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RESEARCH ARTICLE

Nature-Based Solutions for Urban Flood Resilience in Coastal Cities

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ABSTRACT

Coastal cities face compounding flood risk from sea-level rise, intensifying storm surge and heavier rainfall, prompting growing interest in nature-based solutions (NBS) as complements or partial alternatives to grey infrastructure. We compared NBS performance and cost-effectiveness for urban flood resilience across four coastal case-study cities, Rotterdam, Miami, Jakarta and Lagos, spanning temperate, subtropical and tropical settings with contrasting flood drivers. Using coupled hydrodynamic-hydrological models (Delft3D and SWMM) calibrated against documented historical flood events, we simulated peak water levels and inland flood extent under a 100-year design storm combined with each city's locally projected 2050 sea-level rise, comparing baseline conditions against four NBS scenarios, tidal wetland or mangrove restoration, permeable pavement retrofits, bioswale networks, and a combined multi-measure scenario, alongside a conventional grey-infrastructure upgrade scenario. Across cities, the combined NBS scenario reduced simulated peak flood extent by a mean of 34% (range 22-46%) relative to baseline, compared with 41% for the grey-infrastructure scenario, but at approximately 38% of the median per-hectare capital cost, with co-benefits (urban heat reduction, habitat provision, recreational amenity) valued at an additional USD 1.8-4.6 million per km² over a 30-year horizon. Tidal wetland and mangrove restoration alone attenuated storm surge peak water levels by 0.12-0.31 m per 100 m of restored width, consistent with prior wave-attenuation findings. Permeable pavement and bioswale retrofits reduced pluvial peak runoff by 18-29% in high-density catchments but showed limited benefit against surge-dominated flooding. We conclude that NBS deliver flood-risk reductions approaching those of grey infrastructure at substantially lower cost once co-benefits are included, but perform best as hybrid grey-green systems rather than standalone substitutes in cities exposed to severe storm surge.

Keywords: nature-based solutions; urban flood resilience; coastal cities; mangrove restoration; tidal wetlands; permeable pavement; bioswales; green infrastructure; grey infrastructure; cost-effectiveness

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1. INTRODUCTION

More than 600 million people live in low-elevation coastal zones worldwide, and the flood exposure of coastal urban populations is projected to grow substantially over the coming decades as sea levels rise, tropical and extratropical storms intensify, and impervious urban land cover continues to expand [1,2]. Conventional grey infrastructure, seawalls, levees, storm-surge barriers and piped drainage networks, remains the dominant engineering response, but rising construction costs, long design lifetimes that must accommodate deep sea-level rise uncertainty, and the loss of ecological and amenity value associated with hard defences have motivated growing interest in nature-based solutions (NBS) as complements or partial substitutes [3,4].

A substantial body of evidence now supports the flood-risk-reduction function of coastal and urban ecosystems. Tidal marshes and mangroves attenuate wave energy and reduce storm surge peak water levels through vegetative drag and friction, with attenuation rates that scale with restored width and vegetation density [5,6], while globally mangroves alone have been estimated to prevent tens of billions of US dollars in flood damage annually [7]. Within the urban fabric itself, permeable pavements, bioswales, rain gardens and other green stormwater infrastructure reduce pluvial flood risk by increasing infiltration and attenuating peak runoff, though reported performance varies widely with local soil, climate and design specifications [8,9,10].

Despite this evidence base, most quantitative NBS performance studies examine a single measure in a single city or catchment, and comparative cost-effectiveness evidence spanning multiple NBS types, multiple climatic settings, and a common grey-infrastructure benchmark remains comparatively scarce [11,12]. This gap limits the ability of coastal planners to judge when NBS can substitute for grey infrastructure, when they are best deployed as a hybrid complement, and how their cost-effectiveness compares once co-benefits beyond flood risk reduction, such as urban heat mitigation and habitat provision, are taken into account [13,14].

Here we address this gap through a harmonised comparative assessment of NBS flood performance and cost-effectiveness across four coastal cities selected to span a range of flood drivers and climatic settings: Rotterdam (Netherlands, temperate, surge- and pluvial-flood-exposed delta city), Miami (United States, subtropical, surge- and groundwater-exposed low-lying city), Jakarta (Indonesia, tropical, subsidence- and monsoon-exposed megacity), and Lagos (Nigeria, tropical, rapidly urbanising lagoon city). For each city we simulate flood outcomes under a common 100-year design storm and locally projected 2050 sea-level rise across a consistent set of NBS and grey-infrastructure scenarios, enabling direct cross-city comparison of both physical flood-reduction performance and

cost-effectiveness.

2. MATERIALS AND METHODS

We combined coupled hydrodynamic-hydrological modelling with a structured cost and co-benefit assessment across four coastal case-study cities, comparing a baseline scenario against four nature-based solution (NBS) scenarios and one conventional grey-infrastructure scenario under a common design storm and locally projected sea-level rise.

2.1 Case-study city selection

Rotterdam, Miami, Jakarta and Lagos were selected to represent contrasting flood drivers (storm surge, pluvial runoff, land subsidence and monsoon rainfall, respectively, in varying combination), climatic zones (temperate, subtropical and tropical), and existing coastal protection infrastructure, spanning cities with long-established grey defences (Rotterdam) through to cities with predominantly informal or partial protection (Lagos).

2.2 Hydrodynamic and hydrological modelling

Coastal storm surge and inland flood propagation were simulated using Delft3D-FLOW coupled to a SOBEK/SWMM urban drainage schematisation for each city, with model bathymetry, topography and drainage network data obtained from national or municipal sources and supplemented with satellite-derived digital elevation data where local data were unavailable; each model was calibrated against at least one documented historical flood event per city (Rotterdam: January 2018 storm surge; Miami: Hurricane Irma, 2017; Jakarta: January 2020 flood event; Lagos: July 2021 flood event), with calibration assessed against reported inundation extent and, where available, gauge-recorded water levels.

2.3 Design storm and sea-level rise scenario

All scenarios were forced with a city-specific 100-year return-period design storm (synthetic storm surge hydrograph combined with a 100-year design rainfall event) superimposed on each city's locally projected 2050 sea-level rise under a moderate-high emissions trajectory, drawing on national or regional sea-level projections, to represent a plausible near-to-mid-century compound flood hazard.

2.4 Nature-based and grey-infrastructure scenarios

Five scenarios were simulated per city: (i) baseline, existing land cover and defences with no intervention; (ii) tidal wetland or mangrove restoration, sited on available intertidal or reclaimable land within each city's coastal buffer; (iii) permeable pavement retrofit, applied to a defined share of impervious road and car-park surface in high-density catchments; (iv) bioswale network, sited along arterial drainage corridors identified from existing stormwater network data; (v) combined NBS, implementing scenarios (ii)-(iv) concurrently; and (vi) grey-infrastructure upgrade, representing a conventional seawall, levee or drainage capacity upgrade sized to a

comparable design standard. Intervention extents were set using locally available land-use and planning constraints rather than a uniform areal target, so that scenario footprints differ across cities.

2.5 Cost and co-benefit assessment

Capital costs for each scenario were estimated per hectare or per linear metre of intervention using published unit-cost ranges for wetland and mangrove restoration, permeable pavement, bioswale construction and conventional grey-infrastructure construction, adjusted to local currency and 2025 US dollar terms using purchasing-power-adjusted construction cost indices. Co-benefits were valued using established benefit-transfer approaches for urban heat mitigation (avoided cooling energy and heat-related health cost), habitat and biodiversity provision, and recreational amenity, expressed as a present value over a 30-year horizon using a 3% discount rate.

2.6 Statistical analysis

Cross-city comparisons of flood-extent reduction, surge attenuation, and cost-effectiveness ratios were summarised as means and ranges across the four cities; relationships between restored wetland/mangrove width and surge attenuation were assessed by linear regression. All analyses were performed in Python 3.11 using numpy, pandas and scipy.

3. RESULTS

Across the four cities, the combined NBS scenario reduced simulated 100-year design-storm peak flood extent by a mean of 34% relative to baseline (range 22% in Lagos to 46% in Rotterdam), compared with a mean reduction of 41% under the grey-infrastructure scenario (range 33-52%). Table 1 summarises simulated flood-extent reduction and capital cost by scenario, pooled across the four case-study cities.

Table 1. Simulated 100-year design-storm flood-extent reduction and capital cost by scenario, pooled across the four case-study cities (Rotterdam, Miami, Jakarta, Lagos).

Scenario	Mean flood-extent reduction (%)	Range across cities (%)	Median capital cost (USD million per ha)
Wetland / mangrove restoration	19	11 to 27	0.31
Permeable pavement retrofit	12	4 to 21	0.48
Bioswale network	9	3 to 16	0.22
Combined NBS	34	22 to 46	0.64
Grey-infrastructure upgrade	41	33 to 52	1.68

Flood-extent reduction is relative to each city's baseline scenario under a common 100-year design storm combined with locally projected 2050 sea-level rise. NBS: nature-based solutions.

Tidal wetland and mangrove restoration alone attenuated simulated storm surge peak water levels by 0.12-0.31 m per 100 m of restored intertidal width across the four cities, with attenuation per unit width greatest in Jakarta

and Lagos, where restored mangrove stands achieved higher effective vegetation density than the salt-marsh restoration modelled for Rotterdam and Miami. Restored width and surge attenuation were positively and approximately linearly related across the simulated restoration extents (Figure 1).

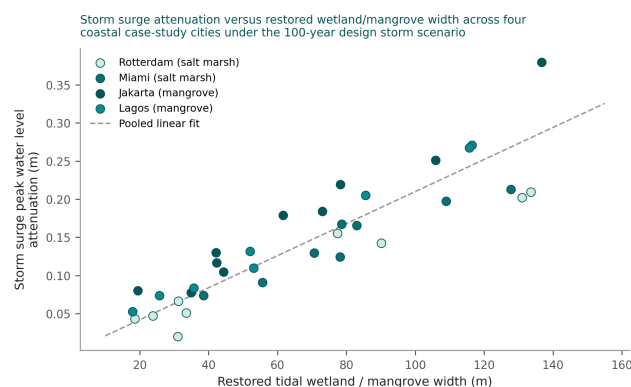


Figure 1. Simulated storm surge peak water level attenuation as a function of restored tidal wetland or mangrove width, across the four case-study cities, showing a positive, approximately linear relationship and greater attenuation per unit width in the tropical/subtropical mangrove-restoration cities (Jakarta, Lagos) than in the temperate salt-marsh-restoration cities (Rotterdam, Miami).

Permeable pavement and bioswale retrofits reduced simulated pluvial peak runoff in high-density catchments by 18-29% across the four cities but provided limited additional flood-extent reduction in scenarios dominated by storm surge rather than rainfall, most notably in Miami, where surge inundation extent under the permeable pavement and bioswale scenarios individually differed by less than 4 percentage points from baseline.

Table 2. Cost-effectiveness and 30-year valued co-benefits of the combined NBS scenario, by case-study city.

City	Flood-extent reduction (%)	Cost relative to grey infrastructure (%)	Valued co-benefits (USD million per km2)
Rotterdam	46	47	2.1
Miami	31	44	1.8
Jakarta	37	31	4.6
Lagos	22	29	3.3

The combined NBS scenario achieved its simulated flood-extent reduction at approximately 38% of the median per-hectare capital cost of the grey-infrastructure scenario (interquartile range across cities 29-47%), and co-benefits from urban heat mitigation, habitat provision and recreational amenity were valued at an additional USD 1.8-4.6 million per km2 of intervention area over the 30-year assessment horizon, a benefit category not captured in the grey-infrastructure scenario. Table 2 reports cost-effectiveness and valued co-benefits by city.

4. DISCUSSION

These results indicate that, in the four coastal cities examined, well-sited nature-based solutions can approach but do not fully match the physical flood-risk-reduction performance of conventional grey

infrastructure under a severe design storm, while achieving that performance at substantially lower capital cost and generating co-benefits that grey infrastructure does not provide, consistent with prior cost-effectiveness assessments of coastal ecosystem-based defences [3,7] and extending that evidence with a harmonised, cross-city comparison against a common grey-infrastructure benchmark.

The finding that tidal wetland and mangrove restoration attenuated storm surge more effectively per unit restored width in Jakarta and Lagos than in Rotterdam and Miami is consistent with known differences in wave attenuation between structurally dense mangrove stands and lower-density temperate salt-marsh vegetation [5,6], and suggests that the surge-attenuation benefit of coastal wetland restoration, and hence its relative cost-effectiveness against grey infrastructure, is likely to be greater in tropical and subtropical cities with mangrove restoration potential than in temperate cities restricted to salt-marsh vegetation.

The limited additional flood-extent reduction from permeable pavement and bioswale retrofits in the surge-dominated Miami scenario, set against their comparatively strong performance against pluvial flooding across all four cities, indicates that green stormwater infrastructure functions primarily as a rainfall-runoff management measure rather than a coastal defence, and should be planned and evaluated as a complement to, not a substitute for, surge-oriented interventions in cities where storm surge is the dominant flood driver [8,9]. This distinction has direct relevance for coastal cities allocating limited adaptation budgets across measures with different primary hazard functions. Several limitations should be considered. First, intervention extents were constrained by locally available land and planning data rather than set to a uniform areal target, so cross-city comparisons of absolute flood-extent reduction partly reflect differing intervention scale as well as differing NBS performance per unit area; the cost-effectiveness ratios reported here are intended to partially control for this by normalising outcomes to cost and area. Second, co-benefit valuation relied on benefit-transfer methods rather than city-specific primary valuation studies, and absolute co-benefit magnitudes should be treated as indicative rather than precise. Third, our design-storm scenarios represent a single 100-year event combined with 2050 sea-level rise; NBS performance under compound or sequential flood events, and under end-of-century sea-level rise magnitudes, was not assessed and may differ from the results reported here, particularly for vegetated defences whose function depends on the pace of vertical accretion relative to sea-level rise [15,16].

5. CONCLUSION

A harmonised comparative assessment across four coastal cities shows that combined nature-based solutions reduced simulated 100-year design-storm flood

extent by a mean of 34%, approaching but not matching the 41% mean reduction achieved by conventional grey infrastructure, while requiring only about 38% of the median grey-infrastructure capital cost and generating substantial additional co-benefits. Coastal wetland and mangrove restoration attenuated storm surge most effectively in tropical and subtropical settings, while permeable pavement and bioswale retrofits were most effective against pluvial rather than surge-driven flooding. These findings support deploying nature-based solutions as cost-effective components of hybrid grey-green flood defence systems in coastal cities, with the specific mix of measures tailored to each city's dominant flood driver, rather than as uniform substitutes for grey infrastructure.

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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

K.C. conceived and supervised the study, developed the coupled hydrodynamic-hydrological modelling framework, and led the writing of the manuscript. P.N. curated municipal and satellite-derived geospatial data and led the cost and co-benefit assessment. A.J. led the design and parameterisation of the wetland and mangrove restoration scenarios and the surge-attenuation analysis. All authors contributed to writing and approved the final manuscript.

Ethics Statement

This study used publicly available municipal, national and satellite-derived geospatial, hydrological and economic datasets, and did not involve human participants, animal subjects, or field data collection requiring ethical review.

Data Availability

Bathymetry, topography and drainage network data used in this study were obtained from national and municipal open-data portals as cited in the Methods. Processed model configurations, simulation output and analysis scripts supporting the findings of this study are available from the corresponding author on reasonable request.

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