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Assessment of Property Exposure to Coastal Flooding in Urban Areas: Application in Miami (FL, USA)

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INTRODUCTION

The fluctuations in nearshore Sea Level Elevation (SLE) are a crucial indicator of climate change, significantly affecting low-lying coastal regions (Williams & Gutierrez, 2009). South Florida (USA) is one of the world's most vulnerable areas, frequently experiencing extreme sea levels due to hurricanes and tropical storms. Miami, with its urban infrastructure exposed to the Atlantic Ocean, is facing risks from such climate-induced adversities (Palm & Bolsen, 2020). Storm surges have inundated coastal areas during past cyclonic weather events, leading to urban disruptions with important socio-economic and environmental impacts.

SCOPE OF STUDY

This study explores new ways to estimate the exposure of properties (at the plot holding level) to coastal flooding based on highly detailed inundation hazard maps (Makris et al., 2024). These are produced by a recent version of the CoastFLOOD model (Makris et al., 2023), specifically designed for high-resolution (1-2 m grid-scale) simulations of coastal inundation driven by extreme SLE scenarios along South Florida's shorelines over a 30-year timeframe (1994-2023). The primary aim is to analyze the interannual variability of urban flooding impacts on key residential areas in Miami while evaluating the building-level exposure to seawater floods along the Biscayne Bay coast and Miami Beach. The study also investigates long-term SLE trends and extremes using historical tide gauge records to minimize the uncertainty of environmental parametric inputs. The goal is to improve understanding of seawater inundation impacts and support coastal flood risk assessment at the building and property levels using detailed GIS flood maps.

METHODOLOGY

Study Area – Sea Level Data

Miami-Dade County (MDC), located in southeastern Florida, is highly susceptible to storm surges, particularly during hurricanes and King Tide events (Chao et al., 2021). The study area (Figure 1) was chosen based on its diverse Land Use and Land Cover (LULC) while considering several local socio-economic factors (e.g., dense population and valuable real estate). The extents of the study area and its simulation domain were defined based on the computational feasibility for flood modelling (~$15{\cdot}10^3$ grid cells). It includes the northern Biscayne Bay coasts and Miami Beach, representing both naturally sheltered regions and highly exposed urban shorelines. SLE data were sourced from NOAA's hourly tide gauge records in Virginia Key (central Biscayne Bay), covering the 1994–2023 period. The highest recorded SLE (=1.172 m >244-year return value) occurred during Hurricane Irma, a devastating Category 5 tropical cyclone in early September 2017.

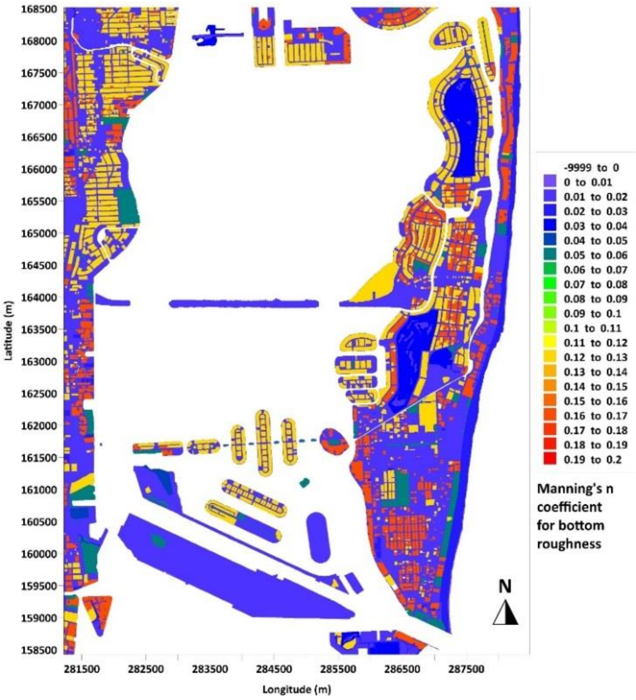

Figure 1. Chorochromatic-type map of the Miami study area's Manning *n* coefficient of terrain bottom roughness based on NLCD's LULC data, overlaid on NOAA's 2-m resolution Digital Surface Model (DSM) for land elevation, measured from North American Vertical Datum 1988.

Numerical Model – Extreme Value Analysis

CoastFLOOD is a high-resolution, raster-based, two-dimensional flood routing simulation model that tracks seawater propagation using mass balance equations (Makris et al., 2023). It integrates Manning's roughness coefficients to represent terrain friction and is calibrated using NOAA datasets (Makris et al., 2024). The model is applied to assess urban flood exposure under various SLE scenarios. Our analysis identifies 2-, 5-, 10-, …, 100-, …, 1000-, … 10000-year return values of SLEs (Table 1), based on a GEV distribution fit of annual block maxima, using the *extRemes* package of R-studio. Thresholds and long-term trends are estimated by applying statistical models such as Empirical Mode Decomposition and Pettit Homogeneity tests.

Property-Level Exposure to Coastal Flooding

The impact of the coastal inundation hazard was estimated based on a generic Flood Cover Percentage (FCP%; Androulidakis et al., 2023). The assessment components of property-level exposure to coastal inundation comprise very high-resolution analyses of both building-level and elements-at-risk impact metrics to manage seawater flooding in coastal cities and their adverse effects (Iliadis et al., 2023). For example, the quantifiable metrics include inundation probability measures per property by number of flooded cells, min-max, standard deviation, median, and high-order percentiles of hazard magnitudes in terms of flooded area, maximum floodwater height and velocity, mean encroached floodwater depth, vicinity of buildings to flood boundaries, etc., defined per discrete property by an effective buffer zone around its bounds, regarding a diverse sample of owners and stakeholders. A classification scheme to categorize buildings and properties by a 5-level Likert-scale ranking formulates a cumulative exposure index for each element at risk.

Table 1. Extreme coastal SLE scenarios at MDC study area.

A/A	Return Period (-years)	SLE_{extr} (m)	A/A	Return Period (-years)	SLE_{extr} (m)
1	2	0.520	7	200	1.126
2	5	0.651	8	500	1.249
3	10	0.741	9	1000	1.344
4	20	0.829	10	2000	1.441
5	50	0.945	11	5000	1.572
6	100	1.035	12	10000	1.674

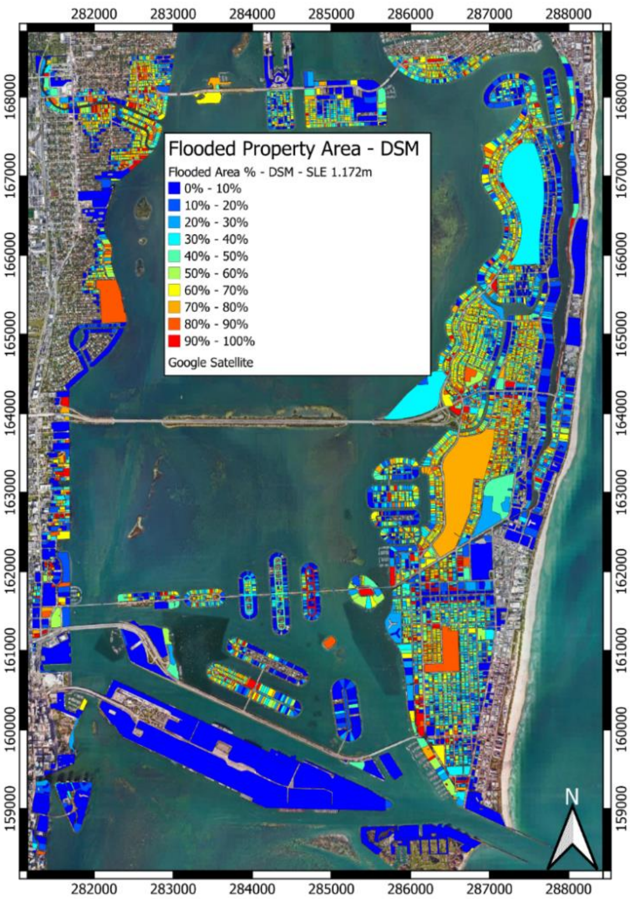

Figure 2. Choropleth-type map of flooded properties portraying the percentage of inundated area within each discrete plot holding over the study region, based on CoastFLOOD simulations for Hurricane Irma (SLE = 1.172 m).

RESULTS

Model Validation - Coastal Inundation Assessment

The model's performance was evaluated by comparing it with NOAA's Sea Level Rise (Bathtub) Viewer outputs, which assess flooded areas under similar SLE conditions. The results revealed a quite high correlation between CoastFLOOD simulations and NOAA estimations, with a Goodness-of-Fit, GoF>0.8. Differentiations are plausible since CoastFLOOD model considers the flow dynamics due to bottom friction. Flood heights are analyzed for significant storm surge events (e.g. Hurricane Irma) and 12 extreme scenarios (Table 1). CoastFLOOD simulations indicate that areas with land elevation up to 2 m above mean sea level are particularly exposed, corroborating the FEMA (2018) reports of surge-induced inundation in downtown MDC.

Property-Level Exposure Analysis

The key findings of flood exposure assessment at the property level using GIS-based spatial analyses (Figure 2) include:

- Low-lying residential areas exhibit high flood exposure, particularly in southwestern Miami Beach and island barriers.
- Properties near Indian Creek and Biscayne Bay's western coastlines are highly exposed to inundation events.
- Coastal infrastructure, such as the port and highways, demonstrates flood pooling due to impermeable surfaces.

CONCLUSIONS

This research presents a high-resolution numerical approach for simulating coastal flooding in Miami-Dade County. We estimate detailed GIS-based impacts by incorporating long-term *in-situ* observations and proper extreme value analysis of SLE, providing insights into property-level exposure to flood hazards. The findings highlight the need for enhanced urban planning and adaptation strategies to mitigate future coastal hazards from hurricane-induced storm surges.

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