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Nature-Based Solutions for Urban Coastal Resilience: Adaptations for Climate Change in Singapore's East Coast

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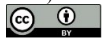
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Abstract

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The East Coast of Singapore has been developed through significant land reclamation, experiences increasing socio-economic threats from climate change and rising sea levels. In response to that, conventional engineering-based coastal defenses have proven to be inadequate, costly, and environmentally damaging. This study critically examines these rigid infrastructure approaches and explores the potential of Nature-based Solutions (NbS), guided by the principles of landscape urbanism, improve resilience and reduce exposure to climate hazards. Using a mixed-method approach of secondary data collection and verified through literature review, this study examines how Nature-based Solutions (NbS) can provide a framework for the East Coast to adapt to climate change while redefining coastal urbanization through an ecological perspective. Additionally, the study fills a critical knowledge gap by translating global NbS discourse into localized spatial strategies for the reclaimed urban East Coast of Singapore.

Keywords: Nature-based solution, Coastal resilience, Climate change adaptation, Ecological regeneration, Landscape urbanism.

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Abstract

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1. Introduction

As climate change accelerates, cities along the coast are facing growing risks of rising seas, stronger storms, and eroding shorelines. Singapore, a city built on the edge of the ocean, is especially vulnerable. With more than 30% of its land lying at or below five meters above sea level, the threat is immediate rather than theoretical. The East Coast, which has been extensively developed through land reclamation, is exemplary of such dangers, where human-induced change has amplified natural coastal instability (Martens, 2013; Chia, 1992). In response, Singapore's approach to coastal protection has historically been dominated by conventional technical solutions like seawalls and breakwaters.

Although these structures provide temporary protection, they have drawbacks, including the disruption of marine habitats, costly maintenance requirements, and a lack of adaptability to future uncertainties (Kabisch et al., 2017). Increasingly, cities around the world are turning to Nature-based Solutions (NbS) that work with natural systems instead of against them. These include restoring mangroves, wetlands, intertidal zones and using sediment dynamics to naturally buffer coasts. The benefits go further than flood protection since NbS are increasingly recognized for enhancing ecological resilience, reducing risk exposure, and delivering socio-economic co-benefits (Narayan et al., 2016; Raymond et al., 2017). In dense urban contexts like Singapore, where spatial constraints limit large-scale interventions, these approaches are often most effective when integrated into the urban fabric through the lens of landscape urbanism, a theoretical approach that treats landscape as the foundational medium for urban development, to explore the spatial and ecological potential of NbS in the East Coast. As defined by Waldheim (2006), Landscape Urbanism emphasizes the use of ecological systems and processes as generative tools for urban form-making. In this study, it is operationalized through a conceptual framework that assesses how layered ecological strategies (e.g., sediment traps, wetland buffers, and mangrove corridors) can be coordinated with urban design to create multifunctional, climate-adaptive coastal spaces.

Rather than segregating nature and infrastructure, it fosters mutualism between them. Being built on soft marine clay, the reclaimed land of the East Coast is already subsiding, and local sea-level rise is happening faster than the global average (Martens, 2013). In addition, Chua and Switzer's (2023) research emphasizes the historic importance of sediment accretion in coastal stabilization - a process increasingly interrupted by urbanization. Restoring these sediment processes via NbS is an attractive future opportunity for resilient adaptation. This research explores how Nature-based Solutions, when guided by landscape urbanism, can offer a more resilient and equitable future for Singapore's East Coast.

While landscape urbanism and NbS have been studied extensively in natural or low-density settings, there is limited research on their adaptation in high-density, reclaimed urban coastlines like Singapore's East Coast. This paper contributes to closing that gap by contextualizing NbS strategies in a spatially constrained and ecologically altered environment. While focused on Singapore's East Coast, the insights are applicable to other urbanized deltaic or reclaimed coastal cities facing similar ecological and spatial constraints.

1.1 Background and Context

In response to sea level rising at an alarming pace, there is an increasing necessity to adopt long-term strategies for safeguarding Singapore's East Coast. As outlined by the Urban Redevelopment Authority (n.d.), the 'Long Island' initiative is being planned primarily as a coastal protection measure. This strategy involves elevating newly reclaimed land to create a continuous flood defence. The plan incorporates twelve coastal discharge points that direct water into a new reservoir, managed by two primary tidal control gates and pumping systems. Nevertheless, this model may physically and experientially separate the urban population from the waterfront, potentially weakening long-established coastal interactions.

A further challenge concerns the sourcing of infill materials. Earlier reclamation activities, such as those in the East Coast Reclamation Scheme, relied on cutting down elevated terrain in areas like Siglap and Tampines to provide soil for extending land in Bedok. As these sources dwindled, Singapore turned to overseas sand imports, eventually becoming the top global importer. However, major regional suppliers such as Malaysia and Indonesia later prohibited sand exports due to environmental degradation.

To address these limitations, an alternative concept involved constructing a three-meter-high protective wall along East Coast Park, with twelve pumping units corresponding to existing drainage channels. While technically feasible, this proposal brings considerable drawbacks— it would limit access to recreational areas for extended periods during construction, and permanently consume significant portions of green and leisure space.

1.2 Historical Overview

Once a serene stretch of sandy beaches of Natural landscapes with mangroves and fishing villages, Singapore's East Coast has transformed into a bustling urban area with inefficient way of development that caused the city to lose significant areas of water bodies, Marine habitats resulting in intensified risk of flood.

Historically, Singapore's East Coast had many highlands and cliffs such as Tanah Merah Cliff, which was demolished in the 1900s to find the land required for land reclamation in the sea. Hence, the organic landscape of highlands and lowlands were disturbed, leading to many of the present problems that East Coast face today. Singapore's East Coast was once thriving ecological zone. It was rich in dense mangrove forests at the shoreline, acting as natural buffers against erosion and storm surges while providing nursery grounds for marine life. It had oyster reefs, improving water quality and offering habitats for marine species. The marine habitat, forming a rich, interconnected ecosystem that supported fisheries and maintained coastal health.

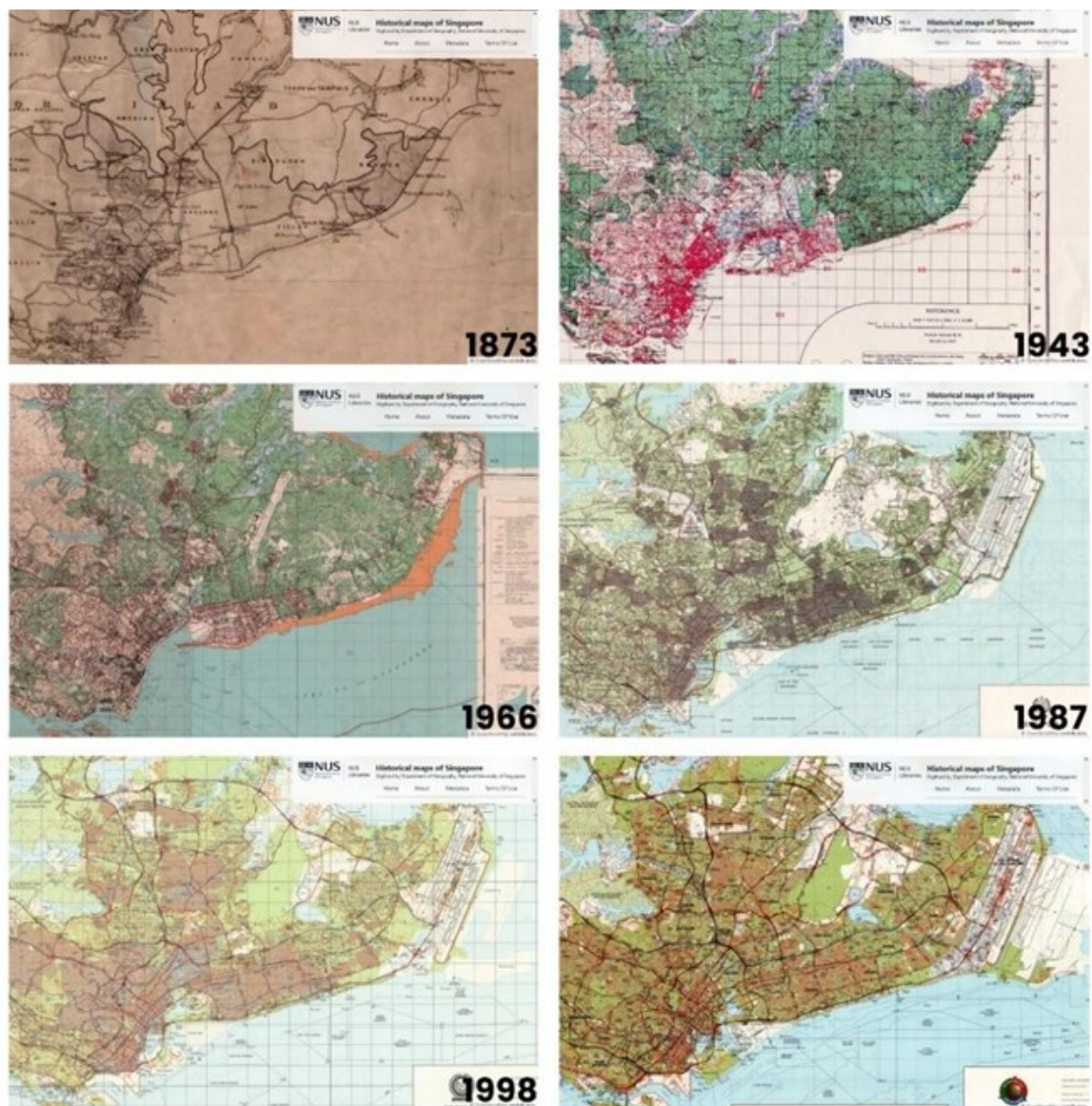


Figure 1: Historical Transformation of Singapore
(Source: <https://www.sg101.gov.sg/>)

Table 1: Historical overview of Singapore East Coast (Developed by authors)

Timeline	Overview
Pre-19th Century	<ul style="list-style-type: none"> · Natural landscapes with mangroves and fishing villages. · Home to indigenous communities like the Orang Kallang and Malay fishermen.
Early 19th Century	<ul style="list-style-type: none"> · Development of agricultural areas, seaside bungalows for colonial settlers.
Late 19th Century	<ul style="list-style-type: none"> · Emergence of industrial growth and traditional shop houses
Early 20th Century	<ul style="list-style-type: none"> · Expanded Industrial zone and residential zones
1940s-1960s	<ul style="list-style-type: none"> · Urban development in eastern portions - Bedok Area
1970s–1980s	<ul style="list-style-type: none"> · East Coast Reclamation Project created East Coast Park, losing natural landscapes and completion of Marina Parade Project
1990s–Present	<ul style="list-style-type: none"> · Continued development and plans for future expansion · Water bodies and Canals are lost

1.2 Climate Risk

The simulation (Sea Level Rise Map and Coastal Flood Tool — US and Global, n.d.: <https://coastal.climatecentral.org/>) shows the locations of high flood risk zone, sea level rising height from the year 2030 to 2100. The zone near Marina parade, Geylang, Geylang Bahru, Kallang, Tanjong Rhu, Boon Keng, Tanah Mera are supposed to be affected first due to sea level rise. The graph also shows the probable flood access points.

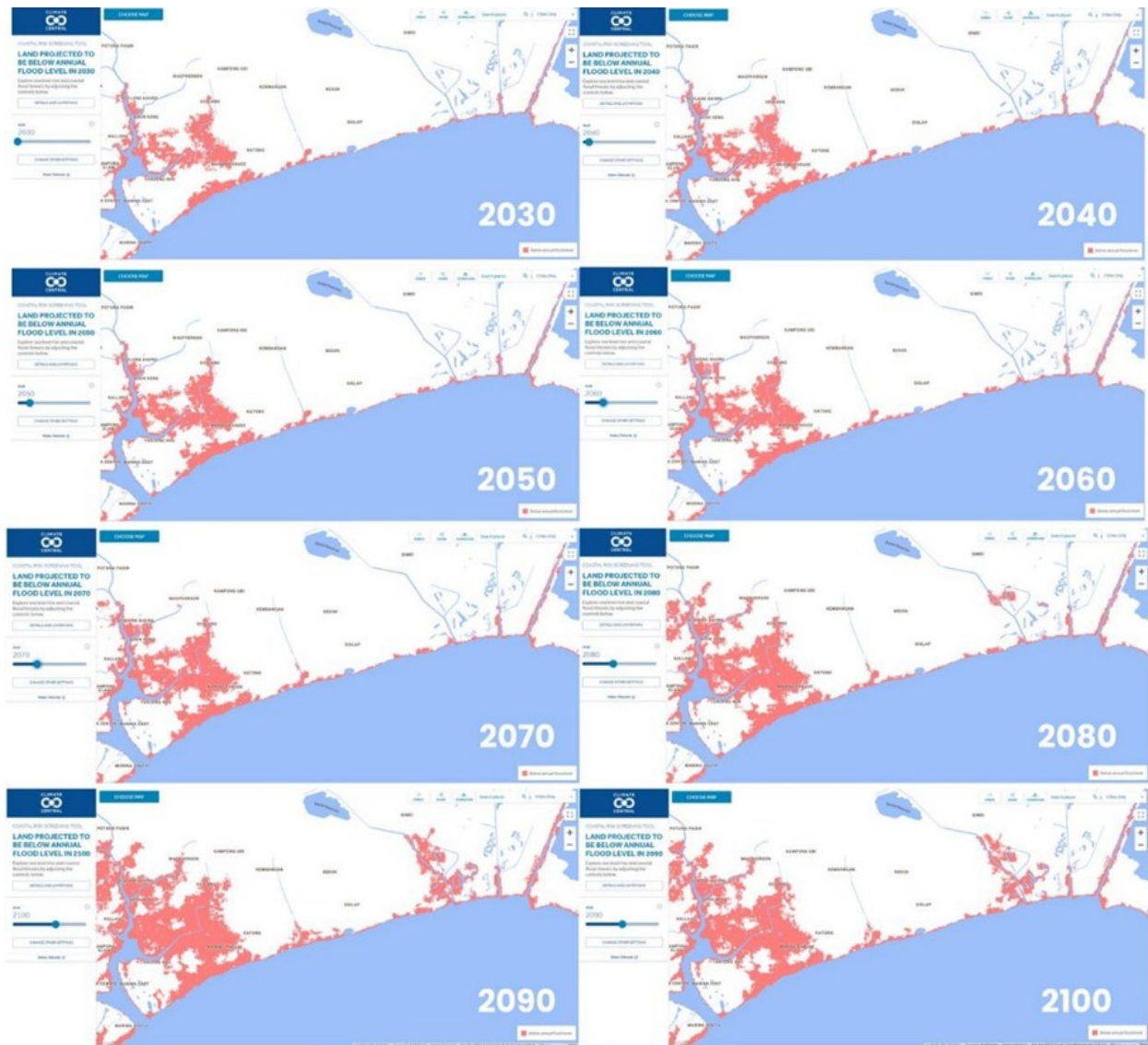


Figure 2: Mapping of areas threatened by sea level rise and coastal flooding of Singapore, East Coast Park (Source: ClimateCentral.org)

1.3 Problem Statement and Research Gap

Climate change in the form of increasing sea levels and subsequent flooding are becoming an increased threat to Singapore’s East Coast, a low-lying and heavily urbanized area of reclaimed shoreline. With the rising awareness of nature-based solutions (NbS) in global coastal planning discourse, the implementation of nature-based solutions have been rather limited in Singapore, especially in the urbanized reclaimed areas like East Coast. Traditional Coastal protections such as tidal gates and seawalls are not so flexible and often hinder natural coastal process. Apart from being environmentally destructive, these hard infrastructures pose long-term sustainability issues, especially in areas where land availability is scarce and pressure for reclamation is high. This has raised concerns about the sustainability as well as longevity of continuous land reclamation and coastal protection techniques involving traditional methods. As a result, there is a great need to investigate other strategies that will increase urban environmental quality, encourage natural regeneration and diminish climate change influence. This study explores the potential of Nature-Based Solutions (NbS) as an alternative approach to addresses land formation and climate change impacts mitigation.

Previous studies on NbS in Singapore are mostly based on standalone ecological projects or hypothetical policy systems where studies lack on how such initiatives can be contextually situated and place-based in Singapore’s East Coast environments. Therefore, the Research Question is: How can Nature-based Solutions be adapted to the reclaimed and urbanized coast of Singapore’s East Coast to improve ecological resilience and address socio-spatial challenges of climate vulnerability? This paper addresses the gap by examining the spatial and ecological potentials of NbS, aiming to develop an integrated adaptation framework that aligns natural processes with urban coastal planning. It explores how ecological strategies such as siltation management, mangrove restoration and wetland incorporation can be adapted to Singapore’s East Coast, where climatic stressors intersect with intensive urban development tendency.

1.4 Objectives and Hypotheses

This study aims to explore the potential of Nature-based Solutions (NbS, guided by Landscape Urbanism, to enhance flood resilience and ecological regeneration in Singapore’s East Coast in response to climate change.

The objectives include:

1. To understand the theoretical basis of Nature based Solution (NbS) and Landscape Urbanism through literature review.
2. To identify and analyze the prevailing challenges of coastal urbanization in Singapore’s East Coast, particularly those related to climate change, land reclamation and flood vulnerability.

Based on these findings, furthermore, the study provides recommendations for incorporating NbS into Singapore’s coastal urban planning that are ecologically regenerative and adaptive, and socially inclusive.

2. Methodology

This study used a two-pronged approach to research, combining a strong method for gathering secondary data [Figure: 3] with a structured way of coming up with flood management strategies [Figure 4]. The study used data sources from government reports, published research and open-source maps of Singapore’s coast. Review of time lapsed maps helped to understand how the coastline and urban areas have changed over time with respect to climate change. To track recent changes, satellite images were reviewed for key points. This provided us with a clear view of how the land evolved. This overlapping of information helped to find locations of lost habitats, spots with less permeability and flood risks. After identifying flood-prone locations, the secondary hydrological data was gathered, and ecological baseline for wetlands, sediments and mangrove were identified. This led to the consultation with experts further forming recommendations for the probable solutions and verified through thorough literature review for validation.

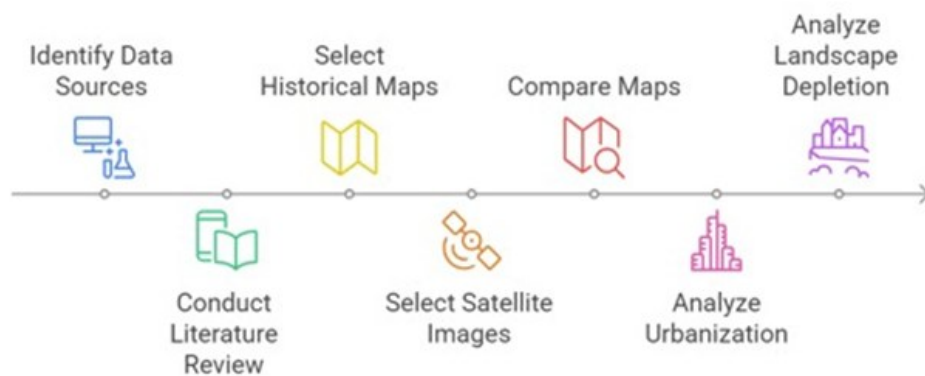


Figure 3: Secondary data collection process (Developed by authors)

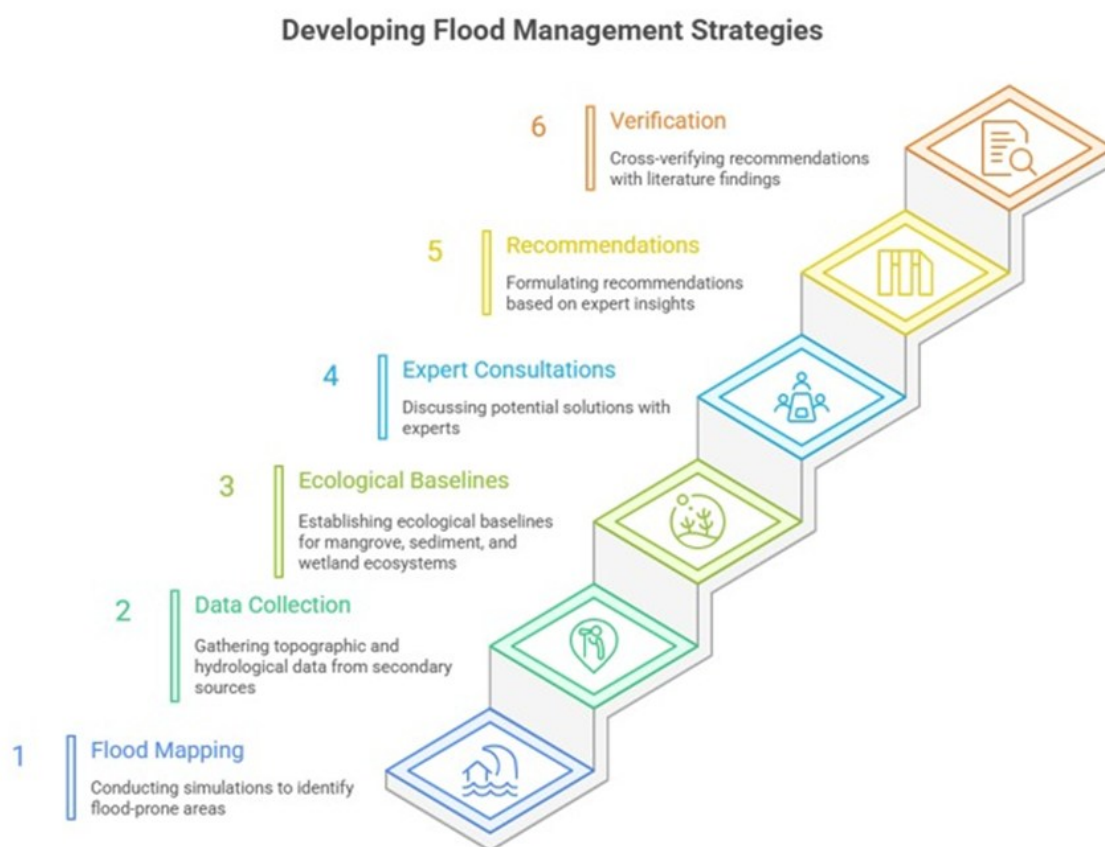


Figure 4: Methodology (Developed by authors)

3. Literature Review

Cities along the coast around the world are facing increasing climate change threats, including sea-level rise, increased storm surges, and regular flooding (Masselink & Lazarus, 2019). Urban responses have conventionally depended on "grey" infrastructure like seawalls, levees, and breakwaters, that, although useful in the short term, disrupt natural sediment processes, degrade ecosystems, and often involve costly maintenance (Kabisch et al., 2017). In the last decades, Nature-Based Solutions (NbS) have emerged as a breakthrough paradigm, delivering ecological interventions with long-term resilience and environmental, social, and economic co-benefits. The International Union for Conservation of Nature (IUCN) defines NbS as actions to safeguard, conserve, and restore natural or modified ecosystems that effectively tackle societal challenges while enhancing human well-being and biodiversity. (IUCN Commission on Ecosystem Management et al., 2016). In densely populated coastal cities like Singapore, where urbanization has drastically changed natural coastlines, the application of NbS requires tailored approaches. These approaches intersect with landscape urbanism, an urban design theory placing landscape as the primary organizing structure of urban form that privileges dynamic ecological processes over permanent built form. (Vicenzotti, 2017). Merging NbS and landscape urbanism offers a way to conceive urban coastlines as adaptive, multifunctional systems rather than static engineered barriers, particularly in places like Singapore's East Coast, where land reclamation, population density, and climatic hazards converge.

3.1 Evolution of Coastal Planning in Singapore

Singapore has expanded its landmass by over 25% since the 1960s through the reclamation of mangroves, mudflats, and coral reefs for industrial, residential, and recreational spaces (Kitazume & Tokyo Institute of Technology, 2022). These ecosystems previously provided vital services, including sediment retention, wave attenuation, and carbon sequestration, and served as natural buffers against coastal hazards. Their removal led to increased vulnerability, with areas like East Coast Park experiencing shoreline instability due to unconsolidated marine clay, disrupted sediment transport, and erosion. Early coastal management relied on defences of a hard nature—seawalls, groynes, and revetments, to safeguard reclaimed land (Sien et al., 1988). However, such structures had the effect of exacerbating erosion, compartmentalizing littoral cells, and disrupting natural sediment cycles. Hydrodynamic modelling revealed that anthropogenic headlands disrupted sediment drift, creating zones of retention that were prone to erosion. These findings are the foundation of a strategic shift towards integrated coastal management (ICAM) in favour of the use of eco-technical solutions that restore natural feedback mechanisms in engineered environments. (Martens, 2013).

3.2 Functions and Benefits of Nature-Based Solutions

3.2.1 Mangrove Ecosystem

Mangroves are renowned for their capacity to reduce wave energy, up to 66%, while stabilization of sediment guards against erosion along the coast and sequesters carbon (Alongi, 2022). Apart from coastal defence, they enhance biodiversity and fisheries that support livelihoods and ecological health. Hydrodynamic modelling indicates that select cells along East Coast Park would be suitable for mangrove reintroduction without impacting existing infrastructure (Martens, 2013).

3.2.2. Wetland and Urban Water System

Wetlands provide multifunctional benefits, like stormwater detention, pollutant filtration, water quality enhancement, and urban heat mitigation through evapotranspiration (Hamel et al., 2021). Embedded in park systems and drainage networks, wetlands are expressions of landscape urbanism aspirations, reshaping utilitarian water management into ecological and recreational amenity.

3.2.3. Sediment Management and Dune Restoration

Coastal stability hinges on healthy sediment dynamics. Artificial headlands along East Coast Park interfere with natural littoral drift, leading to localized erosion (Martens, 2013). Martens (2013) not only pointed out how anthropogenic structures brought changes to littoral cell dynamics, but also defined sediment retention zones amenable for mangrove. In the study by Martens (2013), Delft3D-FLOW was used within the framework of a nested modeling to investigate tidal effects on the sediment transport at East Coast Park, Singapore [Figure 5]. The model simulated 2D tidal currents for understanding the sediment pick up and redistribution, with specific consideration to fine sediments offshore. Results showed that inshore tidal currents were insignificant within 200 meters from the shore, with sediment transport going on at a greater distance from shore. This process of modeling was a component in understanding large-scale coastal morphology and sediment behavior in the framework of sea level rise and management of erosion.

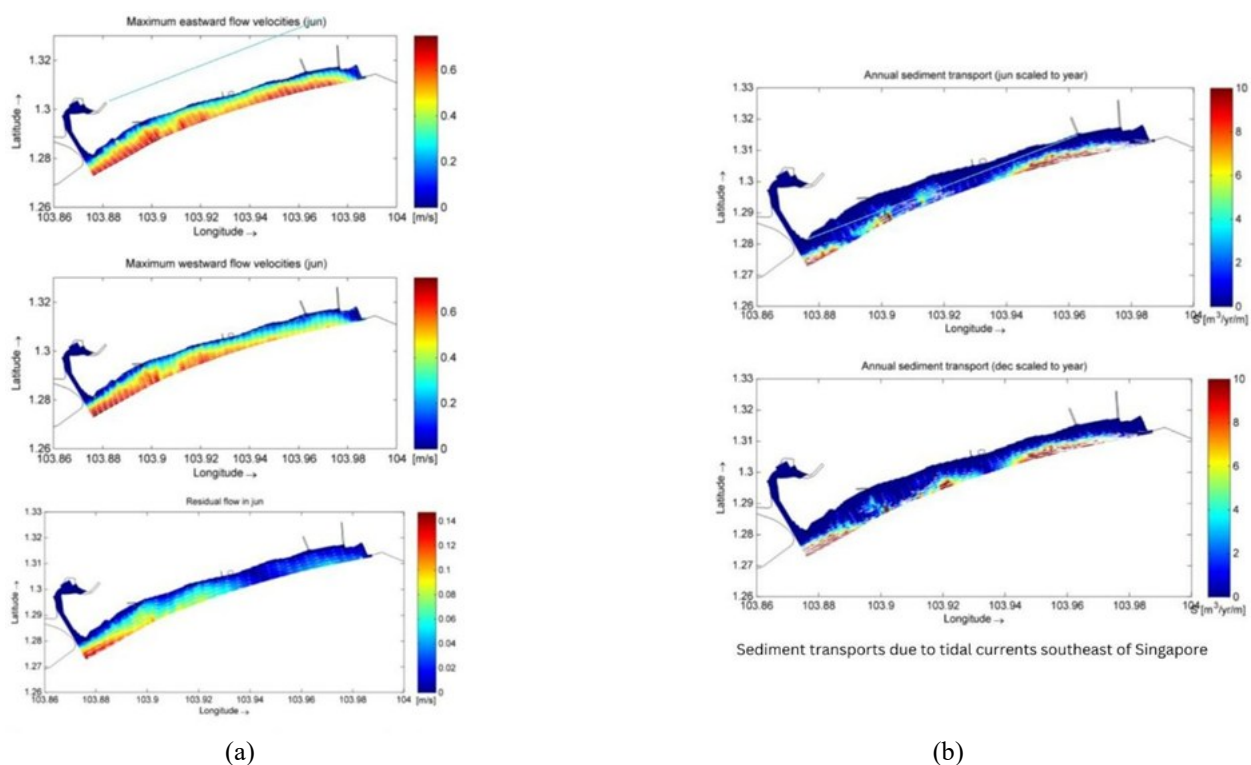


Figure 5: (a) Flow velocity of tidal currents and, (b) sediment transports due to tidal currents southeast of Singapore (Source: Martens, D., 2013. An Analysis of the Physical Coastal System along East Coast Park, Singapore. MSc thesis. Delft University of Technology)

Beach nourishment, managed accretion, and vegetative dune strengthening through nature-based sediment management can potentially restore sediment continuity. International projects, such as the "Sand Motor" in the Netherlands, demonstrate how large-scale, eco-dynamic nourishment creates self-sustaining sea-level rise-resistant coastal barriers (Stive et al., 2013). Translation of such concepts to Singapore's geomorphology can reduce the dependence on hard structures while enhancing ecological functions.

3.2.4. Hydrodynamic and Geotechnical Considerations

NbS in reclaimed land entails working with challenging ground conditions, for instance, dense marine clay that is prone to subsidence and liquefaction (Kitazume & Tokyo Institute of Technology, 2022). Hybrid approaches of conventional soil stabilisation—sand compaction piles, vertical drains, with eco-engineering approaches such as, root-reinforced vegetation and sediment recharging enhance both structural function and ecological function. Advanced modelling software (Delft3D, Unibest-TC, OpenDA) enables realistic simulations of tidal flows, sediment transport, and surf zone dynamics (Martens, 2013). These data-driven insights are necessary to place NbS interventions in a way that enhances, rather than interferes with, natural coastal dynamics.

3.2.5. Socio-Cultural and Economic Dimensions

NbS improves not only ecological resilience, but also socio-economic well-being. They outcompete grey infrastructure in lifecycle costs, offer recreational space, and boost property values while maintaining biodiversity (Narayan et al., 2016). Projects like Bishan-Ang Mo Kio Park demonstrate co-designed NbS, with river naturalization combined with civic facilities and public engagement. Such participatory strategies enhance social legitimacy, enhancing equity in access to ecological infrastructure across different income groups. Despite growing global evidence of NbS effectiveness, there are significant gaps in adapting such solutions to high-density, reclaimed coastlines. Some of the critical challenges are: Limited long-term data on NbS performance under combined stresses of subsidence and accelerated sea-level rise. In this regard, there is a lack of integration of hydrodynamic modelling, sediment transport data, and spatial design methodologies. Socio-economic valuation models for comparing NbS and conventional defences in urban coasts are in short supply (Raymond et al., 2017). Filling these gaps requires a transdisciplinary approach that combines coastal engineering, ecology, urban design, and stakeholder engagement. Landscape urbanism offers a theoretical basis to operationalize NbS, aligning ecological infrastructure with urban form to create adaptive, multifunctional coastal systems.

4. Findings and Discussion

The background study identifies the prevalent issues on the site that can be attributed to climate change and ecological susceptibility to sea level rise, frequent flooding and flash flooding, erosion of natural defences and habitats, oil spill incidents and sand procurement issues [Figure 6]. The problems do not occur in isolation but rather overlap and compound one another, reinforcing the vulnerability and pressure of the coastal ecosystem in Singapore's East Coast.

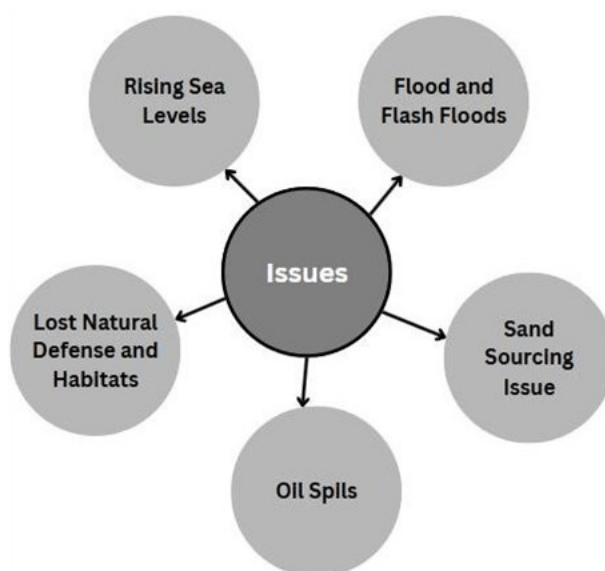


Figure 6: Identified prevalent Issues on the site (Developed by authors)

Application of Nature-based Solutions (NbS) in the East Coast of Singapore focuses on applying spatial design to minimize the environmental susceptibility of the coastal zone. Compared to conventional engineering approaches, NbS provide a set of ecological and societal benefits. For instance, the restoration of mangroves along the coastline serves as a natural defense against storm surges and coastal erosion, whereas municipal wetland systems support both the management of floodwaters and the enhancement of recreational amenities for the population.

Based on the literature and studies conducted, it appears that natural sedimentation can play a big role in developing resilient coasts on the East Coast of Singapore. It is found in coastal geomorphology that strong interactions between fluvial and marine sediments tend to form primary dunes. Secondary dunes are more likely to take form quickly where there is a lot of silt.

Ecological layering is an important part of the geomorphological process. Due to the space between primary dunes and secondary dunes, it is possible for wetlands between them to develop and help reduce floods, as well as increase the number of different species. On the secondary dunes, putting in a mangrove layer features enhances the area’s resilience by maintaining sediment and water while supporting wildlife found in the area. The arrangement of primary dune, inter-dune wetland, and secondary dune covered with mangroves addresses control of erosion, restoration of the local environment, and climate change adaptation as one system.

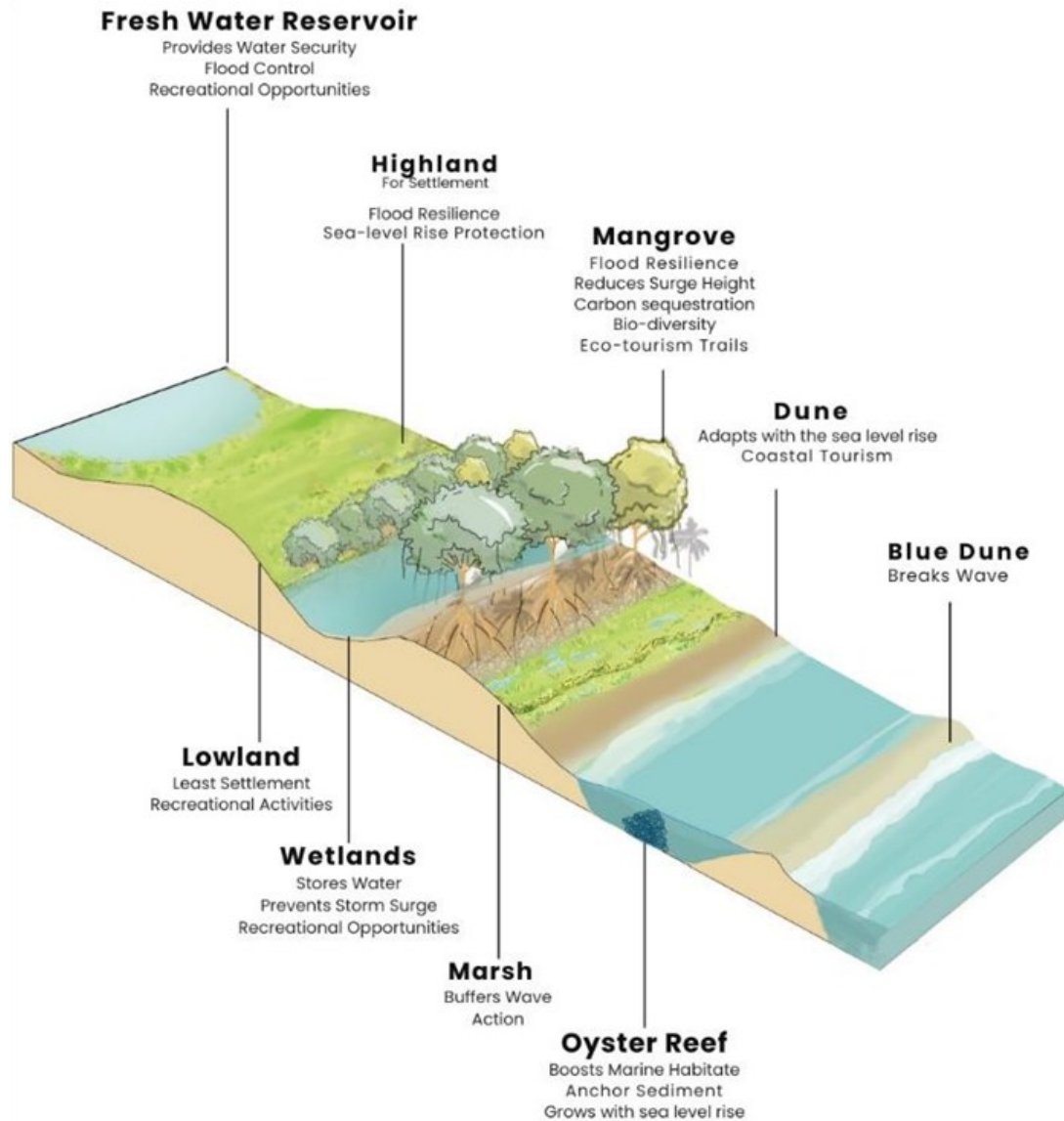


Figure 7: Recommended nature-based coastal development (Developed by authors)

One major challenge is the sand sourcing issue for land reclamation. Researchers have explored innovative alternatives to sand that are both sustainable and climate-conscious. We begin by looking at the Semakau Landfill (Begum, 2024; <https://www.straitstimes.com/singapore/ash-from-semakau-landfill-could-be-used-to-reclaim-land-for-mega-tuas-port-project>), where incineration bottom ash e.g. left after burning waste, is being stored. This material can be recovered and treated by adding a small amount of cement (around 5–10% by weight), turning it into a useful material known as New-Sand. This alternative has already been used in paths and benches across Singapore. Another approach goes even further- By combining this ash with captured carbon dioxide, carbonate-based materials

can be created that are strong, durable and environmentally friendly. Not only does this process recycle waste, but it also traps CO₂, contributing to climate change mitigation in a meaningful way.

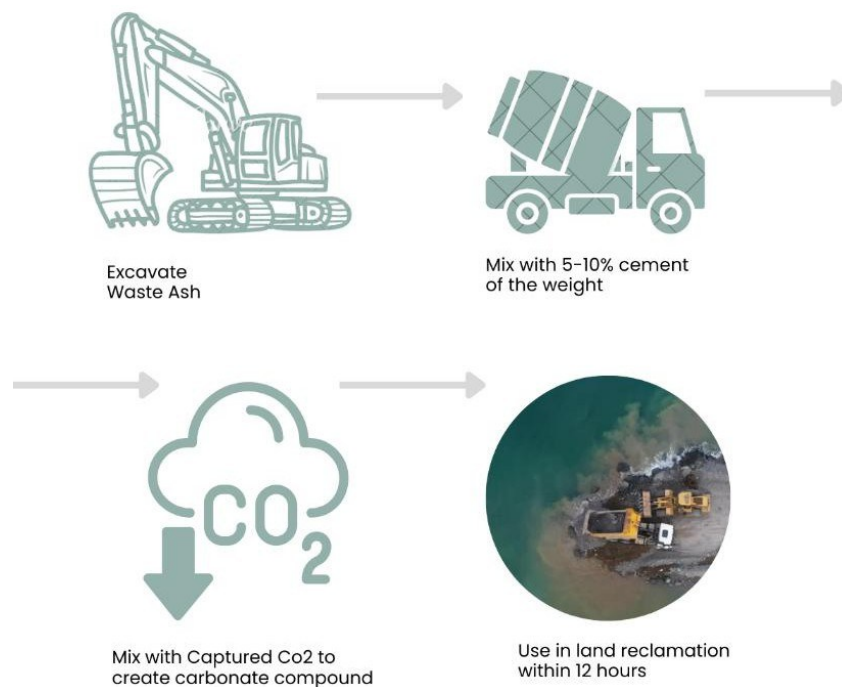


Figure 8: Recommendation alternative method for sand sourcing issue

These ideas reflect a bigger shift- from extractive practices to circular, regenerative systems. By thinking holistically, linking ecology, infrastructure, waste and design, Singapore’s East Coast can become more than just a line of defense. It can become a living, adaptive landscape that responds to risk while also offering new opportunities for connection, sustainability, and innovation.

Though NbS require less maintenance cost and less ecological impact, it requires high initial cost and the growth of mangrove, dune can delay the impact. The policymakers have to incorporate Nbs in strategy planning, simulate modelling, collect quantitative data through survey. The planning process must include perspectives from local residents as they are the primary stakeholders. Initially NbS can be combined with short-term soft engineering to bridge the gap.

4.1 Strengths and Limitations

One of the main strengths of this study lies in its interdisciplinary and site-specific approach—integrating ecological knowledge with spatial design thinking to address climate adaptation in a densely urbanized, reclaimed coastal zone. The research highlights real-world environmental challenges and proposes innovative solutions such as mangrove restoration, dune-wetland layering, and the reuse of incineration ash (NewSand) for reclamation. This creative combination of Nature-based Solutions (NbS) and circular waste strategies reflects a strong systems-thinking approach that can be transferred to similar urban coastal contexts.

However, the study has several limitations. It lacks quantitative modelling, simulation analysis, and empirical fieldwork, which restrict the ability to measure the effectiveness of the proposed NbS strategies. Furthermore, some data are based on secondary sources, which may limit the depth of localized understanding. The long-term impact of mangrove growth, sedimentation, or artificial dune systems was not tested under real environmental conditions, which limits the predictive strength of the recommendations.

5. Conclusion

This research analyzes the vulnerabilities of the area and emphasizes the critical role of Nature-based Solutions (NbS) in fostering urban coastal resilience. The findings contribute to direct a sustainable development framework for the East Coast, promoting long- term sustainability, by working with nature rather than against it. But the study lacks in fieldwork, data survey, quantitative modelling.

Future research should explore site-specific NbS applications, assess their long-term effectiveness, and integrate them into broader urban planning and policy frameworks. The present limitations of applying Nbs in urban planning raises a debate. In order for these ecosystems to be effective, local communities should participate in planning and maintenance. The potential for empirical validation and scientific confirmation of the proposed recommendations is identified as a future use of this study.

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Conflict of Interests

The Author(s) declare(s) that there is no conflict of interest.

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