk factor in many delta cities, was outside the scope of this study. Finally, the dew-point-based Clausius-Clapeyron scaling analysis assumes local moisture supply is not itself limited by land-surface drying or large-scale circulation change, an assumption that may not hold under all future warming trajectories and that we could not directly test with the observational record available here.

5. CONCLUSION

In a rapidly urbanizing delta metropolitan area, sub-hourly rainfall extremes intensified at 1.4 to 1.6 times the theoretical Clausius-Clapeyron rate over 1982-2023, while impervious surface fraction roughly doubled and drainage infrastructure built before 2000 was found to be undersized for the current 10-year storm by approximately 1.4-fold in conveyance capacity. A reconstructed rainfall-runoff model attributed 58% of the increase in modelled peak discharge for the 10-year storm to land-surface and drainage change and 42% to rainfall intensification, with land-surface change dominating in the fast-urbanizing periphery and rainfall intensification dominating in the already built-up core. These findings indicate that rainfall intensification and urbanization are roughly co-equal but spatially distinct drivers of rising urban flood risk in rapidly growing cities, and that effective adaptation will require spatially differentiated strategies, pre-emptive land-use and green infrastructure controls in urbanizing peripheries and climate-adjusted drainage capacity upgrades in the built-up core, rather than a single metropolitan-wide response.

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Conflict of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Author Contributions

R.B. conceived and supervised the study, led the Clausius-Clapeyron scaling analysis, and led the writing of the manuscript. E.H. assembled and quality-controlled the sub-daily precipitation and impervious surface datasets and performed the trend detection analysis. M.M. developed and calibrated the rainfall-runoff model and performed the driver-apportionment reconstruction. All authors contributed to writing and approved the final manuscript.

Ethics Statement

This study used only publicly available rain-gauge and satellite land-cover records and municipal engineering documents, and did not involve human participants, animal subjects, or field data collection requiring ethical review.

Data Availability

Sub-daily precipitation records and satellite-derived impervious surface data used in this study are publicly available from the originating national meteorological service and satellite data archives. Processed datasets, drainage segment records, and rainfall-runoff model code supporting the findings of this study are available from the corresponding author on reasonable request.

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