



Climatica



ISSN: 2989-5391 (Online)

Publisher: Tomorrow's Research Publications (TRP)

An International Peer-Reviewed Open Access Journal

Journal homepage: <https://trpubonline.org/index.php/Climatica>

RESEARCH ARTICLE

Sea Level Rise Vulnerability Mapping for Low-Lying Coastal Megacities

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ABSTRACT

Low-lying coastal megacities face a compound flood hazard in which global mean sea level rise interacts with local land subsidence and storm surge to produce relative water-level increases far larger, and far more spatially uneven, than sea level rise alone would suggest. We built a composite exposure and vulnerability map for five coastal megacities, Jakarta, Lagos, Dhaka, Ho Chi Minh City and Miami, combining a coastal digital elevation model corrected against ICESat-2 and airborne lidar validation points, a decadal Sentinel-1 InSAR subsidence record (2015-2022), sixth Coupled Model Intercomparison Project (CMIP6) sea level rise projections under SSP2-4.5 and SSP5-8.5 for 2050 and 2100, and a 1-in-100-year storm surge return-level estimate for each city, to generate bathtub-model flood extents refined by hydrological connectivity, which we intersected with gridded population (WorldPop) and OpenStreetMap-derived critical infrastructure layers. Composite relative sea level rise by 2100 under SSP5-8.5, sea level rise plus subsidence, ranged from 0.53 m in Miami, where subsidence is localized and slow, to 2.61 m in Jakarta, where subsidence locally exceeds 10 cm per year in groundwater-depleted districts, an order of magnitude greater than the eustatic contribution alone. Across the five cities, the population exposed to the combined 1-in-100-year storm surge on this composite surface reached an estimated 20.8 million residents by 2100 under SSP5-8.5, more than triple the 6.4 million exposed under present-day mean sea level, with Dhaka and Jakarta together accounting for 61% of the added exposure. Critical infrastructure counts followed a similar pattern, with the number of exposed health facilities across all five cities rising from 187 at present to 612 under the 2100 high-emissions composite scenario. Subsidence, rather than eustatic sea level rise, was the dominant driver of projected exposure growth in three of the five cities. These results indicate that vulnerability assessments relying on eustatic sea level rise projections alone substantially underestimate near-term flood exposure in subsidence-affected megacities, and that groundwater management is, in such settings, as consequential for coastal flood risk as global emissions trajectories.

Keywords: sea level rise; coastal megacities; land subsidence; storm surge; flood exposure; InSAR; digital elevation model; population exposure; critical infrastructure; climate adaptation

Received: July 3, 2023 | Accepted: September 27, 2023 | Published: December 20, 2023

Citation: Nielsen E, Sorensen D, Silva M. Sea Level Rise Vulnerability Mapping for Low-Lying Coastal Megacities. *Climatica*. 2023;1(2):1–6. DOI: [10.5281/zenodo.22801061](https://doi.org/10.5281/zenodo.22801061)

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1. INTRODUCTION

More than one in eight people on Earth now lives in a coastal urban agglomeration below 10 m elevation, and a disproportionate share of that population is concentrated in a small number of megacities where rapid, often informal urban expansion has occurred on reclaimed land, river deltas and drained wetlands that were low-lying and flood-prone even before any sea level rise is considered [1,2]. Global mean sea level has risen by roughly 21–24 cm since 1900, with the rate of rise accelerating from about 1.4 mm/yr over the twentieth century to 3.7 mm/yr over 2006–2018, and the most recent generation of process-based projections indicates a plausible range of further rise by 2100 spanning roughly 0.3 m to more than 1 m depending on emissions trajectory and on the still-uncertain contribution of marine ice sheet and ice cliff instabilities in Antarctica [3,4].

Eustatic sea level rise, however, is only one term in the flood hazard equation that coastal megacities actually face. Many of the world's largest coastal cities are subsiding, often rapidly, because of groundwater and hydrocarbon extraction, sediment compaction beneath engineered fill, and the reduction of natural sediment supply following upstream damming and delta channelization; in the most severely affected districts of Jakarta, Bangkok and several other Asian megacities, subsidence rates exceed 10 cm per year, an order of magnitude greater than the global mean rate of sea level rise itself [5,6]. Because subsidence is spatially heterogeneous at the scale of individual city districts, while sea level rise is comparatively uniform along a given coastline, the two hazards combine to produce relative sea level trajectories that vary enormously within a single city, a pattern that a citywide or national-average sea level rise projection cannot represent [7].

Storm surge superimposed on this rising baseline is what converts a gradual increase in mean water level into acute, life-threatening flood events, and the interaction is nonlinear: a modest rise in mean sea level can substantially shorten the return period of a given surge height, so that what was once a rare extreme event recurs every few years rather than every century [8,9]. Coastal flood exposure assessments that consider sea level rise, subsidence and storm surge separately, rather than as a combined relative water level acting on a single terrain surface, therefore risk materially underestimating both the magnitude and the near-term urgency of exposure growth, particularly in subsidence-affected deltaic cities where the local hazard is dominated by a process, groundwater-driven land subsidence, that is in principle far more tractable to manage through policy than global sea level rise itself [10,11].

Remote sensing has transformed the practicality of building such combined hazard surfaces at city scale. Interferometric synthetic aperture radar (InSAR) from Sentinel-1 and earlier missions now provides multi-year, millimeter-precision subsidence time series over large

urban areas at low cost, spaceborne and airborne lidar provide vertical accuracies sufficient to resolve the sub-meter elevation differences that determine which neighborhoods flood first, and high-resolution gridded population and infrastructure datasets allow exposure to be quantified at the scale of individual buildings and facilities rather than administrative averages [12,13,14]. Several prior studies have applied one or two of these data streams to individual megacities, but comparative, consistently processed exposure mapping across multiple subsidence-affected cities using a common combined sea level rise, subsidence and storm surge framework remains comparatively rare [15,16].

Here we construct such a comparative framework for five coastal megacities selected to span a range of subsidence severity and hydrodynamic setting, Jakarta, Lagos, Dhaka, Ho Chi Minh City and Miami, combining bias-corrected coastal terrain, decadal InSAR subsidence records, CMIP6-based sea level rise projections for 2050 and 2100 under two emissions scenarios, and city-specific 1-in-100-year storm surge return levels into a single composite relative water-level surface for each city. We intersect the resulting flood extents with gridded population and critical infrastructure data to quantify present and projected exposure, and we decompose the growth in exposure by hazard component to test whether subsidence or eustatic sea level rise is the dominant driver of projected flood risk growth in each city, a distinction with direct relevance for whether local or global interventions offer the more tractable near-term risk reduction pathway.

2. MATERIALS AND METHODS

We built a composite relative sea level surface for five coastal megacities by combining a bias-corrected coastal digital elevation model, a decadal InSAR subsidence record, CMIP6 sea level rise projections, and city-specific storm surge return levels, and intersected the resulting flood extents with gridded population and infrastructure datasets to quantify present-day and projected exposure under two emissions scenarios.

2.1 Study cities and coastal terrain data

Five coastal megacities were selected to span a range of subsidence severity, coastal geomorphology and regional storm climatology: Jakarta (Indonesia), Lagos (Nigeria), Dhaka (Bangladesh), Ho Chi Minh City (Vietnam) and Miami (United States). For each city we assembled a coastal terrain model at 10 m horizontal resolution by merging the Copernicus GLO-30 digital elevation model with ICESat-2 ATL08 and, where available, airborne lidar validation points, applying a locally fitted vertical bias correction because radar-derived elevation models are known to overestimate ground elevation in dense urban and vegetated terrain by up to 3–5 m, an error large enough to substantially distort low-lying flood extents if left uncorrected [17,18]. Corrected elevations were

referenced to each city's local mean sea level datum using tide gauge records with at least 15 years of continuous data.

2.2 Land subsidence from InSAR time series

Vertical land motion for 2015–2022 was derived from Sentinel-1 interferometric wide-swath acquisitions processed with a small baseline subset (SBAS) time series approach, referenced to stable ground control points identified outside each city's known subsidence bowls using long-term GNSS station records where available. Subsidence rates were interpolated to a common 100 m grid for each city and linearly extrapolated to 2050 and 2100 under the assumption of unchanged groundwater extraction practices, an assumption we treat explicitly as a limitation given documented cases of subsidence deceleration following groundwater regulation elsewhere [6].

2.3 Sea level rise and storm surge scenarios

Eustatic sea level rise projections for each city's coastal grid cell were taken from the IPCC AR6 sea level projection dataset under SSP2-4.5 and SSP5-8.5, for the 2050 and 2100 horizons, using the median projection and treating the likely range as a source of scenario uncertainty discussed separately. City-specific 1-in-100-year storm surge return levels were obtained from published regional surge modeling studies and, where unavailable at city scale, from the nearest long-record tide gauge extreme value analysis, added to the composite relative sea level surface as a uniform offset along each city's open coastline and attenuated inland along mapped tidal and drainage channels.

2.4 Composite flood surface and hydrological connectivity

For each city, scenario and horizon we constructed a composite relative water level surface as the sum of present terrain elevation (negative subsidence to 2015–2022, extrapolated subsidence to the target year, eustatic sea level rise to the target year, and the 1-in-100-year storm surge offset. Flood extent was delineated using a modified bathtub approach that enforces hydrological connectivity to the open coast or a mapped tidal channel, excluding topographically enclosed low points not connected to a water source, which we found in preliminary testing to remove a meaningful fraction of spurious inland flood polygons generated by a naive elevation-threshold approach, consistent with prior critiques of unmodified bathtub flood mapping [19,20].

2.5 Population and infrastructure exposure

Population exposure was quantified using WorldPop 100 m gridded population estimates for the most recent available year, held constant in absolute count across scenarios to isolate the effect of changing flood extent from that of population growth, with population growth treated separately in a sensitivity calculation reported in the discussion. Critical infrastructure layers, health facilities, schools, electricity substations and major

roads, were extracted from OpenStreetMap and cross-checked against national facility registries where available. A population or facility was classified as exposed if it fell within the composite flood extent for a given city, scenario and horizon.

2.6 Uncertainty characterization and decomposition

To decompose the relative contribution of eustatic sea level rise versus subsidence to projected exposure growth, we recomputed the composite flood surface and resulting exposure with subsidence held at its 2022 level (isolating the sea level rise contribution) and, separately, with sea level rise held at its 2022 level (isolating the subsidence contribution), for each city under SSP5-8.5 at 2100. Uncertainty in exposure estimates arising from digital elevation model vertical error was assessed by repeating the flood delineation with the terrain surface perturbed by plus and minus one root-mean-square vertical error estimate derived from the ICESat-2 and lidar validation points.

3. RESULTS

Composite relative sea level rise by 2100 under SSP5-8.5, combining eustatic rise and extrapolated subsidence, varied more than fourfold across the five cities, from 0.53 m in Miami to 2.61 m in Jakarta (Table 1). Dhaka (1.44 m) and Ho Chi Minh City (1.18 m) fell in an intermediate range dominated by moderate but widespread subsidence across large areas of low-lying delta terrain, while Lagos (0.71 m) showed a composite rise only modestly above the eustatic contribution alone, consistent with its comparatively localized and lower-rate subsidence pattern in the InSAR record.

Table 1. Composite relative sea level rise and population exposed to the 1-in-100-year storm surge, by city and scenario.

City	Present exposed population (millions)	Composite RSLR 2100, SSP5-8.5 (m)	Exposed population 2100, SSP2-4.5 (millions)	Exposed population 2100, SSP5-8.5 (millions)
Jakarta, Indonesia	2.1	2.61	4.6	7.4
Dhaka, Bangladesh	1.8	1.44	3.3	5.7
Ho Chi Minh City, Vietnam	1.0	1.18	1.9	3.3
Lagos, Nigeria	1.2	0.71	1.7	3.6
Miami, United States	0.3	0.53	0.6	0.8
Five-city total	6.4	-	12.1	20.8

RSLR: composite relative sea level rise (eustatic sea level rise plus extrapolated land subsidence). Exposed population is estimated resident population within the composite 1-in-100-year storm surge flood extent, WorldPop grid held constant across scenarios.

Population exposed to the combined 1-in-100-year storm surge on the composite flood surface rose from an estimated 6.4 million residents across the five cities under present-day conditions to 12.1 million under

SSP2-4.5 at 2100 and 20.8 million under SSP5-8.5 at 2100. Jakarta and Dhaka together accounted for 61% of the added exposure between present-day and the SSP5-8.5/2100 scenario, reflecting both their high composite relative sea level rise and the large populations resident on newly inundated low-elevation land; Miami, by contrast, showed the smallest absolute increase in exposed population of the five cities despite its high asset density, because its subsidence signal is weak and localized rather than basin-wide.



Figure 1. Decomposition of projected 2100 (SSP5-8.5) exposed-population growth attributable to eustatic sea level rise versus land subsidence, by city, relative to the full composite scenario.

The hazard decomposition (Figure 1) shows that subsidence, not eustatic sea level rise, was the dominant contributor to projected 2100 exposure growth in three of the five cities, Jakarta, Dhaka and Ho Chi Minh City, where holding subsidence at its 2022 level reduced projected exposed population by 54%, 41% and 37% respectively relative to the full composite scenario, versus reductions of only 9% and 14% in Lagos and Miami when subsidence was held fixed. Holding eustatic sea level rise at its 2022 level while allowing subsidence to continue reduced exposure by a comparatively modest 12-19% across all five cities, underscoring that in the three subsidence-dominated cities, local groundwater management, rather than global emissions trajectory, is the larger near-term lever on projected flood exposure.

Table 2. Critical infrastructure facilities exposed to the composite 1-in-100-year storm surge flood extent, present day versus 2100 (SSP5-8.5), five-city total.

Infrastructure type	Present exposed count	Exposed count, 2100 SSP5-8.5	Increase (factor)
Health facilities	187	612	3.3x
Schools	410	1,285	3.1x
Electricity substations	34	129	3.8x
Major road segments (km)	890	2,640	3.0x

Critical infrastructure exposure followed a broadly similar pattern. The number of exposed health facilities across all five cities rose from 187 at present to 340 under SSP2-4.5/2100 and 612 under SSP5-8.5/2100, with Jakarta alone accounting for 218 of the 612 facilities exposed under the high-emissions 2100 scenario, more than a third of the five-city total despite Jakarta

representing a smaller share of total exposed population. Exposed electricity substations showed the steepest relative increase of any infrastructure category, rising from 34 at present to 129 under SSP5-8.5/2100 across the five cities, a finding with direct implications for cascading power-outage risk during future surge events given that several exposed substations serve areas beyond the directly flooded footprint (Table 2).

4. DISCUSSION

These results reinforce a point made increasingly often in the coastal hazard literature but still inconsistently reflected in vulnerability assessments that rely on eustatic sea level rise projections alone: in subsidence-affected deltaic megacities, land subsidence is frequently the larger and more immediate driver of relative sea level rise, and consequently of flood exposure growth, than global emissions trajectory over the coming decades [5,6,21]. The scale of the difference we find, subsidence responsible for more than half of projected 2100 exposure growth in Jakarta versus roughly one-tenth in Miami, illustrates why a single global sea level rise narrative, however well constrained, cannot substitute for city-specific hazard assessment incorporating local land motion.

The practical implication is that the two dominant hazard components identified here respond to different, and largely independent, policy levers. Eustatic sea level rise is governed by cumulative global greenhouse gas emissions and is not meaningfully alterable by any single city's actions on a multi-decade timescale [3,4], whereas groundwater-driven subsidence has in several documented cases been substantially slowed by regulating extraction and expanding piped water supply, most notably in Tokyo and, more recently, in parts of Shanghai [6,22]. For Jakarta, Dhaka and Ho Chi Minh City, our decomposition suggests that sustained groundwater management could plausibly avert a majority of the subsidence-attributable share of projected exposure growth, an intervention with a far shorter timescale of effectiveness than emissions mitigation, though one that carries its own substantial cost, governance and freshwater-supply trade-offs that this study does not evaluate.

The disproportionate exposure of health facilities and electricity substations relative to population, particularly in Jakarta, is consistent with the tendency of critical infrastructure in rapidly urbanized deltaic megacities to have been sited on reclaimed or low-lying land decades before either subsidence or sea level rise were considered planning constraints [11,23]. Because a single exposed substation or hospital can affect services well beyond its immediate flood footprint, infrastructure-focused exposure metrics of the kind reported here may better capture the functional consequences of coastal flooding than population-exposure counts alone, and we would encourage future assessments to report both rather than

treating population as a sufficient proxy for infrastructural risk.

Several limitations should qualify these findings. First, our subsidence extrapolation to 2050 and 2100 assumes unchanged groundwater extraction practices, which is a deliberately conservative baseline rather than a prediction, and cities that implement effective groundwater regulation, as parts of Jakarta have begun to pursue, would see materially lower composite relative sea level rise than we project here [6]. Second, the bathtub-with-connectivity flood model used here, while an improvement on a naive elevation threshold, does not resolve wave run-up, coastal defense infrastructure such as sea walls and polders, or the dynamic interaction between storm surge and river discharge during compound flood events, all of which can materially alter flood extent and are better captured by full hydrodynamic modeling at the cost of far greater computational and data demands [19,24]. Third, holding population constant across scenarios isolates the hazard signal but understates total future exposure in rapidly growing cities; a sensitivity calculation applying medium-variant United Nations population growth projections to Lagos and Dhaka, the two fastest-growing cities in our sample, increased projected 2100 SSP5-8.5 exposed population by a further 28% and 19% respectively beyond the figures reported here. Finally, storm surge return levels were drawn from existing published studies of varying vintage and methodology across the five cities rather than derived from a single consistently configured surge model, introducing a source of cross-city inconsistency that a fully integrated hydrodynamic framework would resolve but that was outside the scope of the present remote-sensing-based comparative assessment [8,9].

5. CONCLUSION

Combining coastal terrain, InSAR-derived subsidence, CMIP6 sea level rise projections and storm surge return levels into a single composite flood exposure framework across five coastal megacities shows that projected population and infrastructure exposure to coastal flooding varies far more steeply across cities than eustatic sea level rise alone would predict, and that land subsidence, not global emissions trajectory, is the dominant driver of projected 2100 exposure growth in Jakarta, Dhaka and Ho Chi Minh City. Population exposed to a 1-in-100-year storm surge across the five cities is projected to more than triple by 2100 under a high-emissions scenario, from 6.4 to 20.8 million, with critical infrastructure exposure, particularly health facilities and electricity substations, growing disproportionately in the most subsidence-affected cities. These findings support prioritizing local groundwater and land-use management alongside global emissions mitigation as a near-term, city-scale lever for reducing coastal flood exposure in subsidence-prone megacities, and argue for coastal vulnerability assessments to incorporate local land motion rather than relying on

eustatic sea level rise projections alone.

Acknowledgements

The authors thank the national mapping and meteorological agencies of the five study cities for access to tide gauge and storm surge reference data, and colleagues at the Nordic Institute of Climate and Ecology for helpful discussion of the InSAR subsidence processing chain. We also thank the open data communities behind OpenStreetMap and WorldPop, whose datasets made the infrastructure and population exposure analysis possible.

Funding

This work was supported by internal research funds from the Northmoor School of Meteorology and Climate Science, the Nordic Institute of Climate and Ecology, and the Baltic Institute of Renewable Energy. No external grant funding was received for this study, and the funders had no role in study design, data collection or analysis, the decision to publish, or preparation of the manuscript.

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

E.N. conceived and supervised the study, designed the composite flood surface methodology, and led the writing of the manuscript. D.S. processed the Sentinel-1 InSAR subsidence time series and the coastal digital elevation model corrections. M.S. assembled and analyzed the population and infrastructure exposure datasets and performed the hazard decomposition analysis. All authors contributed to writing and approved the final manuscript.

Ethics Statement

This study used only publicly available satellite imagery, elevation, population and infrastructure datasets, and did not involve human participants, animal subjects, or field data collection requiring ethical review.

Data Availability

Sentinel-1 imagery, Copernicus GLO-30 elevation data, WorldPop population grids and OpenStreetMap infrastructure layers used in this study are publicly available from their respective originating archives. Processed composite flood surfaces, subsidence rasters, and exposure analysis code supporting the findings of this study are available from the corresponding author on reasonable request.

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