A Guide to Implementing Coastal Nature-based Solutions for Singapore

CENTRE for LiveableCities SINGAPORE

NATIONAL PARKS
LET'S MAKE SINGAPORE OUR CITY IN NATURE

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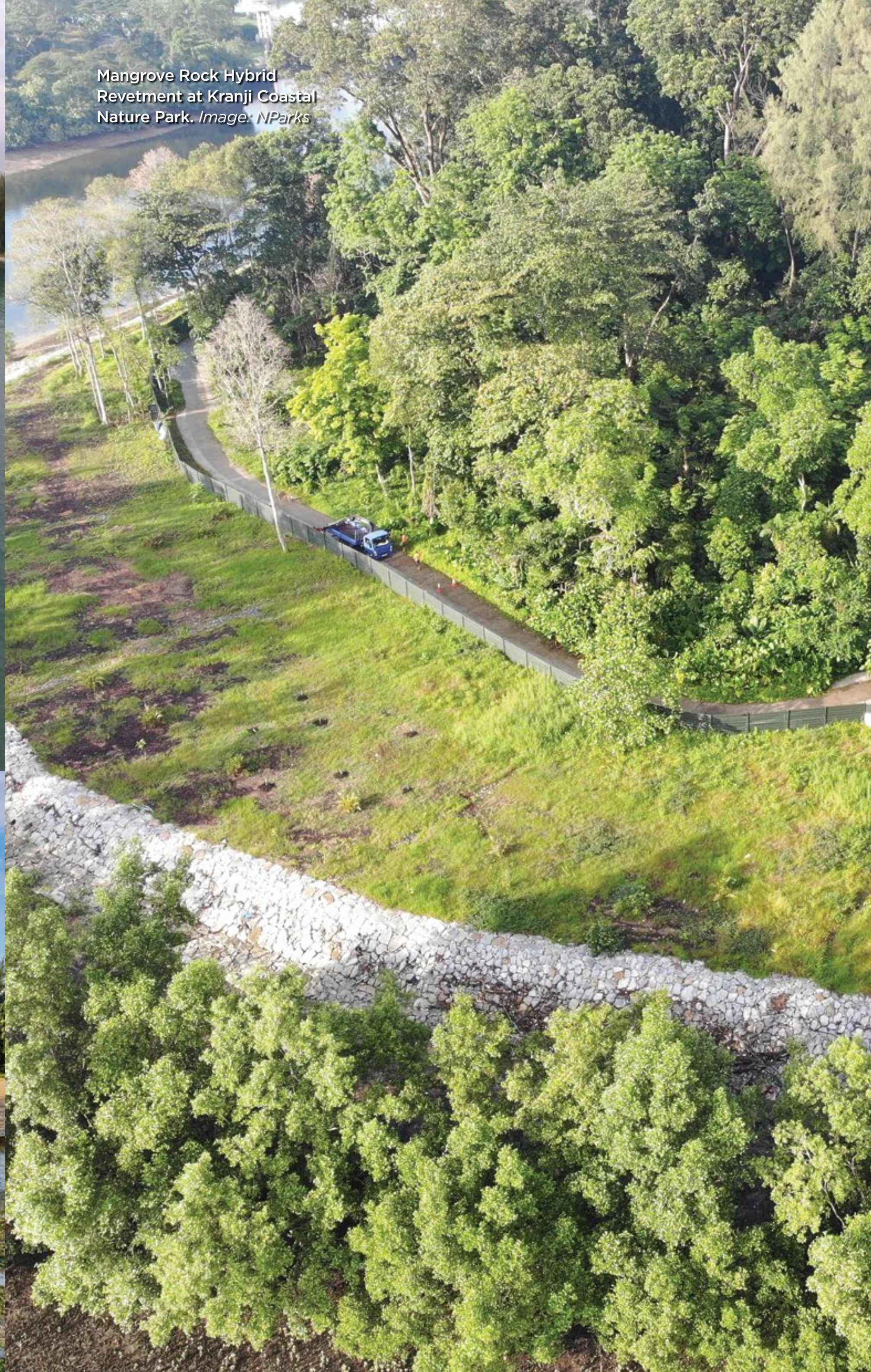
Recclaimed Lagoon with Seawalls, Sisters' Islands Marine Park. *Image: NParks*



Mangrove Rock Hybrid Revetment at Kranji Coastal Nature Park. *Image: NParks*

Seagrass Meadows at Changi Beach. *Image: NParks*

CONTENTS

Foreword

Hugh Lim
Executive Director
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Singapore's pioneer leaders conceived the vision of a "Garden City" as early as 1967. This set in motion Singapore's transformation into a city with abundant lush greenery and a clean environment, and enhanced its competitive advantage as a city in tandem with economic development.

More than 50 years on, we continue to derive a multitude of benefits from this vision, from the provision of inclusive spaces for community and family bonding, scenic places to relieve the stresses of urban life, the attraction of tourism and investments to our shores. Even during the challenging "circuit-breaker" period of the COVID-19 pandemic, our natural and green spaces were kept accessible for citizens to maintain their physical and mental well-being in a crisis.

Providing and enhancing both the natural ecosystem and human assets is important to a city's resilience. Nevertheless, in land scarce Singapore, planners and policy-makers are constantly weighing benefits, costs and trade-offs, and engaging with stakeholders holding diverse perspectives and interests, to strike a delicate balance between development objectives and conserving our nature capital.

The concept of nature-based solutions offers a way ahead for easing the tensions and allowing us to reap multiple benefits for the city, the society and the planet as a whole. This prompts a key question: Going forward, how can we establish a mutually-reinforcing, symbiotic relationship between the built environment and natural ecosystems in a dense city?

Through our research in developing this guide, we came across several emerging practices to planning, designing and implementing nature-based solutions worldwide. There are also knowledge gaps to be resolved both locally and in other tropical regions to enable the adoption and scaling-up of such solutions. One common thread in our research: nature-based solutions require a collaborative culture and an "ecosystem" of stakeholders in public, private and people sectors working in partnership, to come up with more sustainable ways of using our limited land and resources, aligning with and respecting nature. Through a bold vision, a spirit of "learning by doing" and an enduring value of stewardship, we can set our city on a regenerative pathway of net-positive development.

Foreword

Kenneth Er
Chief Executive Officer
National Parks Board

Despite being one of the densest cities in the world, Singapore is home to a stunning array of ecosystems, from primary rainforests to freshwater swamps to coral reefs. They provide a variety of ecosystem services, like cleaning our air and water, protecting our coastlines, and at the same time making our city-state more liveable.

Hence, Singapore is working to extend and enhance our natural capital, while integrating nature further into our urban fabric. Through these efforts, Singapore will be more resilient to the impacts of climate change and urbanisation, with nature-based solutions a key strategy to achieving this goal. In doing so, we will transform Singapore into a City in Nature, a key pillar in the Singapore Green Plan 2030 to advance Singapore's agenda on sustainable development.

Globally, cities are increasingly turning to nature-based solutions to address challenges from climate change and development to improve resilience of both humans and nature. By protecting, managing and restoring ecosystems, nature-based solutions have been used to alleviate flooding from stormwater, cool cities, protect coastlines, sequester carbon to mitigate climate change and so much more.

Likewise, nature-based solutions form an integral part of Singapore's green strategies towards greater climate resilience. This guide contains a myriad of examples of designs that have been found to work well in local tropical conditions, serving ecological functions, as well as societal needs. Many of these designs showcase how nature can co-exist with development in an urban environment if the right conditions are met. For example, we have perched beaches with breakwaters along East Coast which not only protect the coastline from erosion, but also create calm conditions for seagrass to thrive and lagoons for recreation.

As we continue to explore the role that nature-based solutions can play to mitigate the impacts of climate change, it is important to ensure that they are underpinned by sound science. Together with other government stakeholders, NParks has established the Marine Climate Change Science research programme to explore how we can help our ecosystems adapt to climate change, as well as leverage nature-based solutions to maximise our blue carbon sequestration potential and protect our coasts against rising sea levels. As we continue to integrate nature into the urban environment, these nature-based solutions can also help our biodiversity to persist in our city for decades to come, allowing our future generations to enjoy our City in Nature.

I hope this guide will inspire more practitioners such as developers, landscape architects and qualified persons to consider incorporating nature-based solutions when planning and designing their developments.

Introduction

As an island city-state, Singapore faces numerous challenges given the inherent constraints in land and natural resources. Climate change poses an existential threat. With projected mean sea level rise up to 1 metre by 2100, Singapore needs to prepare for the stresses and potential impacts on the low-lying coastal regions caused by the confluence of extreme high tides and storm surges. As a key target under the Singapore Green Plan 2030, the government is embarking on the studies to formulate coastal protection solutions, based on the profiles of different segments of the coastlines.

More and more, coastal cities around the world are dealing with complex challenges and constraints posed by climate change, and it is becoming clear that cities have to invest proactively in climate resilience, beyond just fixing immediate problems that come their way. Broadly, resilience is the ability of a system, community or society exposed to hazards to prepare against, withstand, and recover from the stresses and shocks, and the ability to adapt and evolve new responses. Truly resilient systems can turn challenges into opportunities to transform and surpass their pre-disturbance state and thrive under these new conditions.

One goal of resilient cities articulated by the City Resilience Framework, developed by 100 Resilient Cities, is "providing and enhancing protective natural and man-made assets" that reduce the physical vulnerability of city systems. Natural assets, including ecosystems and biodiversity, are critical to ensuring the well-being of society through the diversity of ecosystem services and other benefits they provide. These include provisioning services (e.g., food and water), regulating services (e.g., floods and drought mitigation), supporting services (e.g., soil formation and nutrient cycling) and cultural services (e.g., recreational, spiritual, religious benefits) (Alcamo et al., 2003). The preservation and management of urban ecosystems are fundamental to urban resilience as they provide a local source of food, water and materials, and serve as a buffer to the externalities of urban development by providing heat attenuation, flood control, pollution absorption and other functions/amenities (Roberts, 2010).

In recognition of the importance and potential of ecosystem services, cities are turning to *Nature-based Solutions* (NbS) to address future challenges, particularly impacts of climate change. In 2020, the United Nations declared "Our Solutions are in Nature" as the theme for the International Day of Biological Diversity, highlighting the importance of leveraging natural systems to provide services and benefits for both humans and nature. There have been extensive and varied efforts globally to leverage nature (e.g., biodiversity and habitats) to achieve resilient outcomes and additional environmental, economic, and social benefits. In particular, NbS have been used to enhance and protect coastlines, while improving environmental sustainability and human wellbeing, and can be more cost-effective relative to conventional, grey infrastructural alternatives (Sutton-Grier et al., 2015).

Through the year-long public engagement conducted in 2021 – 2022, the Long-Term Plan Review found that ensuring Singapore's long-term sustainability has become even more important with climate change and resource scarcity. Active stewardship of natural capital, and restoration of nature into urban landscape could both improve well-being and enhance the city's climate resilience, through mitigating urban heat and floods, and supporting coastal protection efforts.

Over decades of coastal urban development and reclamation, Singapore has lost much of its original coastal and marine ecosystems (Lai et al, 2015), and their associated ecosystem services. Despite this, marine biodiversity and critical habitats continue to thrive in its waters, presenting an opportunity for planners to leverage them to make the coastal regions more liveable and resilient. The loss of the natural coastline and diverse ecology could be restored and regenerated in the long run, if coastal adaptation measures can be envisioned, planned and designed with sustainable and ecological-oriented approaches through integrating nature seamlessly to create multi-functional spaces and climate-resilient infrastructure at scale.

This practitioner's guide explores the "what"—the concept of NbS and other similar but related terms—and highlights the "how"—key planning and design considerations when implementing NbS in coastal areas. Through a series of local and international case studies, the guide will demonstrate how NbS have been successfully applied at localised scales and/or integrated into large-scale/district-level planning.

This guide aims to provide background information, typology examples and guiding principles for coastal NbS, and is intended to be used as a resource for policymakers, stakeholders and researchers to seek opportunities to align with the vision of "City in Nature" in planning and infrastructure development for climate and coastal resilience in Singapore.

Planted mangroves at Pulau Semakau.
Image: National Environment Agency

Nature-based Solutions: What's in a name?

The term NbS was introduced in 2016 by the International Union for the Conservation of Nature (IUCN) defined as "**actions to protect, sustainably manage, and restore natural or modified ecosystems, that address societal challenges effectively and adaptively, simultaneously providing human well-being and biodiversity benefits**" (Cohen-Shacham et al., 2016). NbS is an umbrella concept that encompasses a family of approaches, which fall under five main categories: ecosystem restoration, issue-specific ecosystem-related approaches, infrastructure-related approaches, ecosystem-based management and ecosystem protection (Figure 1). In March 2022, the 5th United Nations Environment Assembly formally adopted the definition of NbS as "***nature-based solutions are actions to protect, conserve, restore, sustainably use and manage natural and modified terrestrial, freshwater, coastal and marine ecosystems which address social, economic and environmental challenges effectively and adaptively, while simultaneously providing human well-being, ecosystem services, resilience and biodiversity benefits***".

This means that NbS cover a wide range of approaches, encompassing both structural and non-structural options. For example, planting a mangrove for coastal protection (soft ecological engineering) and integrated coastal zone management (ecosystem-based management) are both considered NbS approaches. When it comes to climate change, NbS is often associated with the terms "ecosystem-based adaptation", or "blue and green infrastructure" to achieve specific adaptation goals (i.e., flood control, heat abatement) while providing ecosystems benefits and mitigating climate change by carbon sequestration at the same time. NbS has already been used for climate change adaptation in Singapore despite the fact that conservation/restoration of ecology may not be the explicit objective—the re-naturalisation of the canal at Bishan-Ang Mo Kio Park in the Active, Beautiful, Clean Waters Programme is an example that shows how a riverine system with an extended floodplain can be used to manage flooding (which

Fig 1. Conceptual framework for Nature-based Solutions. *Source: IUCN*

will become more severe with climate change)—while providing a range of ecosystem services and social value for the communities. Another notable programme is the Urban Redevelopment Authority (URA)'s Landscaping for Urban Spaces and High-Rises (LUSH), which promotes pervasive and accessible greenery in high-rise urban environment to mitigate the urban heat island (UHI) effects and improve air quality.

In coastal areas, NbS are increasingly seen as ways to provide necessary adaptive functions like shoreline protection, enhance social/recreational values, while regenerating nature and mitigating climate change. Examples include using reefs or mangrove forests for coastal protection, instead of conventional infrastructural approaches (often called "grey" solutions) like seawalls, groynes or breakwaters. These NbS are often similar or related to many other existing concepts (Nesshöver et al., 2017). Regardless, it is important to remember that at its core, **NbS aim to leverage natural or modified ecosystems to provide benefits to both humans and biodiversity**. In this guide, we focus on NbS applied to the coastline for shoreline protection, recreation and nature, at the local and integrated district planning scales. We examine the intended values and considerations when using NbS and outline the general steps in their implementation.

Why should we consider Nature-based Solutions for the coast?

Increasingly, NbS are being applied to the integrated planning and management of coastal areas worldwide for a myriad of purposes, ranging from enhancing and/or complementing coastal protection systems or enhancing landscape and social/recreational activities. While not a panacea to coastal challenges, NbS have many positive attributes that are useful when developing on the coastline to strengthen resilience against future hazards and challenges.

1. NbS can provide a wide range of benefits

One of the key advantages of NbS over conventional grey infrastructure is their ability to generate multiple co-benefits such as supporting commercial or recreational fisheries; improving water quality; providing tourism and educational opportunities; maintaining and enhancing biodiversity; and improving the aesthetics of the coast (Sutton-Grier et al., 2018). These co-benefits ensure that the NbS create more value by enhancing the environment compared to hard infrastructure solutions, while also growing the intrinsic value of biodiversity and natural ecosystems.

2. NbS can be more cost-effective

A growing number of studies have also demonstrated that NbS can be more cost-effective than conventional grey alternatives in certain contexts (Sutton-Grier et al., 2018), like when applied to less extreme hazard scenarios. Large infrastructure projects like seawalls or hard coastal revetments, while providing robust protection against severe coastal hazards, can often be costly to install and have high maintenance and replacement costs (Moberg and Rönnbäck, 2003). If a suitable NbS is selected, implementation or maintenance costs could be far lower (Narayan et al., 2016). A study of the cost-effectiveness of coral restoration compared to breakwaters in terms of coastal defense benefits across eight Caribbean nations found that reef restoration was far more cost-effective (CCRIF, 2010). If we look beyond just immediate protection functions and monetary costs, and holistically take the direct and indirect benefits into planning consideration (e.g., value to human health, natural capital, boost in land value, etc.), there is greater potential for NbS to be more cost-efficient because of the additional benefits to be accrued in the long run. With the lack of land space required for large-scale implementation of NbS, hybrid alternatives like eco-engineering solutions might be a way to balance the effectiveness in risk reduction, while regenerating ecosystems services.

3. NbS can adapt to changing environmental conditions

NbS are "living" solutions which are able to adapt to changing conditions. For example, compared to static seawalls which pose a challenge to be built incrementally, natural habitats like mangroves or coral reefs can potentially grow concomitantly with low to moderate rates of rising sea levels given the right conditions (Bouma et al., 2014). Such adaptability is fundamental to resilience, as it allows coastal systems to be more resistant to hazards and bounce back quicker. This is especially pertinent for climate change impacts, which are difficult to predict with a high degree of certainty. However, the adaptability of NbS is context-specific and needs to be well-supported by piloting and research, so as to ensure the adoption of a holistic and science-based approach. These natural habitats can also be vulnerable to rapid sea level rise and the increasing frequency and intensity of climate change hazards, and how well they can recover will depend greatly on ecological (e.g., connectivity, diversity) and physical factors (e.g., hydrodynamics, sedimentation) (Seddib et al., 2019).

Similar, related concepts incorporating Nature-based Solutions:

Ecological engineering (Eco-engineering)	The "design of sustainable ecosystems that integrate human society with its natural environment for the benefit of both" (Mitsch and Jørgensen, 2003), and is considered a form of NbS. When applied to shorelines, its fundamental aim is to "build more inclusive, resilient and safe coasts for people and nature, which maximise benefits for ecosystems, society and economies" (Morris et al., 2019). Eco-engineering approaches can range from "soft" (using natural habitats like mangroves and salt marshes) to "hybrid" (combining natural elements with hard coastal structures) to "hard" (altering hard coastal structures) (Chapman and Underwood, 2011).
Ecosystem-based Adaptation	The concept of Ecosystem-based Adaptation involves the management of ecosystems and their services to reduce the vulnerability of human communities to the impacts of climate change. It was promoted through international forums such as Convention on Biological Diversity (CBD, 2009).
Living shorelines	A broad term that encompasses a "range of shoreline stabilisation techniques along estuarine coasts, bays, sheltered coastlines, and tributaries" (NOAA, 2015). Unlike eco-engineering, living shorelines tend toward the "soft" to "hybrid" range of approaches and focus on restoring natural habitats as the main goal (Bilkovic et al., 2017).
Green/Blue/Grey infrastructure/ solutions	Green infrastructure refers to a "network of natural or semi-natural features that has the same objectives as grey [built] infrastructure" (Palmer et al., 2015). Occasionally, "green" can also describe the use of vegetation in infrastructure and "blue" to describe the use of water, which are contrasted against the traditional "grey" of man-made infrastructure. "Blue" is also occasionally used broadly to refer to coastal eco-engineering. Often, these terms are used in combination (e.g., grey-green-blue) to denote hybrid designs.
Building with Nature (BwN)	An approach that "takes advantage of natural processes for realising hydraulic infrastructure, while at the same time providing opportunities for nature development" (De Vriend et al., 2014). Based on a research programme between the Dutch government and private sector, universities and knowledge institutes, this approach has been applied to tropical, temperate, freshwater and coastal ecosystems.
Nature-based infrastructure	Defined as "infrastructure that mimics characteristics of natural infrastructure but is created by human design, engineering, and construction to provide specific services" (Sutton-Grier et al., 2018). There are broader definitions that also include "natural ecosystems" such as mangroves (Lipiec, 2020).
Restoration	The "act of bringing a degraded ecosystem back into, as nearly as possible, its original condition" (Edwards et al., 2010). In some cases, NbS could involve restoring a natural habitat to provide co-benefits to society (e.g., restoring mangroves for coastal protection). Full restoration is rarely possible due to climate and anthropogenic impacts, and/or difficulties in defining what "original condition" entails.

Rehabilitation	The "act of partially or, more rarely, fully replacing structural or functional characteristics of an ecosystem that have been diminished or lost, or the substitution of alternative qualities or characteristics than those originally present with the proviso that they have more social, economic or ecological value than existed in the disturbed or degraded state" (Edwards et al., 2010). In reality, this is more commonly applied when recreating habitats for NbS.
Regenerative Design	"Regenerative Design" has been increasingly recognised internationally as both an architecture and a planning concept. Building on the ecological design and permaculture practices, regenerative design promotes a "whole systems" approach in adopting biomimetic, nature-based approaches to achieve circularity and net-positive ecological gains, and to foster co-evolving relationship between human and nature. (Mang and Reed, 2012).

Related International NbS Frameworks and Guidelines

The use of NbS in coastal planning has been growing and it has been featured prominently in planning guidelines and disaster risk management frameworks globally. Notable examples include:

- **Implementing Nature-Based Flood Protection: Principles and Implementation Guidance (World Bank).** Published by the World Bank in 2017, this publication aimed to be a step towards "standardized guidelines for all nature-based solutions". It provides principles and implementation guidance for planning NbS for flood risk management (including coastal areas) as an alternative to, or complementary to, conventional engineering measures.

- **Integrating Nature-based Solutions for Climate Change Adaptation and Disaster Risk Management: A Practitioner's Guide (Asian Development Bank).** A guide published by ADB in June 2022, documenting challenges and opportunities to implementing NbS for climate change adaptation based on successful case studies in Asian countries funded by ADB.

- **Building with Nature (Delta Programme, The Netherlands).** Coordinates national flood, water and climate management, and uses the preferred strategy of "Building with Nature", whereby natural systems and natural processes and materials are used to meet society's need for multi-purpose infrastructure that combines flexibility and sustainability.

- **Engineering with Nature (US Army Corps of Engineers, United States).** An initiative of the U.S. Army Corps of Engineers (USACE) to enable water resources infrastructure to deliver economic, social and environmental benefits. It is part of USACE's "Sustainable Solutions to America's Water Resources Needs: Civil Works Strategic Plan 2011 – 2015" and includes a variety of strategies that are documented in the EWN Atlas.

- **Ecosystem-Based Disaster Risk Reduction in Japan (Ministry of the Environment, Japan).** A practitioner's handbook published in 2016 by the Nature Conservation Bureau of Japan's Ministry of the Environment for ecosystem-based disaster risk reduction, which aims to leverage the preventative and mitigative functions of healthy ecosystems to reduce disaster risk.

- **Directives for Ecological Sea Dyke Construction of Reclamation and Polder Projects (Ministry of Natural Resources, China).** The new directive was published in January 2020, aiming to strengthen the existing Chinese National Standard on Sea Dyke Engineering Design (GB/T 51015-2014) with quantified standards to enhance coastal ecological restoration post-implementation.

- **The Australian Guide to Nature-based Methods for Reducing Risk from Coastal Hazards (National Centre for Coast and Climate, Australia).** A comprehensive guideline published in 2021 by NSCC in collaboration with six Australian universities, designed to increase awareness and outline what needs to be considered in the implementation of nature-based methods specific to Australian coastal systems.

Please see Resources for a compilation of guides on the implementation of NbS.

General steps for implementation of coastal Nature-based Solutions

Through a survey of these global efforts, this guide identified and distilled the commonalities in the design and implementation processes into the following guiding steps (Figure 2):

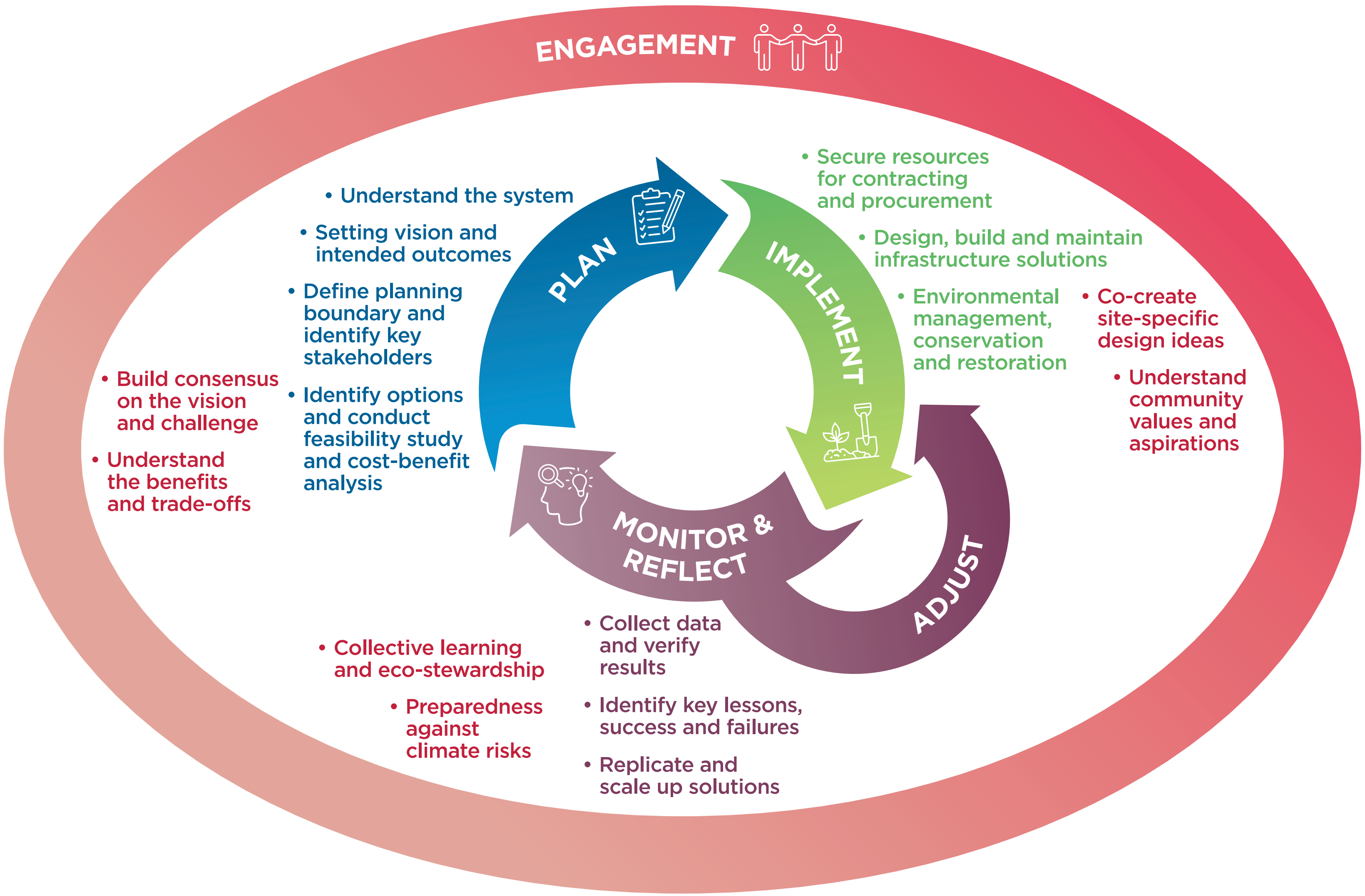


Fig 2. Outline of steps in implementing Nature-based Solutions

1. Defining the problems, project scope and objectives

In an urban environment like Singapore, problems rarely occur in isolation of others, and it is important to consider solutions in concert with their interconnected systems. For example, edge treatment NbS are typically applied in reaction to coastal erosion, but there might be related issues such as the loss of existing use of the coastline (e.g., for recreation), loss of biodiversity, or alteration of the hydrodynamics of the area. Mapping out the boundaries of the problem and interactions between various social, economic, ecological and governance dimensions is also useful in identifying possible blind spots or opportunities (World Bank, 2017).

If the problems are clearly defined, it will be easier to identify the **objectives of the NbS**. While multiple goals (with multiple co-benefits) are possible, it is also important to recognise the trade-offs. As much as possible, these goals should be specific, quantifiable and measurable, which will enable the monitoring of the NbS to evaluate its success and allow for adaptive management (see **Monitoring and Evaluation**, and **Engagement**). Goals for NbS could fall under the following categories:

- **Adaptability:** Part of the increasing popularity of NbS is their ability to adapt to evolving climate conditions and/or contribute to climate mitigation. For example, mangroves are known to reduce the impact of storms and erosion (Alongi, 2008), and could potentially grow and keep pace with sea level rise in the right conditions or restoration regime (Sasmito et al., 2016; Schuerch et al., 2018). If climate adaptation is a goal of the NbS, it will be crucial to analyse how it would stand up to a wide range of future climate impacts, and how its interactions with the community and environment around it might change with these impacts (Calliari et al., 2019).
- **Sustainability:** Sustainability generally refers to the use of resources in a way that "meets the needs of the present without compromising the ability of future generations to meet their own needs" (Visser and Brundtland, 1987). Minimising damage to natural habitats, maintaining stocks of flora and fauna, keeping air and water free from pollution, and reducing carbon emissions to reduce damage from global warming are all examples of sustainability. Because NbS promote biodiversity, they tend to be inherently more sustainable than traditional infrastructural solutions. They often also have other co-benefits like sequestering carbon from the atmosphere (Alongi, 2012) or reducing runoff. However, the assessment of NbS solutions and alternatives requires a holistic appraisal of the upfront resource/cost efficiency, as well as the long-term effectiveness and maintenance needs.
- **Biodiversity:** At its core, NbS are supposed to deliver ecological benefits. This can be done through the preservation or rehabilitation of natural habitats, or modification of artificial coastline/structures to enable them to support high biodiversity (Morris et al., 2018). The suite of biodiversity (also known as community or assemblage) that is to be recruited or supported in the area should be targeted, as the type of NbS implemented will inherently determine what will thrive (see **Understanding the System**).
- **Human wellbeing:** A major benefit of NbS is that they tend to improve the human wellbeing of an area by being more aesthetically pleasing. Depending on the type of NbS, they can also help improve air and water quality, reduce heat stress, provide recreational and educational spaces, and play a role in place-making and improving social resilience (Tallis et al., 2015; Morris et al., 2018; Gulsrud et al., 2018). They are thus an opportunity to create a space that caters to the needs of communities and enhance their quality of life.
- **Engineering performance:** In traditional infrastructure options, engineering performance tends to be the foremost goal. Maximising the longevity of the solution is one of their major considerations. For coastal protection measures, the efficacy of the solution in reducing risk and ensuring safety is also critical. A common criticism of NbS is that there is a lack of data supporting the effectiveness or longevity of these solutions, creating a barrier to implementation and scaling-up. Investment in piloting and long-term monitoring is required to better develop these techniques for large-scale use (Morris et al., 2018).

- **Risk reduction:** As a solution for climate change adaptation, NbS in the coastal protection context should be assessed for its effectiveness in wave attenuation, preventing flood inundation, as well as shoreline protection (mitigating coastline erosion). Studies have shown that natural coastal habitats like coral reefs, seagrass, saltmarshes and kelp can offer some protection from coastal hazards and sea level rise (Narayan et al., 2016), though the extent of effectiveness is context and site-specific. Aside from studying the specific site conditions to determine appropriate NbS, it is also important to recognise their limitations. For example, while mangroves can vertically accrete sediments, they may not be able to keep pace with the rate of sea level rise beyond a certain threshold (Saintilan, 2020). Any proposed NbS must be studied holistically to determine if it meets the intended goal of coastal protection.

- **Cost and benefit:** Another practical consideration is cost, which is often weighed against the projected benefit of the solution. It is crucial for practitioners to approach these cost-benefit analyses holistically and capture a wide-range of socio-economic and ecological costs and benefits over long timescales (Morris et al., 2018). For example, while a shoreline with a gradual profile and inter-tidal space may require more land and cost more to implement than a vertical seawall to protect the coastline against sea level rise, it may provide more value in terms of utility for recreation, biodiversity, and have a lower long-term maintenance cost.

2. Understanding the System

It is important to note that there is no "one-size-fits-all" NbS. Each solution needs to fit the unique circumstances of the site profile, environmental conditions and socio-economic characteristics. Developing a thorough understanding of the baseline or context of the system of interest is another critical step when deciding between different suites of NbS options (Calliari et al., 2019). In most cases, the physical environment would dictate what kind of NbS would be applicable. Forcing a NbS into the wrong environment might render it useless and even cause unforeseen negative impacts.

- **Hydrology:** For coastal NbS, the interaction between seawater and the coastline is a central factor in determining the options available. Hydrodynamics (e.g., currents, waves) can significantly affect the longevity of NbS that provide coastal protection and will also determine the profile of the coastline. For example, East Coast Beach is protected by a series of breakwaters, but is now suffering from coastline retreat due to erosion driven by monsoon-induced seasonality (Martens, 2013), and has not been systematically nourished with sediment. Generally, intertidal ecosystems (e.g., mangroves) perform better in low-energy environments with mild average hydrodynamic stress, although they can offer valuable protection during rare high-energy events (e.g., storm surges) (Lee et al., 2021; Zhang et al., 2012). Hydrodynamics also have implications on the biodiversity that can establish or thrive, determining the connectivity of organisms (which is crucial for the exchange of genetic material or supply of larvae), or the conditions under which certain organisms can persist (Bouma et al., 2014).

- Modelling the hydrodynamics of the area and how it would be changed depending on the solution implemented is critical to the decision-making process. For example, modelling current and future flood risk is key for climate resilience, due to the threat of sea level rise and changes in rainfall patterns. It is important to note that **for coastal adaptation, hard infrastructure solutions and nature are not mutually exclusive**. Engineering measures can be used to alter the hydrology of an area to make it more suitable for the establishment of natural habitats like seagrass meadows or mangroves.

- **Geomorphology:** The geography of the coastline is another factor affecting the options available. Is the profile of the coast steep or gradual? Generally, longer and more gradual foreshores are better for the stability and long-term sustainability of intertidal ecosystems as part of coastal protection (Bouma et al., 2014). Does the shore comprise soft sediment (e.g., beach, sandflat, mudflat) or hard substrate (e.g., reef, rocky shore)? Is it natural or artificial (e.g., reclaimed)? If a steep or vertical seawall already exists due to the local bathymetry and hydrology, replacing it with a mangrove might not be feasible. On the other hand, if the coastline comprises gradual beaches with low wave energy, hybrid eco-engineering with seagrass restoration might be more suitable than just hard defences. Understanding the dynamic interactions between organisms (particularly ecosystem engineers like seagrass, mangroves and corals) and the coastal landform (i.e., biogeomorphology) will also be critical to developing NbS that can thrive and are effective in the long run.

- **Ecology:** Given that NbS leverage nature to achieve their goals, it is crucial that there is a clear understanding of the ecology (i.e., how organisms interact with one another and their physical environment) of the natural ecosystem/biodiversity to be utilised. This is particularly true if the focus of the NbS is on the restoration or rehabilitation of natural habitats. A starting point would be to identify the original habitats that existed in the area, which may indicate what could thrive and what the NbS should cater to. For example, the south-eastern coastline of Singapore largely comprised sandy/muddy shores and seagrass meadows before its reclamation. Today, these areas have successfully recruited seagrass and the meadows have naturally re-established (Yaakub et al., 2014) to provide some sediment stabilisation co-benefits. Ensuring connectivity to sources of larvae or propagules is also critical to the sustenance of a healthy functioning ecosystem (Gillis et al., 2017).

  The biodiversity that can be sustained in an NbS greatly depends on having the right environmental conditions. Most of the solutions used in temperate areas such as salt marshes and oyster beds (Borsje et al., 2011; Mitchell and Bilkovic, 2019) may not apply in the tropical urban context of Singapore, so the country may need to innovate and find its own solutions that are tailored to local conditions.

- **Value and Utility:** It is also important to consider what the coastline is used for and what the stakeholders and users value them for. This is a critical part of ensuring that the NbS takes into account the values and functions of the area (e.g., lifestyle and recreation, nature appreciation, business activities, heritage, etc.).

  Engaging stakeholders is key to a successful NbS (Raymond et al., 2017), so practitioners should aim to do so as early in the planning process as possible, to enable different societal valuations to be included in the final design, and also minimise negative blowback further downstream (see Section on **Monitoring**, **Evaluation** and **Engagement**).

- **Temporal and spatial scale:** Based on the factors above, it is clear that NbS are often affected by large-scale environmental processes, such as hydrodynamics, water catchments, ecological connectivity, etc. Many NbS are also effective over long periods (20 to 50 years or longer), sometimes requiring a certain successional period for the biological community to stabilise, or for it to respond to long-term impacts (e.g., sea level rise) (World Bank, 2017). It is thus crucial to consider NbS over appropriate temporal and spatial scales when evaluating their cost-benefits and effectiveness.

3. Identification of various options

Based on the analysis of the system, various options for intervention can be proposed. These can range from soft ecosystem-based solutions to co-located hybrid solutions, and options to enhance hard engineering-based measures. NbS can also be complemented by non-structural measures (e.g., adaptive spatial planning, risk management and warning systems). These solutions should help reduce the risks and achieve the objectives identified. In the next section, we examine a range of NbS options that have been applied in different contexts around the world.

4. Cost-benefit analysis

Aside from monetary costs and benefits, the analysis should quantify how the different options identified affect the risks (e.g., using flood-risk modelling) and co-benefits they bring, like ecosystem services, or socio-economic and environmental benefits, which are not easily monetised. The accessibility and utility of certain co-benefits should be taken into account. For example, the recreational or aesthetic value of an NbS can only be realised if the general public can appreciate and utilise the amenities.

It is also important to assess the social and environmental impacts of the intervention, and to account for the temporal distribution of the costs (e.g., costs are higher in the earlier years during construction, but benefits could be realised yearly for decades after). There are several ways to do this, such as scoring different costs and benefits (Watkin et al., 2019), or using selected performance metrics to estimate system responses (Bridge et al., 2015). In Singapore, this could be coupled with the Environmental Impact Assessment process.

5. Select and design intervention

Apart from cost-benefit analysis, a multi-criteria decision analysis is instrumental in choosing the design of the intervention. This should be communicated to stakeholders so that the decision-making process is collaborative and inclusive. This can be done informally, as with the example of **Rebuild by Design** (RBD), whereby stakeholders meet with agencies and consultants regularly to discuss design options (see section on **Engagement**). A more structured approach, whereby stakeholder preferences are used to weigh metrics for trade-off analyses, can also be adopted. USACE has developed a structured decision-making process that uses stakeholder preferences to weigh different objectives (e.g., ecosystem services, reducing erosion etc.) and uses them in a trade-off analysis to rank various design alternatives (Bridges et al., 2015). Maintenance should be a key consideration in this decision analysis, as it may constitute a major component of the project cost in the long run.

6. Implement and construct

Close monitoring and continued stakeholder interaction during the construction phase are important to limiting impacts. This could be coupled with the Environmental Monitoring and Management Programme (EMMP) process that is often used in development projects to ensure environmental regulation compliance, or by involving the community (e.g., NGOs, citizen scientists).

7. Monitoring, evaluation and maintenance

Post-implementation monitoring is critical to evaluating the success of the NbS and can help inform future designs (see section on Adaptive Management). Practitioners should consider tapping on the community in some of this monitoring (e.g., citizen science surveys), to encourage continued co-ownership of the NbS and to build social resilience. Some NbS may also require long-term maintenance (e.g., sand or sediment nourishment), monitoring or intervention beyond the immediate post-implementation phase.

Nature-based Solutions include both natural and modified ecosystems, which can be applied in various forms in the urban environment, depending on the land use and the intended functions.

Top: Kampung Admiralty is designed with a range of thoughtful planting schemes woven into the building to enhance the wellbeing of its occupants. *Source: NParks*

Bottom: Jurong Lake Gardens has an extensive network of green-blue infrastructure which provides different habitats for wildlife, enhances water circularity and flood resilience, and enables people of all ages to enjoy. *Source: NParks*

Singapore’s Coastal and Marine Environment

Located at the confluence of the Indian and Pacific oceans, Singapore has always been a meeting place for immigrants from different parts of the world, resulting in rich diversity. This is no less true for its coastal and marine biodiversity. Being just outside the Coral Triangle—the centre of diversity for the world’s tropical marine ecosystems—Singapore is home to 255 species of hard coral (one-third the global total), 35 species of mangrove (half the global total, based on Polidoro et al, 2010), and 12 species of seagrass (one-fifth the global total). Despite urban development and reclamation leading to severe habitat loss, there remains a wide variety of coastal ecosystems. In their natural state, these ecosystems are located side-by-side with strong ecological linkages and interdependencies (Figure 3 and Figure 4):

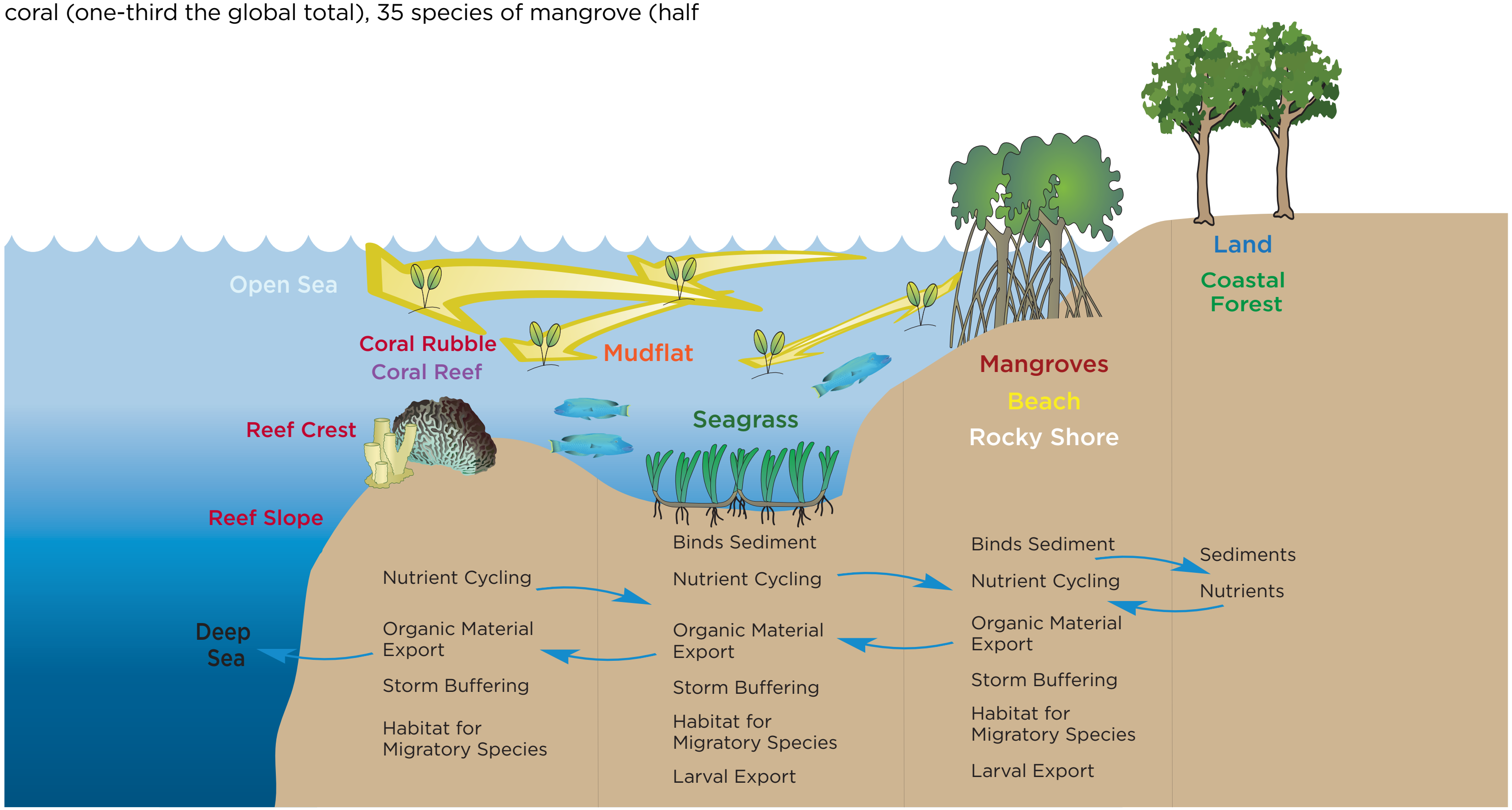


Fig 3. Diagram of how coastal ecosystems are interdependent; adapted from *For a World Without Boundaries: Connectivity Between Marine Tropical Ecosystems in Times of Change* (Earp et al, 2018).

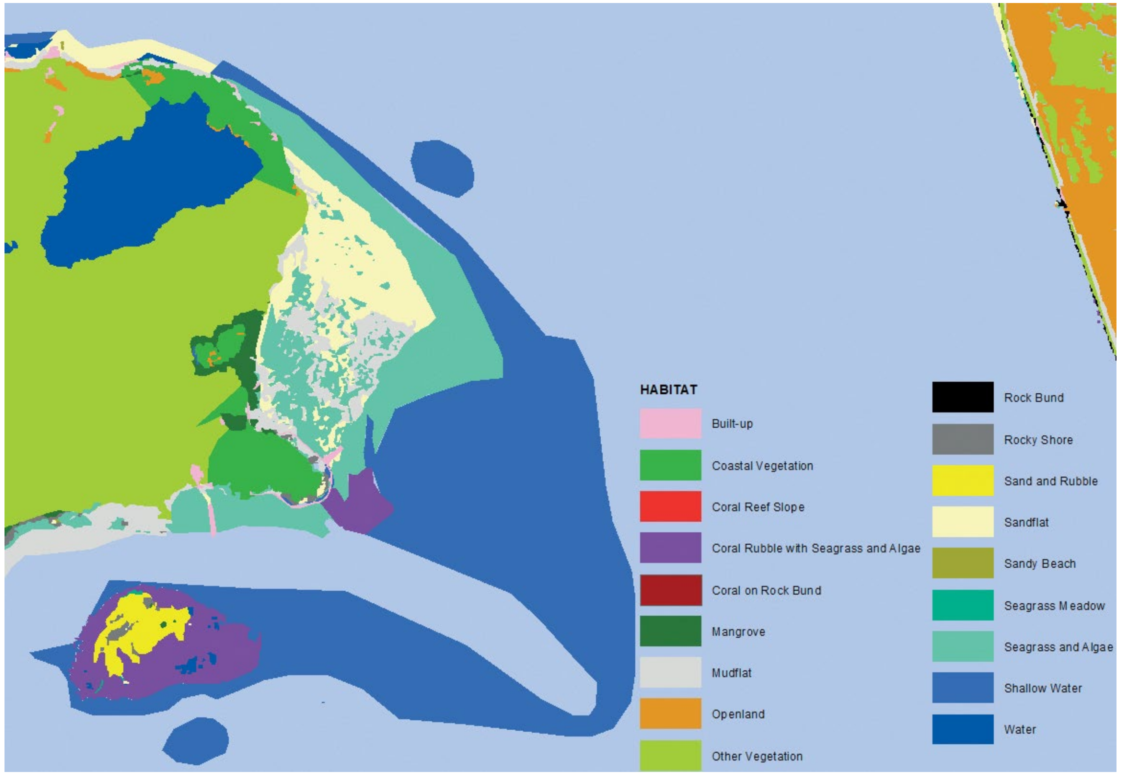


Fig 4. Example of how different coastal and marine ecosystems lie side-by-side at Chek Jawa Wetlands on Pulau Ubin.
Images: Jonathan Tan (top); NParks (bottom)

Rocky cliff coastal forest at Sentosa (top) and sandy shore coastal forest at Pulau Tekukor (bottom).
Images: Jonathan Tan

Coastal Forests

Coastal forests are found above the high-tide mark, with plants that can deal with nutrient-poor, saline soil, as well as exposure to strong winds and storms. Flat areas with sandy soil tend to favour fast-growing pioneer species, while steep rocky areas tend to favour slow-growing specialists. Many of the plant species here are found exclusively along the coast and are critically endangered in Singapore due to habitat loss. Their effectiveness in providing erosion or storm protection is poorly studied compared to mangrove forests.

These forests provide nesting habitat for large, charismatic coastal birds such as herons and raptors. A number of forest-dwelling mammals such as monkeys and bats are also found here.

Mandai Mangrove and Mudflats *(Image: NParks)*. Tidal mudflats are often found seawards of mangroves and support rich birdlife.

Mangrove Forests

Mangrove forests are highly productive wetlands found along estuarine rivers and low-lying coasts, providing food, fuel, fibre and medicine, as well as being key sites for research, education, recreation and eco-tourism. Growing within the intertidal zone, mangroves physically protect coastlines by breaking waves and help shield seagrass beds and coral reefs from the effects of siltation from land-based runoff. In addition, they are a key nursery ground for many fish species and support rich biodiversity such as migratory birds, crocodiles, otters and snakes.

Rocky Shores

Rocky shores consist of rocks, outcrops and boulders overgrown with algae, and animals such as molluscs, sea stars and crabs are found both on and under the rocks. Animals here are adapted to direct sunlight exposure and high temperatures. Uneven and irregular shapes and surfaces create rugosity, providing crevices for animals to take shelter in as well as attenuating wave energy.

Rocky shores are often found in association with cliffs with visible stratification; these form part of Singapore's geological heritage.

Sandy beach at East Coast Park with a pair of mating Coastal Horseshoe Crabs. *Images: Jonathan Tan*

Sandy Beaches

Stretches of bare sand stretching from above the high-tide mark down to the low spring-tide mark, these are low in resident biodiversity. However, they are key nesting grounds for endangered species such as sea turtles and horseshoe crabs, and are also popular recreational sites for water sports, swimming and picnics.

Migratory shorebirds feeding on a mudflat at Mandai. *Image: David Li*

Mudflats

Exposed at low tides, mudflats are often found near mangroves but in waters too deep for mangroves to grow. They are composed of anoxic fine sediments rich in burrowing worms and bivalves. This in turn supports migratory birds that use Singapore as a refuelling stop, as well as resident shorebirds. Crabs and fish such as mudskippers are also common here.

Sandflat at East Coast Park. *Images: Jonathan Tan*

Sandflats

Exposed at low tides, sandflats look devoid of life but burrowing animals such as clams, crabs, sea stars, sand dollars and snails are found just beneath the surface. Shorebirds also visit these areas to forage. Prior to reclamation, extensive sandflats stretched along the coast from Tanjong Rhu to Changi Point and supported rich fishing grounds.

Seagrass meadow at Pulau Semakau *(top image: Ria Tan)* **and examples of seagrass animals** *(bottom images: Jonathan Tan)*

Seagrass Meadows

Seagrasses are flowering plants that play important roles in the marine environment. Apart from being a source of food for herbivores, seagrass meadows are nurseries for juvenile animals such as crabs, shrimps and fishes. The structural complexity of seagrasses makes seagrass meadows areas of rich marine biodiversity, with high densities of echinoderms, molluscs and crustaceans. Dugongs are known to forage in Singapore's seagrass areas.

Seagrass meadows can sequester extremely high levels of carbon in their sediments and may also contribute to wave attenuation if they grow at a high enough density and height. The rich diversity of animals in seagrass meadows makes them popular sites for intertidal walks.

Coral rubble on the reef flat at Pulau Jong exposed during low spring tide (top). Many marine animals inhabit the reef flat despite its occasional exposure (bottom).
Images: Jonathan Tan

Singapore's coral reef crests and slopes are home to a rich array of marine life despite the turbidity. *Images: Jonathan Tan*

Coral Reefs

The coral reefs of Singapore are located mainly in the islands south of Singapore. Contrary to the belief that our reefs have been permanently devastated, they still support rich marine life with more than 250 species of hard corals from 55 genera, over 200 species of sponges, 120 species of reef fish and an undetermined number of gorgonians, nudibranchs and other invertebrates.

Each reef can be sub-divided into several zones: the reef flat, reef crest and reef slope. The shallow reef flat is exposed to air at low spring tides and hence has lower live coral cover. However, coral rubble, the broken-up skeletons of dead corals, provides shelter for a rich diversity of animals.

The reef crest is usually never exposed, and consequently, has the highest density of marine life. The reef slopes to the seabed and as depth increases, the density of marine organisms decreases and the community changes to species adapted to low-light conditions. The sea floor is usually silty or sandy, but where rocky surfaces appear, they are festooned with sea whips and sea fans and colourful cave corals.

Both offshore and fringing reefs provide protection against wave action, and may have the potential to grow with sea level rise. In addition to supporting recreationally important fisheries, Singapore's reefs are used for research, recreational diving and intertidal walks.

Dolphins (top) and terns (bottom) are often seen in Singapore's pelagic waters. *Images: Jonathan Tan*

Despite the lack of light, a wide variety of animals can be found on the seafloor *(top images: Jonathan Tan and Ria Tan)***. This includes large, endangered fishes caught at Bedok Jetty** *(bottom images: Raj Bharathi and Nature Society Singapore, from Facebook)*

Open Sea and Seafloor

Pelagic and benthic habitats are the most extensive but also least-studied of Singapore's coastal ecosystems.

Singapore's pelagic waters support a range of large animals such as dolphins, game fish (e.g., giant trevally) and sea eagles. The local ecology of these animals remains poorly studied.

Anecdotal evidence from fishermen as well as scientific research suggest that large globally endangered whiprays and shovelnose rays forage along Singapore's seafloor. Surveys suggest that the seabed is heterogenous, with various areas holding high densities of sponges, feather stars and sea cucumbers. Parts of the seafloor stretch to as deep as 200 m and are home to rare animals such as basket stars. More research is needed to assess how these benthic habitats may be affected by coastal protection measures.

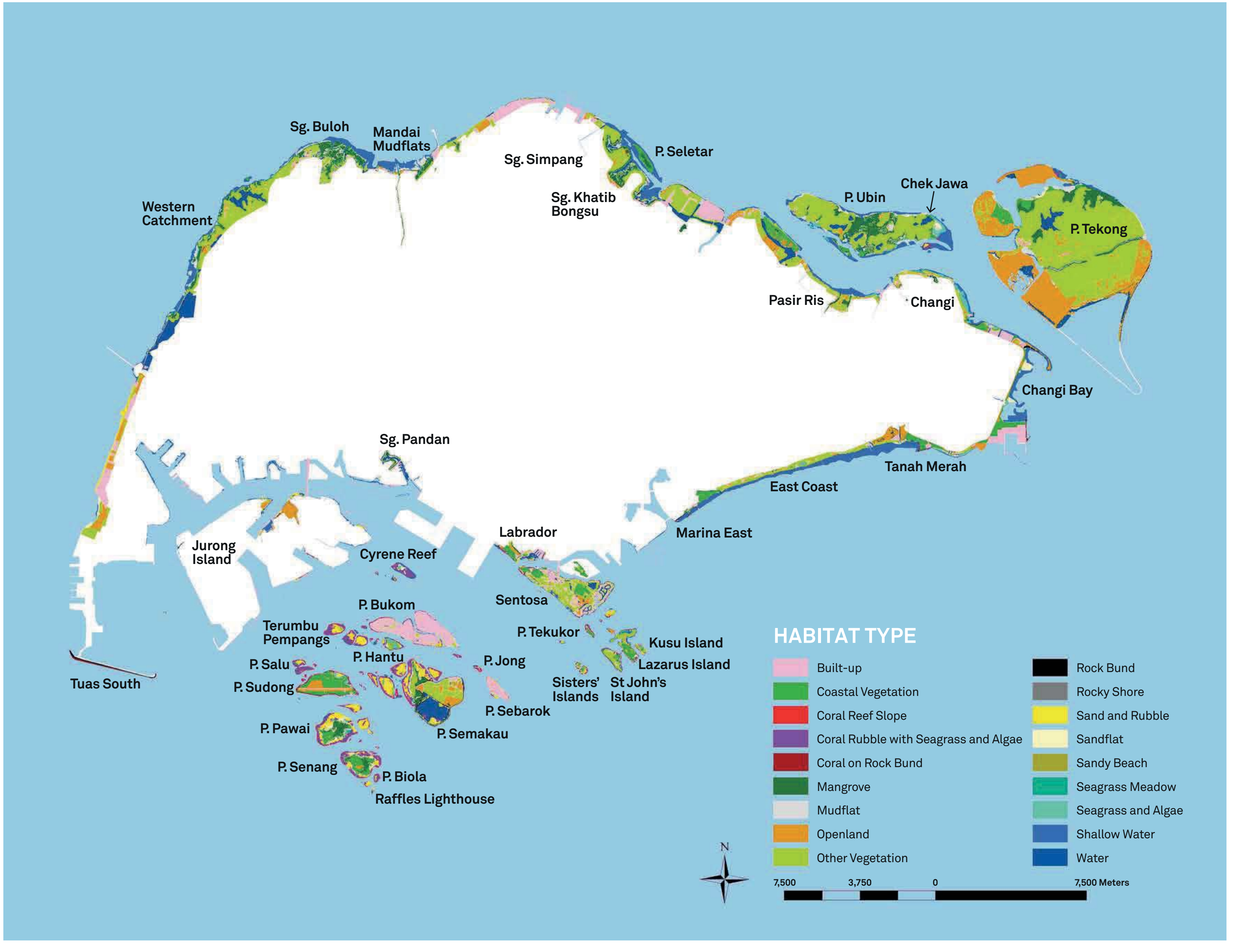


Fig 5. The coastal and marine habitat map of Singapore based primarily on satellite images taken from 2015 to 2018. The extent of this map does not reflect Singapore's territorial boundaries, and the full map is available on GeoSpace, GeoSpace-Sea and Data.gov.sg. *Source: NParks; see Tan et al (2022)*

Habitat Type	Definition	Area (ha)
Built-up	Built structures	–
Coastal Vegetation	Terrestrial vegetation with canopy cover, dominated by coastal species	804.7
Coral on Rock Bund	Intertidal and subtidal flat/slope, rock revetment, live coral cover	42.0
Coral Reef Slope	Subtidal slope, coral reef, live coral/seagrass/algae cover	101.6
Coral Rubble with Seagrass and Algae	Intertidal flat, coral rubble, live coral/seagrass/algae cover	383.2
Mangrove	Intertidal and terrestrial vegetation with canopy cover, dominated by mangrove species	931.1
Mudflat	Intertidal flat, mud, low surface biotic cover	400.7
Openland	Terrestrial vegetation without canopy cover	–
Other Vegetation	Terrestrial vegetation with canopy cover, not dominated by coastal species	–
Rock Bund	Terrestrial and intertidal rock revetment, low to moderate algae cover	–
Rocky Shore	Intertidal flat/slope, natural rock, low to moderate algae cover	41.2
Sand and Rubble	Intertidal flat, sand and coral/rock rubble, low to moderate surface biotic cover	451.8
Sandflat	Intertidal flat, sand, low surface biotic cover	235.6
Sandy Beach	Intertidal slope, sand, no or minimal surface biota	118.0
Seagrass and Algae	Intertidal or shallow subtidal flat, sand or mud, moderate seagrass and/or algae cover	188.8
Seagrass Meadow	Intertidal or shallow subtidal flat, sand or mud, high seagrass cover and low algae cover	40.8
Shallow Water	Subtidal areas up to 2 m depth below chart datum	–
Water	Freshwater bodies; semi-enclosed marine waterbodies deeper than 2 m	–

Large stretches of mangroves and mudflats are found along the northwest coast (Mandai, Sungei Buloh, Lim Chu Kang, Western Catchment), northeast coast (Pulau Seletar, Sungei Khatib Bongsu, Sungei Simpang, Pasir Ris), and on the northeastern islands of Pulau Ubin and Pulau Tekong. Smaller patches are found along the southern coast (Sungei Pandan, Berlayar Creek) the southwestern islands of Pulau Semakau, Pulau Senang, and Pulau Pawai. Seagrass areas are found mainly on the eastern coast (Changi, East Coast, Pasir Ris), and scattered amongst the offshore islands of Pulau Ubin and the southern islands. Coral reefs (intertidal coral rubble and subtidal reef slope) are found mostly in the southwestern islands and their associated patch reefs, with smaller patches at Sentosa Island and the islands to its southeast. There is also coral growing on rock bunds along various parts of the southern coast (Changi Bay, Marina East, Pulau Semakau, Tanah Merah, Tuas South). Shallow water areas (defined as up to 2 m depth below Chart Datum) are found all around Singapore, but especially along the eastern coasts, northwestern coast, and Pulau Ubin.

The heterogeneity of Singapore's coastlines and diversity of ecosystem types mean that coastal protection measures need to be tailored to local site conditions in order to maximise ecological and social co-benefits.

As a result of development, most of Singapore's shores, concentrated mainly in the southern and southwestern coast, Jurong Island, some of the southern islands, and Pulau Tekong, are deemed Protected Coastline. These areas tend to be highly urbanised due to the presence of industrial and commercial districts, or hold other critical assets such as military or municipal infrastructure. With two-thirds of the coastline having been built over with grey infrastructure, a holistic strategy for strengthening the resilience of Singapore's marine ecosystems and natural heritage could include enhancing these hard shorelines to be more conducive for biodiversity to thrive. Hard and hybrid eco-engineering solutions that can be deployed in highly urbanised areas with limited space will thus have a major role to play in providing additional ecosystem benefits.

Mangrove-rock hybrid revetment at Kranji Coastal Nature Park. *Image: NParks*

Coastal Nature-based Solutions in Singapore

Source: NParks

Coastal Nature-based Solutions for Tropical Environments

A coastal NbS system should seek to create an environment that is sustainable and adaptable, to broaden its values for both society and ecosystem. This can be achieved through a systemic approach to thinking, planning and design, to provide three key functions: coastal and flood risk reduction, nature regeneration, and human well-being, recreational or educational values (Figure 3). By deepening the understanding of the hydrology, geography and ecology of the area and to inform the planning and design of nature-based solutions along the coastline, the coastline's resilience is enhanced by nature's ability to adapt to changing stresses and risk profile, and its provision of various infrastructural and ecosystem services. When the three key functions are considered together, NbS ensures that future generations can continue to have access to, and enjoy the unique experience of coastal nature and habitats, to generate long-term societal values through symbiotic relationship between human and ecosystem.

There are a variety of coastal NbS that have been developed and trialed worldwide. This branch of NbS typically falls under the realm of ecological engineering (eco-engineering) and can range from hard options, which tend to rely more on artificial structures, to soft/green options, which use more natural elements such as planting (Morris et al., 2019). This is contrasted against traditional reinforcements, which are not specifically designed to provide ecosystem services or benefit biodiversity (Figure 6).

Hard or hybrid eco-engineering NbS are usually applied in more urbanised areas to mitigate ecological impacts of development, or improve the typically low aesthetical and biodiversity value of grey infrastructure (e.g., seawalls, piers), while soft solutions are usually applied to derive additional ecological benefits such as conservation of existing habitats (Morris et al., 2019). Natural ecosystems or soft solutions are not necessarily less effective at reducing climate risks; studies have shown that natural habitats provide protection by attenuating waves, stabilising shorelines and reducing flood surge propagation (Bouma et al., 2014). Having a long-term objective in planning and design, hard engineering solutions could also be applied intentionally to create the right environment to support an ecosystem's regeneration, as seen in Building/Engineering with Nature frameworks. The planning and design of NbS thus requires a mindset shift from that of a static one-off solution towards creating a dynamic and adaptable system to achieve the intended goals and benefits in the long run.

This section examines a series of local and international examples of coastal NbS strategies, ranging from hard to hybrid to soft solutions, evaluating their applicability to the local context and potential co-benefits.

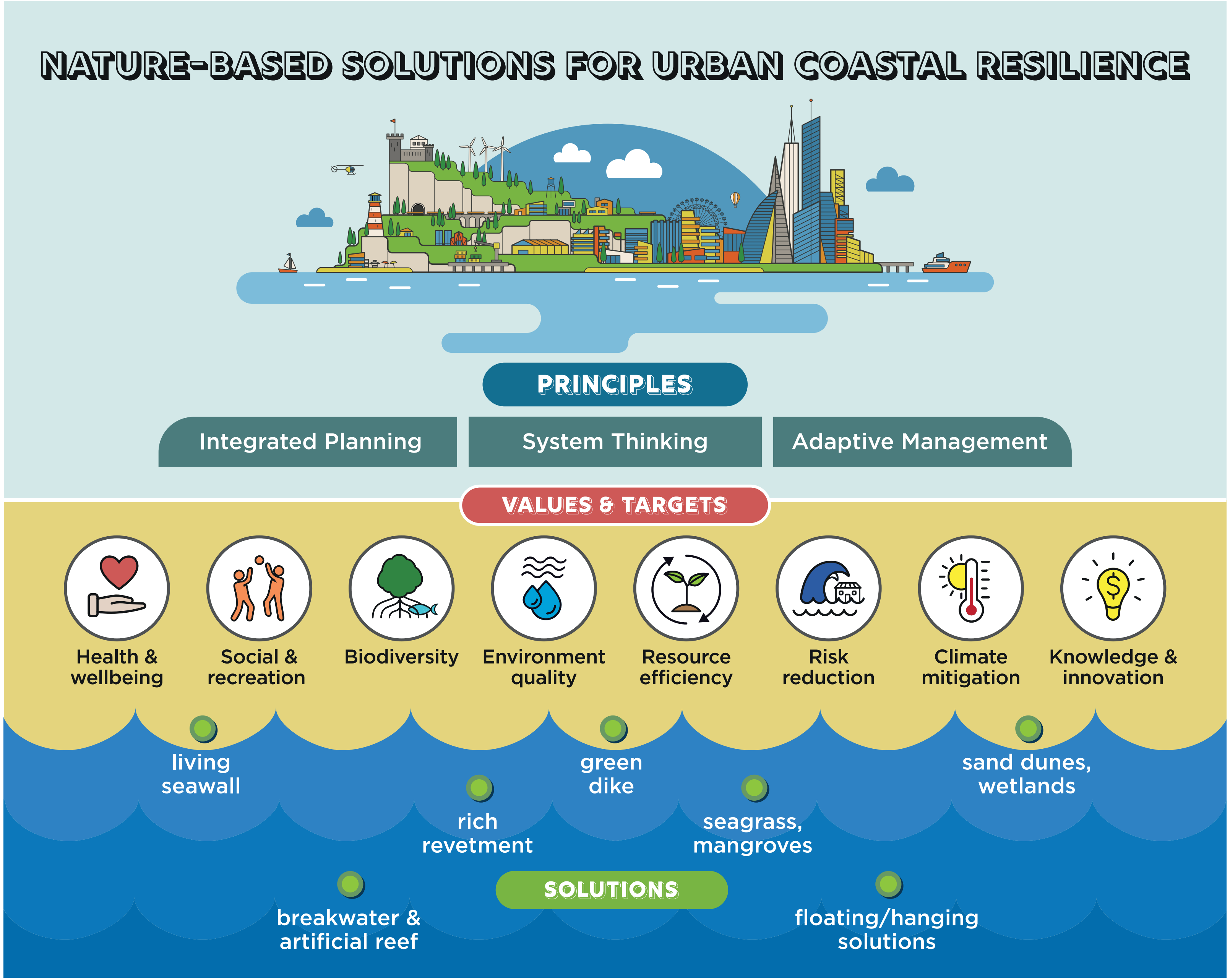


Fig 6. Nature-based solutions for urban coastal resilience, values/targets and a spectrum of solutions. *Source: CLC*

Living Seawall Installation at Blues Point in Sydney Harbour (top and centre) and Biodiversity Enhancement Tiles in Changi Beach Park (bottom). *Images: Dr Maria Vozzo; Dr Lynette Loke*

Biodiversity Enhancement Tiles

Seawalls or steep coastal revetments are typically used to effectively protect urban coastlines against tidal erosion and surges without significant land take. However, they tend to have low ecological, social, or recreational value due to the lack of landscape/aesthetic considerations in design, and restricted access to the shoreline due to safety reasons. The lack of crevices in seawalls eliminates water retention and shelter provisioning functions, both of which would help reduce heat and wave impacts on marine organisms. One way of enhancing these structures without extensive modification is to retrofit biodiversity enhancing tiles, which introduce a range of pits and holes of various sizes and configurations. These complex tiles provide the refugia that support significantly greater intertidal biodiversity than plain seawalls, thereby improving their ecological value, while still protecting the shoreline.

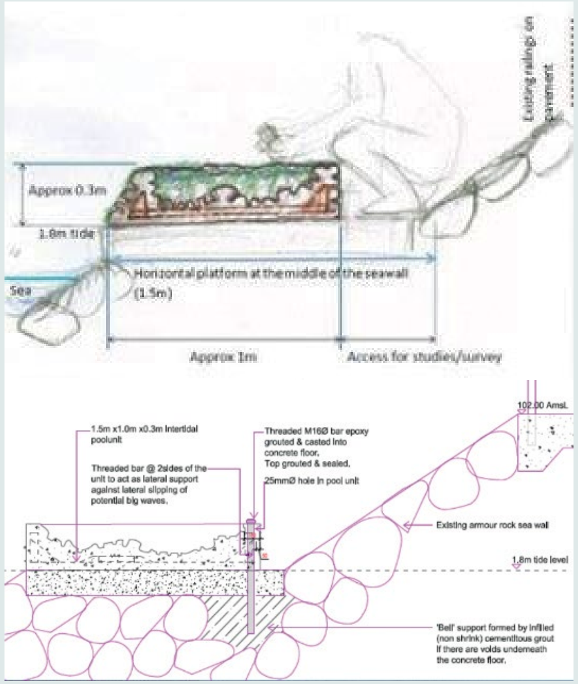
A key local example is BioBoss, a tool that was developed by researchers at the National University of Singapore (NUS) specifically to enhance biodiversity on seawalls (Loke et al., 2019). Current research focuses on the design, material, configuration and density of tiles needed to optimise biodiversity recruitment, and scaling up this solution with better material and cost efficiency.

Examples of Locations: Changi, Pulau Hantu, Keppel Marina, Singapore; Sydney, Australia
Type: Ecological enhancement
Potential Co-benefits: Biodiversity enhancement of hard infrastructure, upcycled material

Land Use: This solution can be retrofitted onto existing hard defences like seawalls or revetments and does not require significant land take or cost. While it does have biodiversity co-benefits, the social or economic co-benefits like recreation, education, etc could be limited due to the steep surface and inaccessibility.

Relevance: This solution was developed in Singapore and has been tested in various locations like Changi, Pulau Hantu, Kusu Island, and Sentosa. It is therefore suitable for enhancing existing hard intertidal structures where softer or hybrid solutions are not possible due to space constraint. The biodiversity that it ultimately recruits and establishes on the tiles is dependent on available sources of larvae and propagules.

As these tiles can be attached to seawalls and other hard coastal defences, land take and sea-space requirements are negligible and it is less costly to other solutions listed here, with maintenance being minimal as well. However, its potential recreational or aesthetic co-benefits are also more limited, as the biodiversity recruited to these tiles tend to be less accessible and visible to the public.



Cross-sectional designs (top) and photo of intertidal terrace and pools piloted at Changi Beach Park (bottom).
Images: NParks

Intertidal Terrace and Tidal Pools

Similar to biodiversity enhancing tiles, these tidal pools can be installed on seawalls that feature an intertidal terrace (i.e., flat portion in the intertidal zone) to enhance their ecological and recreational value. These pools enhance biodiversity by reducing desiccation and heat stress during low tide, and its design can be modified to increase habitats available for different wildlife. In Singapore, locally developed Complexity for Artificial Substrates software (CASU; Loke et al., 2014) was used to inform the use of internal grooves and pits to increase habitats. Tidal pools could be made accessible to the public during low tide to improve recreational and educational value. This has been done worldwide through integrating them into coastal design typologies (Browne and Chapman, 2011; Morris et al., 2019). There are also project case studies in developing tidal pools with eco-concrete or upcycled material to achieve added benefit of material circularity.

Examples of Locations: Changi Beach Park, Singapore; Tung Chung, Hong Kong
Type: Hard eco-engineering
Potential Co-benefits: Biodiversity enhancement of hard infrastructure, education and recreation values, added shoreline protection/wave attenuation, upcycled material

Land Use: This solution can be retrofitted onto existing hard infrastructure like seawalls or revetments and does not require significant land take or cost. While it does have biodiversity co-benefits, accessibility needs to be consciously planned for it to provide social benefits like recreation, education, etc. This could include having rough-floored staircases with railings onto the revetment to enable safe access.

Relevance: This solution was developed in Singapore and has been tested at Changi. The contoured pools allowed a year-round habitat for a community of rocky shore invertebrates such as molluscs. However, its effectiveness in recruiting biodiversity may be better if it could be retrofitted lower down the seawall, where the pools would be below the tide mark and thus submerged for longer periods of time. The smoothness of the granite wall would also reduce the types of habitats that could have been established. Such constraints reveal design limitations in deploying this type of NbS as an add-on to infrastructure.

Marine life colonising floating pontoons at Marina @ Keppel Bay. *Images: Nathaniel Soon*

Floating and Hanging structures

Floating pontoons can create rich and diverse marine habitats. Rare and endangered species such as hawksbill sea turtles and seahorses are known to seek refuge amongst such structures. Being close to the water surface, these pontoons receive ample light that supports corals, algae and other sessile organisms on their submerged undersides, creating a habitat for species typical of coral reef communities.

Floating and hanging structures could also host filter feeders and contribute to the improvement of water quality and aesthetics, and indirectly enhance the landscape and recreational value of the coastal waters. They could be strategically deployed in urban or industrial areas such as ports to mitigate environmental impacts of development and restore ecosystem. For example, an inexpensive solution of 'polehulas' made mostly of nylon ropes hanging from jetties were piloted in the Port of Rotterdam by the Netherlands' research institutions.

Examples of Locations: Marina @ Keppel Bay, Singapore; Port of Rotterdam, the Netherlands
Type: Hard eco-engineering
Potential Co-benefits: Biodiversity restoration, wave attenuation, water quality, aesthetics, education and recreation values

Land Use: This solution can be deployed for nature to extend seawards from hard infrastructure like seawalls or revetments. However, it may require a hydrologically sheltered environment to avoid high maintenance costs. As it can be easily made visible and accessible to the public, it also provides ample opportunity for recreation and education.

Relevance: A successful local example is Marina at Keppel Bay, which supports a thriving coral reef community. Its design allows seawater to readily flush in and out with the tides, bringing nutrients and plankton (including larvae) to support a healthy coral reef community. In addition, vessels are prohibited from discharging sewage into the marina, and boat-owners are encouraged to use biodegradable detergents in this no-wake zone. Such floating pontoons could be deployed in other hydrologically sheltered areas. Further modifications such as growing coastal plants on the pontoon or piloting handing structures could be explored to further improve the habitat diversity and co-benefits.

Corals at the bottom of the revetment at Tanah Merah Ferry Terminal. *Images: Loh Kok Sheng*

Intertidal Seawall Reef

Intertidal seawall reefs are built by installing a low-tide revetment berm at the base of a seawall to improve ecological value while complementing protective functions of a seawall, such as reducing tidal surge and wave run-up. The berm can comprise of rocks/boulders extending from sloping revetments, creating a plateau that shields communities from direct wave action (Pilarczyk, 2003), and when placed at the low-tide mark, allows the habitat to be consistently submerged and sheltered to support coral recruitment and other intertidal reef organisms that depend on it (Ng et al., 2012). Although current examples use smooth granite boulders, other materials with rough surfaces should also be considered if they could better promote coral growth.

Examples of Locations: Tanah Merah Ferry Terminal, Singapore
Type: Assisted natural regeneration
Potential Co-benefits: Biodiversity restoration, water quality, aesthetics, recreation, wave attenuation, erosion control, carbon sequestration

Land Use: Additional land take is variable, depending on the width of the berm. It can be integrated with recreational and educational use through the construction of a parallel boardwalk. This solution can coexist with shipping infrastructure, as seen at Tanah Merah Ferry Terminal.

Relevance: This solution has been demonstrated effectively on both mainland and offshore Singapore, providing habitat for a young and dense intertidal coral reef community, albeit less diverse than natural reefs (Ng et al., 2012).

To increase their effectiveness, intertidal seawall reefs should adopt gentle sloping, or have a plateau to provide the sheltered environment ideal for coral larvae recruitment. These habitats should also be shallow, at a depth with sufficient sunlight to promote coral regeneration (i.e., 0.4 m above to ~7 m below chart datum; Ng et al., 2012). Corals are found to be able to grow sub-tidally on the granite slopes of the seawalls, reaching density as high as 80%, essentially making the revetment an artificial reef.

Coral reefs growing on such structures could be made more accessible for nature-based recreation through boardwalks extending from shore, similar to the Labrador Nature Reserve jetty. The presence of reef communities also support/attract fish populations, which make them popular with recreational fishermen. Water-based recreations such as kayaking, or scuba diving could also be considered along seawalls with high subtidal coral density.

Corals found on sloping seawall in Singapore.
Images: Yuichi Kikuzawa

Subtidal Seawall Reef

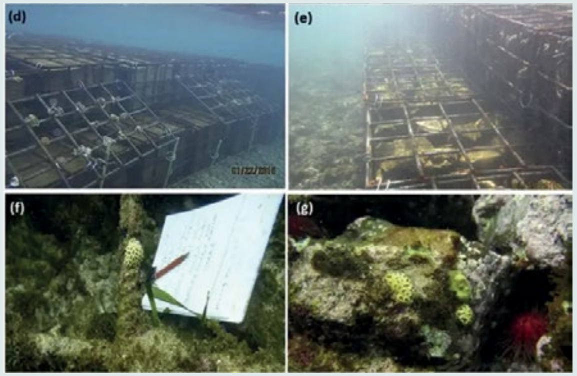
Sloping seawalls make ideal habitats for corals to grow as there is greater surface area for recruitment. Approximately 63% of Singapore's coastline consists of seawall defenses with a mix of vertical and sloping designs typically constructed of granite rip-rap or concrete (Lai et al., 2015; Ng et al., 2012). Such artificial sloping seawalls have shown to be able to support a wide variety of corals, demonstrating their potential to be viable nature-based solutions to not only protect our shorelines but also encourage biodiversity regeneration.

Examples of Locations: Southern Islands, various locations, Singapore
Type: Assisted natural regeneration
Potential Co-benefits: Biodiversity regeneration, water quality, aesthetics, recreation, carbon sequestration

Land Use: These subtidal seawalls are found to be associated with a variety of land-uses, including landfills (Pulau Semakau), recreation (St John's Island) and marinas (SAF Yacht Club). They help provide a stable environment for corals to recruit on, whilst serving other multiple functions, which can be replicated along Singapore's coastal areas where there are existing marinas (e.g., Keppel Bay) and for recreation.

Relevance: The sloping design of seawalls is thus recommended to maximise recruitment area and exposure to sunlight. A study comparing coral colonisation on sloping and vertical seawalls found that hard coral comprised approximately 17% of sloping seawalls versus 10% on vertical seawalls (Kikuzawa et al., 2020). In terms of material, sloping granite rip-rap seawalls tend to have more crevices and topographical complexity, allowing them to recruit a wider range of species.

Regenerated coral community on the subtidal seawall reef could contribute to wave attenuation and potentially grow with sea level rise, and present a source of blue carton. The long-term resilience of these regenerated coral community to climate change and rising sea temperature needs to be further studied.



Reef breakwater in Greville, Grenada (top) and artificial reef in Sisters' Islands Marine Park, Singapore. *Images: Reguero et al. 2018; Nicholas Chew*

Offshore Artificial Reefs

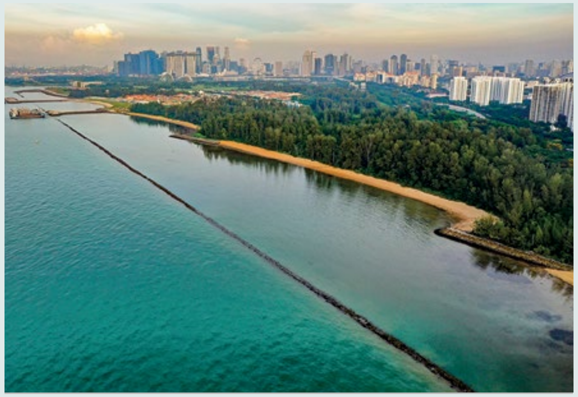
Offshore artificial reef structures can reduce wave action and prevent shoreline erosion in place of traditional infrastructure like bulkheads or breakwaters. Coral reefs are known to modify local hydrodynamic conditions, reducing wave energy and shoreline erosion in bay areas. Artificial reefs can also promote coral recruitment and growth. A pilot study by Reguero et al. (2018) in Grenville, Grenada, demonstrated coral recruitment and fish aggregation near the structures within a year, which provided a source of livelihood/income for local fisheries. The study utilised reef structures (8 m x 5 m) using steel baskets filled with stones or cement cinder blocks, installed 0.25 m below mean sea level to attenuate waves. The study thus exemplifies the co-benefits of utilising NbS such as offshore artificial reefs beyond just enhancing biodiversity.

Examples of Locations: Grenville, Grenada; Sisters' Islands Marine Park, Singapore
Type: Hybrid eco-engineering
Potential Co-benefits: Biodiversity regeneration, shoreline protection, wave attenuation, erosion control, carbon sequestration, aquaculture

Land Use: As these artificial reef structures are placed offshore, land take is minimal. The location, extent and height of these structures will depend greatly on the hydrodynamic conditions of the area. It is also important to consider its impact on vessel movement and navigation.

Relevance: Singapore has experimented with artificial reef structures and studies have shown that corals can recruit naturally to them. Recently, JTC lowered eight multi-storey artificial reefs into the waters around Sisters' Islands Marine Park. Within a year of monitoring, it was found that the reefs were rapidly colonised by large numbers of fish and encrusting animals, and the intent is to transplant corals onto them. These reefs were deliberately designed to have minimal impact on hydrodynamics, so further research is needed to see if they can be redesigned to reduce wave energy and coastal erosion, thereby protecting our shorelines and beaches.

Perched Beach with Submerged or Partially Submerged Offshore Breakwaters



Submerged breakwater off Marina East (top) and hard corals on a submerged breakwater off Marina East (bottom).
Images: Nathaniel Soon

Where offshore breakwaters have to be used to reduce wave energy and coastal erosion, they can also be designed to support and maximise both ecological and recreational value. A long breakwater parallel to the shore could potentially trap sediment and create a calm lagoon environment landward, allowing seagrass meadows to grow while the breakwater itself can be colonised by corals and reef organisms.

Submerged reef structure could also be used to attenuate waves and reduce erosion of sandy beach. Wellington City Council implemented a combination of concrete and boulder-based artificial reefs to protect the recreational beaches of Oriental Bay.

Examples of Locations: East Coast Park, Singapore; Oriental Bay, Wellington, New Zealand
Type: Hybrid eco-engineering
Potential Co-benefits: Biodiversity, water quality, aesthetics, recreation, education, shoreline protection, wave reduction, erosion control, carbon sequestration

Land Use: This solution is deployed offshore, but may require the seafloor up to the breakwater to be reclaimed. It provides direct protection against beach erosion by reducing wave action, hence it can be deployed in areas where there is a need to protect long stretches of sandy beach. It can be further integrated with recreational and educational uses through the installation of a parallel boardwalk.

Relevance: A key example can be found at East Coast Park Area B, where the breakwater is fully submerged and has since been colonised on top by a dense and diverse community of intertidal hard corals. Seagrass grows in the sheltered intertidal area behind it. Another example at the Tanah Merah Ferry Terminal has a breakwater that is partially submerged and has trapped sediment in the lagoon behind it, giving rise to a rich seagrass meadow with corals also growing on the seaward edge of the breakwater. At both of these areas, the soil further up the shore is held together by coastal forest (Casuarina), creating a naturalistic view.

This solution can be deployed where an earthen bund (i.e., upper beach berm) can be used and/or there is a need to protect a long sandy beach. Although current examples use smooth granite boulders to build the breakwater, other materials could be considered if they promote better coral growth. The potential of the breakwater to grow with sea level rise as corals build on it could be studied in more detail as a form of regenerative design.

Mangrove with Rock Revetment

Mangroves colonising rock revetment at Pulau Hantu (top left). Mangrove shoreline eroding at Pulau Tekong before intervention (top right). Mangrove rock revetment hybrid at Pulau Tekong (bottom). *Images: Ria Tan; NParks*

Natural mangroves are known to provide a wide range of biophysical ecosystem services, including the crucial function of coastal protection through reducing wave impact and coastline erosion (Alemu et al., 2021; Lee et al. 2014; Spalding et al. 2014; Gijsman et al. 2021). They have shown to reduce impacts of extreme storm events on coastal communities during the 2004 Indian Ocean tsunami (Badola & Hussain, 2005; Tanaka et al. 2007; Hochard et al. 2021). Mangroves can also be a self-sustaining coastal protection solution, with healthy mangroves being able to absorb and naturally recover following disturbances (Smith et al. 2020; Gijsman et al. 2021). An unsealed, low-lying rock revetment may be used to restore physical conditions for mangroves in areas where hydrodynamic conditions are less ideal for natural mangrove to establish. This eco-engineered design serves multiple functions: the rock revetment fortifies the coastline against erosion, reduces wave energy and promotes the accretion of sediments, and provides crevices between rocks for mangroves to grow. Colonisation of the revetment by mangroves may take place by natural recruitment or be assisted through planting.

Examples of Locations: Pulau Tekong, Kranji Coastal Nature Park, Sungei Buloh Wetland Reserve, Pulau Hantu
Type: Assisted natural regeneration
Potential Co-benefits: Biodiversity regeneration, shoreline protection, wave reduction, carbon sequestration, aesthetics, recreation, education etc.

Land Use: This solution can be deployed in areas with stronger wave energy or facing coastal erosion. Supplementary planting can enhance the ecosystem benefits and increase long-term resilience. Where lagoons are created using revetments, the inner rock wall can also be left unsealed for natural recruitment and/or planting mangroves.

Relevance: This NbS approach with different modifications and enhancements have been piloted in Singapore such as Pulau Tekong, Kranji Coastal Nature Park where the sites were facing coastal erosion resulting in loss of coastal land and biodiversity (NParks, unpublished).

Nevertheless, an understanding of the physical conditions, including the hydrodynamic conditions (e.g., hydrologic flows) and ecological conditions (e.g., if substrate and source for mangrove propagules are available) is needed to inform suitable and effective hybrid ecosystem designs. When available, scientific data such as modelling on ecological connectivity of different mangroves can be used to provide a strong scientific basis for the natural recruitment strategy.

Hybrid eco-engineering measures are most relevant to improve the resilience of Singapore's remaining mangrove shorelines by providing the right conditions for the rate of natural regeneration to keep up with rising sea levels, and to protect built assets further inland. Higher societal benefits could also be considered, including eco-tourism and educational activities such as guided tours, kayaking and bird watching.

Reclaimed Lagoons

Reclaimed lagoons at Sisters' Islands Marine Park.
Image: NParks

Sheltered beaches and lagoons can be created in areas designated for recreation (e.g., parks) by enclosing shallow seabed areas with rock revetments to improve both ecological and recreational values. Such areas of calm water create conditions for high intertidal biodiversity with minimal human intervention, including habitat-forming species like seagrass and corals. The sheltered beaches also act as sea turtle nesting sites. These lagoons and beaches are also important for a range of water-based leisure activities like swimming, wakeboarding, kayaking and snorkelling.

However, these coastal typologies require larger shallow foreshore area to support both ecology and human activities, compared to other coastal design strategies. Therefore, they may compete for sea space with commercial uses and maritime needs (e.g., shipping channel and anchorage space).

Examples of Locations: St John's Island, Lazarus Island, Kusu Island, Sisters' Islands, Pulau Hantu, Sentosa, Pulau Sudong, Raffles Lighthouse; East Coast Lagoon
Type: Hybrid eco-engineering
Potential Co-benefits: Biodiversity, shoreline protection, wave reduction, carbon sequestration, aesthetics, etc.

Land Use: As these lagoons and beaches are inundated by the tide, they are often associated with recreational functions. As their profiles are often gradual, they tend to require greater land take. This solution can be deployed to create sheltered bays/beaches for recreational use.

Relevance: In the 1960s and 1970s, parts of Singapore (East Coast and Southern Islands) were reclaimed to create sheltered beaches and lagoons, mostly for recreational purposes, providing a calm area for swimming and water activities. Typically, they were enclosed by rock revetments to protect the beach from erosion. These lagoons now support high intertidal biodiversity, including seagrass meadows, sandy shores and coral reef flats. Corals have also been documented to recruit along the revetments. There are numerous records of sea turtles nesting on these beaches. Singapore's first turtle hatchery was established on a reclaimed beach on Sisters' Islands.

Nevertheless, as these lagoons were not originally designed to promote biodiversity, further studies need to be conducted on how various designs affect hydrodynamics and sediment dynamics to allow for the development of targeted and more effective solutions. Another key consideration is the availability of larvae/propagule sources to enable the natural recruitment of biodiversity.

Taken into account potential high land-take and cost of development, planners should strive to broaden the societal values of such areas through both regenerating coastal ecosystem and enhancing human wellbeing for the citizens.

Tidal Drain Intertidal Flats

Tidal flat with seagrass at the base of CCD-1 South.
Image: NParks

Large tidal storm drains can also be allowed to support intertidal habitats of ecological value by calibrating their sediment dredging frequency and regime. Many large tidal storm drains accumulate sediment on their beds upstream, potentially creating intertidal habitats with both ecological and landscape aesthetics value. This supports communities, from benthic invertebrates and fishes to the shorebirds that feed on them. Reducing the dredging frequency and magnitude of siltation removal of these storm drains could allow benthic communities to better establish without physical modifications to the drains themselves, thereby also retaining their original drainage functions. International case studies from Building/Engineering with Nature programmes also showed the importance of strategic placement of dredged sediment to replenish these areas, with added benefit of material circularity.

Examples of Locations: Tanah Merah, Singapore
Type: Assisted natural regeneration
Potential Co-benefits: Biodiversity regeneration, water quality, aesthetics, recreation, education, carbon sequestration, material circularity

Land Use: There may be a small increase in land use as drains may have to be widened slightly to accommodate the additional thin layer of sediment on the drain bed. However, this is likely to be relatively negligible as the surface of the sediment layer only needs to be approximately 0.5 m above chart datum (CD) and the bed of the drain.

Relevance: One example of intertidal habitats forming within a large storm drain is CCD-1 (South), where sediments have accumulated at the bed of the canal and seagrass can grow within the storm drain close to where it meets the sea. The potential of such drains to host brackish/marine intertidal ecosystems is proven by how estuarine species such as rock oysters and nerite snails can be found far inland, so long as tidal influence reaches the site.

As drain widening is one of the key infrastructure adaptation initiatives to prevent flooding from the combination of rising sea levels and storm surge events, there will be increased land take for such infrastructure. This solution results in multifunctional use of the land occupied by tidal drains and allows for some biodiversity to flourish. It can be paired with the deployment of biodiversity enhancement tiles along the drain walls to further increase biodiversity value.

With sea level rise, tidal gates may be required to guard coastal estuaries and canals, which might be kept closed for long periods of time or discharge water at higher flow rate. Research could inform the optimal design of these gates/drains, or develop new solutions or maintenance programmes to allow these habitats to continue to thrive.

Sungei Api-Api (top) runs through both existing and future HDB estates before entering the sea at Pasir Ris Park. Mudflat at the mouth of Sungei Pang Sua (bottom), which is unconcretised, fed by sediments accreting into a rich habitat for shorebirds adjacent to an industrial estate fringed by mangroves. *Images: Nathanael Soon; NParks*

Uncanalised Tidal Mangroves

Tidal storm drains can be widened and naturalised into mangrove rivers without compromising flood protection. This creates habitats for biodiversity and introduces natural ecosystems into the urban environment, providing easy access to nature-based recreation and enhancing landscape aesthetics value. As sea levels rise, the platform level of the land lining the waterway can be raised to prevent flooding in the event of heavy rains coinciding with high tides.

Examples of Locations: Berlayar Creek, Sungei Api-Api, Sungei Pang Sua, Sungei Tampines
Type: Assisted natural regeneration
Potential Co-benefits: Biodiversity regeneration, aesthetics, recreation, carbon sequestration

Land Use: Existing linear storm drains may have to be further widened to accommodate mangroves on the riverbanks, but existing examples show that this can be done even in dense urban areas such as HDB estates.

Relevance: Before canalisation, Singapore's tidal waterways were all lined by mangroves. Most were linearised and the mangroves were eventually cleared. However, some of them, such as Berlayar Creek, Sungei Api-Api, Sungei Pang Sua and Sungei Tampines, were naturally recolonised by mangroves as they were not concretised. These regenerated mangrove rivers double up as storm drains and host rich biodiversity including otters, kingfishers and monitor lizards, bringing biodiversity into the urban landscape, even at HDB estates nearby (Sungei Api-Api). They are also potential refugia for endangered species such as rare mollusc species in Berlayar Creek, and the only self-sown mainland population of the rare ***Sonneratia caseolaris*** tree in Sungei Pang Sua. Flooding of the adjacent areas does not occur even during heavy storm events, as the platform levels of the banks are sufficiently high.

Naturalisation of canal into a mangrove waterway will require more land take. Similar to Tidal Drain Intertidal Flats, this typology will be affected by the installation of tidal gates in response to future sea level rise, and may require further research to ensure that such vegetation can continue to thrive, whilst ensuring that the space remains usable for other needs.

Outlet Drain Bays and Promontories

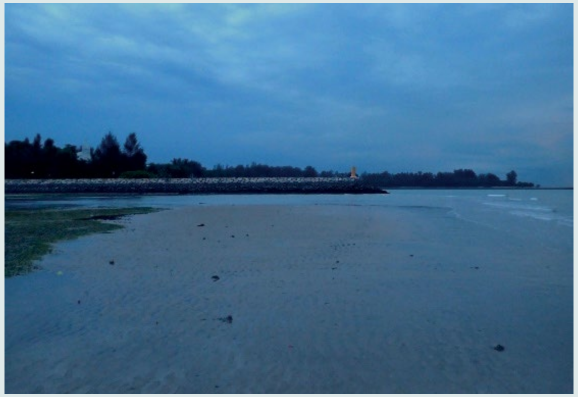
Where large outlet drains meet the sea, hydrologically sheltered bay areas can be created through shoreline profile design, or through the construction of promontories. With the input of sediments from land through the outlet drain, shallow intertidal areas can naturally form and be naturally colonised by seagrass meadows as long as there is a nearby source of seagrass seeds/vegetative fragments. Other intertidal habitats such as sandflats and coral communities may also form naturally and coexist with seagrass meadows, creating a rich diversity of ecosystem types. This can be combined with recreational sandy beaches and coastal parks and vegetation to create a continuum of natural and artificial habitats from land to sea.

Examples of Locations: East Coast Park, Singapore
Type: Integrated coastal zone management
Potential Co-benefits: Biodiversity regeneration, aesthetics, recreation, education, carbon sequestration, material circularity

Land Use: The deliberate design of shoreline profile should not have much impact on land use as the land itself can be used for other purposes. Promontories are also unlikely to have an impact on navigational space as they would not extend far out enough to intrude into anchorages or fairways.

Relevance: Several examples of rich intertidal habitat already exist, forming at the mouth of three large storm drains in Singapore along East Coast Park: CCD1, a canal next to the National Service Resort & Country Club (NSRCC), and Sungei Bedok. At CCD1, the shoreline profile forms a bay, with seagrass growing at the mouth and within the storm drain. Dugong feeding trails have since been observed while corals have also recruited along the eastern edge of the bay. At NSRCC, a promontory juts out from the east side of the drain mouth, allowing a seagrass meadow and sandflats to form in the bay to the west. The sandy beach is also a key turtle nesting site. At Sungei Bedok, a promontory extending from the west side of the drain mouth and a breakwater west of that creates a seagrass meadow and sheltered bay used by the National Sailing Centre, thereby also having high recreational value.

Modifying existing drain outlets by adding promontories and deliberately designing future reclaimed shoreline profiles to create bays at drain outlets is thus a cost-effective way of regenerating intertidal habitats through leveraging natural processes and material flow. The marine plants and animals that form the community assemblage of these ecosystems can colonise the area without intervention, provided there is a suitable source of seeds/larvae. Hydrological modelling by NParks and current case studies suggest that Singapore's southern and northeast islands can be planned with this strategy.



Seagrass meadow (top) and sandflat (bottom) in a bay at the mouth of the outlet drain. The promontory that extends from the drain mouth is visible in the background.
Images: Jonathan Tan

Upper Beach Berm or Green Dike

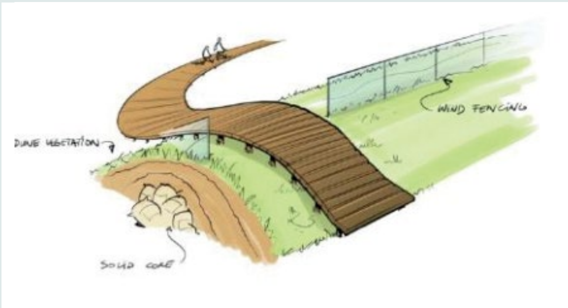
Nature-based, or more ecologically designed coastal protection solutions can also be applied at the landward edge. Berms are a common natural morphological feature formed through wave actions, which can also be purposely created in the form of natural elevations to reduce coastal flood risk by preventing overtopping during extreme high tides and storm surges. These berms consist of a sediment body located at the landward margin of the dry beach or higher intertidal zone. Another similar solution is the concept of "broad green dikes" in the Netherlands, where ripened clay from river dredging was applied in the construction. These measures could be vegetated to stabilise the sediments and prevent erosion.

Compared to conventional engineered coastal protection measures, these naturalised or ecologically designed solutions can preserve the soft shoreline and maintain the nature connectivity and material exchange between foreshore and inland area.
They can be further integrated into the urban fabric or park land to incorporate greater social value, such as supporting space for leisure activities if the solution is sufficiently wide with a gentle slope. Depending on the site context, these solutions may be implemented in combination with other shoreline protection or erosion control strategies.

Example of location: Delfzijl, the Netherlands
Type: Soft/hybrid eco-engineering
Potential Co-benefits: Biodiversity enhancement, flood protection, aesthetics, recreation, material circularity.

Land Use: Beach berms or green dikes are suitable at coastal parks that have recreational beaches. They can be a cost-effective way of protecting the inland area from flooding, while simultaneously being used as recreation space.

Relevance: Ecologically designed coastal protection strategies that can be integrated into the landscape should be considered in place of grey infrastructure-based shoreline protection given the high recreational values of beaches such as East Coast, Changi, Sentosa, and the Southern Islands. These beaches are also nesting sites for the critically endangered hawksbill sea turtle. Rising sea levels threaten these nesting sites by causing coastal flooding if no intervention is done. Upper beach berms can provide a soft solution that preserves the natural character of the sandy beach that makes it popular amongst beachgoers and conducive for turtle nesting, thereby addressing these issues. Further research could be conducted on their engineering performance compared to conventional solutions, and sustainability in terms of material efficiency and carbon footprint.



Upper beach berm concept from East Coast Park design pilot (top) and "Broad Green Dike" – trial dike with dried mud (bottom). *Images: NUS-Deltares; Waterschap Hunze en Aa's*

Mangrove Planting/Restoration

Nature areas that are suitable for mangroves can be restored to provide coastal protection and achieve other co-benefits including fishery enhancement, carbon sequestration and supporting biodiversity (Cheong et al., 2013). The success of restoration efforts depends on the right species being planted in areas with the right hydrology (e.g., seabed level, sediment input, shelter from strong currents). Suitable conditions can be created through engineering interventions (e.g., *bakau* pole fences, rock revetments, seabed raising, inundation of low-lying areas—see **Mangrove-Rock Hybrid Revetment**). Where suitable conditions can be created, natural recolonisation may occur, reducing the need for mangrove planting.

Examples of Locations: Pulau Semakau, Pasir Ris, Pulau Ubin, Singapore; Hawkesbury Estuary, Sydney, Australia
Type: Assisted natural regeneration
Potential Co-benefits: Biodiversity regeneration, shoreline protection, wave reduction, carbon sequestration

Land Use: A "soft" approach of restoring a mangrove would require sea space-take (raising the seabed/planting in mudflats) or retreat or realignment of the dry shoreline landwards (land inundation). In Singapore, past efforts have ranged from 1 to 13.6 ha. This solution tends to be more compatible with recreational use (e.g., park space, rural areas) but can be incorporated into areas with low sea-space usage.

Relevance: A wide, dense and mature mangrove can reduce wave impact (Hashim et al, 2013) and aid in holding sediments (Van Santen et al., 2007) thus protecting against erosion. Mangroves also can grow with sea level rise under the right conditions such as sufficient sediment input to support its growth (Lovelock et al., 2015).

Locally, there have been several mangrove restoration projects. The efforts at Pulau Semakau was primarily aimed at replacing a habitat lost to reclamation, and involved planting two species (*Rhizophora apiculta* and *Rhizophora mucronata*) in reclaimed zones overlain with mangrove mud (Tatini et al., 2001). A rock revetment enclosed this reclaimed zone, with tidal channels to ensure hydrological connection to the sea. At Pasir Ris Park, a 5-ha patch of mature mangrove was preserved during reclamation by maintaining tidal inundation; a rivulet was dug to connect it with Sungei Tampines. An additional 1 ha of levelled vacant ground was then subjected to inundation in 1989, with mangroves colonising as soon as three months after tidal flooding was reintroduced. At Pulau Ubin, the Restore Ubin Mangroves project aims to modify hydrological conditions to facilitate the natural recolonisation of mangroves in abandoned aquaculture ponds (see **Box Text**). These successful pilots demonstrate that a regenerative approach using mangrove can be adopted to protect our coastline as a supplementary strategy to coastal adaptation measures, with recreational and eco benefits.

Planted mangroves at Pulau Semakau (top) and community members helping planting mangrove seedlings in the Hawkesbury Estuary, Australia (bottom). *Images: National Environment Agency; Hornsby Shire Council*

Mangrove sapling planting where the platform level has been lowered and channels dug adjacent to Pasir Ris Mangrove (top). Existing mature trees were left standing. Beachfront sapling planting on low-lying flood-prone land at Pasir Ris Park, just behind existing mangrove stands (bottom).
Images: Kalthom Abd Latiff

Assisted Mangrove Retreat

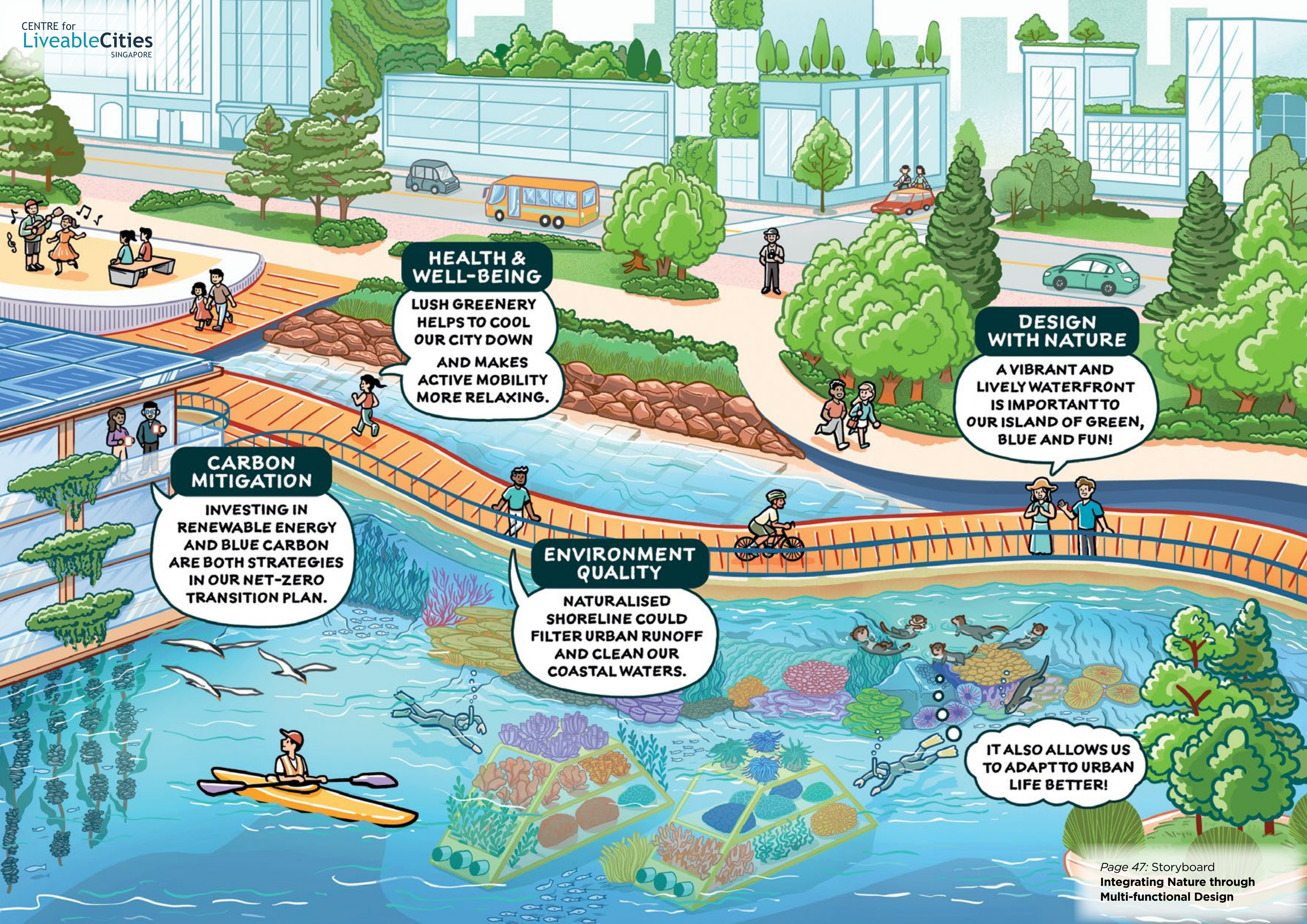
As sea levels rise, mangroves are at risk of habitat loss as there would be greater coastal erosion, or loss of sediment or nutrient sources from intensified urban development. Low-lying areas with low-intensity land use can be identified for conversion to mangrove habitat by lowering the platform level, digging channels for water to enter at high tide, and planting saplings.

Examples of Locations: Pasir Ris Park, Coney Island Park
Type: Soft eco-engineering/re-naturalisation
Potential Co-benefits: Biodiversity, shoreline protection, wave reduction, carbon sequestration, aesthetics, recreation, education

Land Use: This solution can be deployed at low-lying flood-prone areas, preferably landwards from existing mangrove conservation areas, and where land use is of low-intensity and may offer multi-purpose development (e.g. parkland or brownfield rehabilitation). Hard defenses can be built further inland to protect high value built assets from coastal flooding due to extreme high tides.

Relevance: This solution has been implemented in Singapore as a form of habitat restoration in Pasir Ris Park and Coney Island Park, inland from existing mangroves as well as just behind the sandy beach. Implementing this will better safeguard the long-term survival of existing mangroves and their erosion protection function, as the newly established inland mangroves get an early head start to grow into maturity. As these habitats will allow urban sediments to accumulate over time and create a natural buffer that protects the inland area from coastal surge, while providing a host of ecosystems benefits. This would have been absent in artificial, hard defences that are less adaptive to sea level changes. Hence, assisted mangrove retreat can serve a dual function of increasing existing mangrove habitats while improving coastal flooding protection.

Given the potential high land-take, this strategy may compete with other low density land uses such as agriculture. Higher societal benefits need to be considered, including leisure, educational and eco-tourism activities to justify its long-term value.



Page 47: Storyboard
Integrating Nature through Multi-functional Design

Integrating Nature through Multi-functional Design

NbS can also be applied at the district planning level through urban design or landscape infrastructure projects, with the key focus on leveraging nature to achieve human-centric outcomes. This requires a coordinated systems approach that takes into account the complex interactions between different components within a coastal system (Figure 7). Considering the cross-cutting nature of such an effort, this would require close collaboration between agencies, academia, the private sector and the community, working towards a set of common principles and goals (see **Defining Objectives**). NbS should also be considered upfront in the planning process, and not be added in as an afterthought or a mitigative measure once development plans have been confirmed.

This section examines the case studies of the Rebuild by Design competition and East Dike Shenzhen, both of which were initiated in response to natural disasters. While Rebuild by Design used a

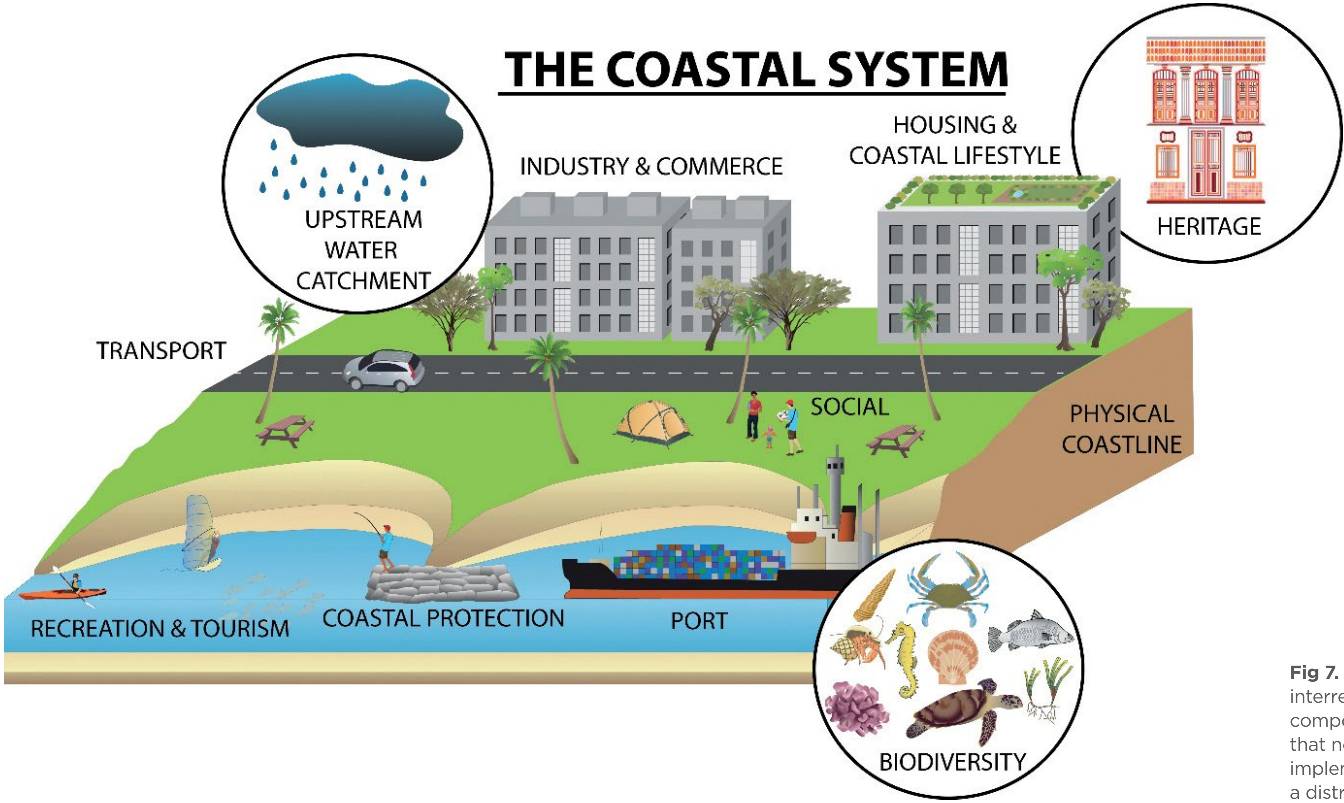


Fig 7. An example of different interrelated and interacting components within a coastal system that need to be part of a larger plan to implement Nature-based Solutions on a district planning scale. *Source: CLC*

competition model to generate new and innovative designs for coastal regions, East Dike Shenzhen was driven by a traditional consultancy-based approach. We also look at a case study from New York's Brooklyn Bridge Park, which exemplifies how public-private partnerships can effectively deliver flood protection through nature-based designs.

Case Study: Rebuild by Design, the United States

Hurricane Sandy hit northeast United States in 2012 and caused widespread casualties and damage to property and infrastructure amounting to US$65 billion. In the aftermath, US President Obama launched the Hurricane Sandy Rebuilding Task Force. Based on the vision to create a more proactive approach to disaster response, and to align government policies and resources with local needs and priorities, the task force developed the Rebuild by Design (RBD) competition, which aimed to "develop innovative resilient design solutions that address the Sandy-affected region's most pressing vulnerabilities".

The process comprised four broad steps:

1. **Talent gathering:** The task force called for teams to assemble themselves in interdisciplinary partnerships (spanning fields of ecology, engineering, planning, sociology, landscaping, architecture, water management, climate forecasting) that could build resilience in complex coastal systems. Ten teams, which encompassed a diverse set of skills and approaches, were selected.

2. **Research:** The shortlisted teams conducted intensive field research for three months with local stakeholders in different areas to understand the context of each location, the effects of the storm and long-standing problems. Research was collaborative across teams and a research advisory board encouraged teams to take a variety of perspectives. The teams were then asked to present conceptual "design opportunities" that would be selected for the Design phase.

3. **Design:** The task force selected design opportunities for the teams to develop in greater detail. In this phase, the teams engaged diverse local stakeholders over four months to co-design final interventions. Ten fully developed and implementable resilience proposals that represented the community's visions were then put up for funding.

4. **Implementation:** A jury selected seven designs for funding and implementation. The task force ensures continued community involvement during the implementation phase, which is currently ongoing.

Detailed information about the programme and winning designs can be found in *Rebuild by Design* (2015).

Long Island, New York: Living with the Bay

Nassau County, New York has a unique hydrology setting with a river that winds through the communities, entering Hewlett Bay through a narrow estuary. The bay itself is framed by a barrier island (Long Beach Island), which is an important recreational hotspot for the area. With so many communities and important infrastructure located close to fresh and seawater, the area was extremely vulnerable to water threats like flooding, wave action and sea level rise. The area suffered devastating losses during Hurricane Sandy, with 14 casualties and thousands of homes destroyed or damaged.

As one of the winners of RBD, the Living with the Bay (LWTB) programme was awarded US$125 million to reduce the county's risk and improve its resilience. The team recognised the interconnectedness of upstream and downstream elements, and as such designed interventions that addressed water issues along the watershed, utilising both grey and green solutions.

For example, it proposed building up oceanfront dunes to capture and manage sediment to create conditions for marshlands (some of which would be restored) to stabilise the coastal areas. In critical areas with high urban density, it also proposed building a dike to protect the population from storm surges. Further upstream, it proposed creating accessible greenways and introducing green infrastructure that would increase absorptiveness and serve social/recreational functions (Figure 8).

Fig 8. Bioswales as a neighbourhood amenity in the Lowlands. *Image: The Interboro Team/Rebuild by Design*

The LWTB programme is guided by five key goals: Resilience, Quality of Life, Environmental Improvements, Waterfront Access and Public Education. Based on these goals and the broad solutions developed by the RBD process, the local government is now funding 35 potential projects across the watershed, the majority of them NbS such as habitat restoration and green infrastructure like bioswales. With common goals and a good understanding of the interconnected water systems, Nassau County was able to create a cohesive resilience plan for an entire district to serve the community in diverse ways.

Staten Island, New York: Living Breakwaters

Unlike Long Island, Staten Island's threats come mostly from the sea. The island experienced severe damage from storm waves during Hurricane Sandy and the shoreline has faced chronic erosion problems over the past 35 years, with some areas eroding as rapidly as 3 ft per year. To combat this, the team created the "Living Breakwaters" concept that aims to increase physical, ecological and social resilience (Figure 9). The project takes a thematic and spatially-layered approach by acknowledging the interconnectedness of their goals to reduce coastal risk, promote local culture and education, and protect and enhance habitats and biodiversity.

To achieve all these goals, the project uses a mixture of hybrid and soft eco-engineering and programming. For example, through extensive hydrodynamic modelling for future climate scenarios, Living Breakwaters designed a series of offshore breakwaters along the coast to capture sediment to reduce erosion and promote shoreline widening. The breakwaters are positioned to protect key areas and infrastructure in the region from future storms. However, these breakwaters were also designed to serve an ecological function, unlike traditional breakwaters (Figure 10). The use of structurally complex configurations with bio-enhancing concrete (ECOncrete) encourages the recruitment of biodiversity. This is supplemented by active oyster restoration on and around the breakwaters, which also helps revive the cultural connection to historical oyster fisheries in the area. Closer to shore, some areas will be replenished with sand to counter erosion and restore historical shore profiles.

All of these "infrastructural" NbS help to enhance recreational opportunities along the sheltered coast. They will also be supported by programming and education to encourage residents

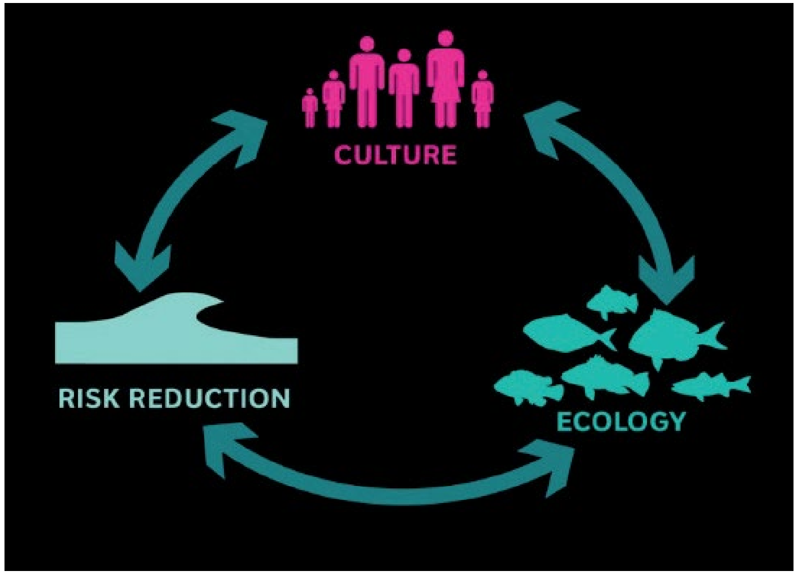


Fig 9. Interdependency of the three target resiliencies tackled in the Living Breakwaters project. *Image: SCAPE Landscape Architecture/Rebuild by Design*

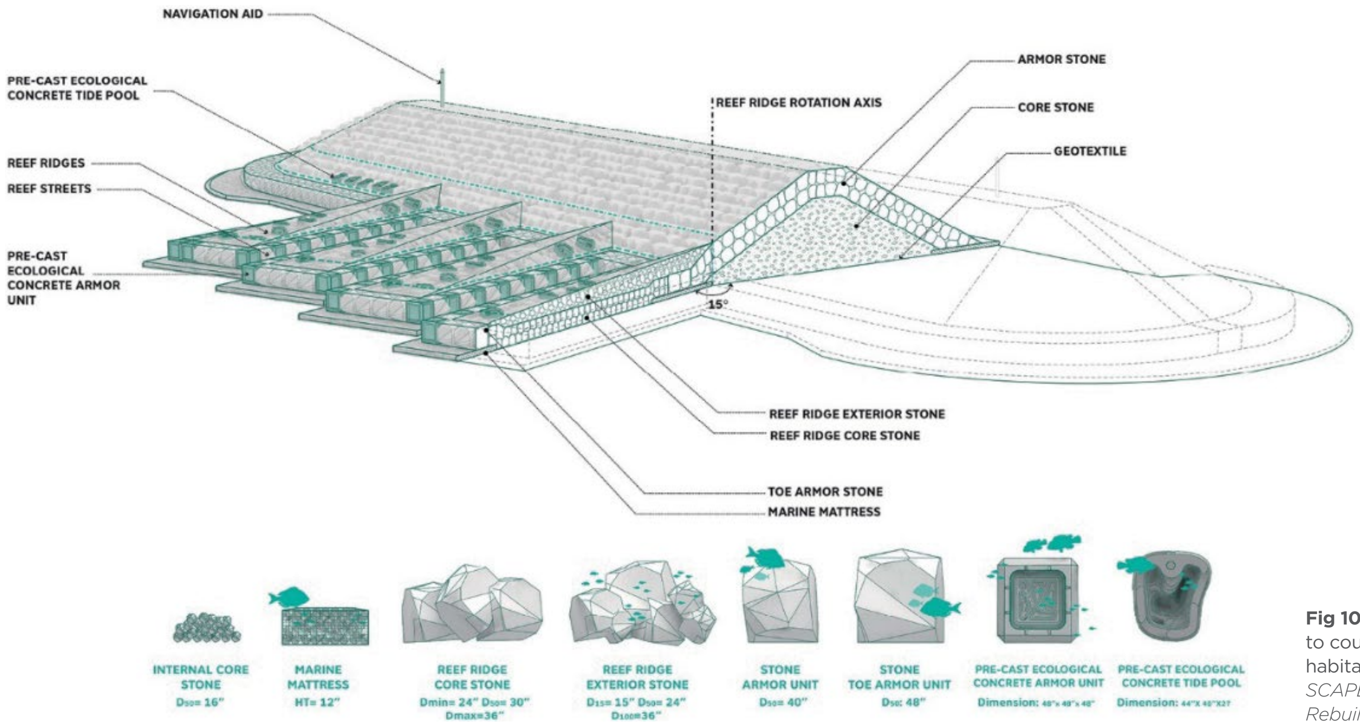


Fig 10. Living Breakwaters designed to counter erosion while providing habitats for biodiversity. *Image: SCAPE Landscape Architecture/ Rebuild by Design*

to become stewards of the environment, thereby improving social resilience. The project proposed using a vessel as a "Floating Water Hub" to serve as a classroom for education and continued monitoring of the Living Breakwaters.

This layered and multi-pronged approach to tackle the project's key goals demonstrates how NbS can be used on a broad scale and have impacts beyond enhancing and preserving habitats. The social component, which is critical to overall resilience, sometimes can be achieved without infrastructural interventions and can even be coupled with NbS for greater outcomes (e.g., environmental stewardship).

Case Study: Sino-Singapore Tianjin Eco-City's Coastal Planning and Design with Nature, China

The Directive for Ecological Sea Dyke Construction of Reclamation and Polder Projects has been adopted in pilot projects across China in more developed coastal cities such as the Sino-Singapore Tianjin Eco-City Sea Dike Park project and Shenzhen Dapeng East Dike project. An urban design-oriented approach is usually taken, in conjunction with the **Sponge City framework**, to build the coastal area's resilience against extreme events.

The 2016 Sino-Singapore Tianjin Eco-City Masterplan adopted an integrated coastal planning strategy with the vision of becoming an "Ecological and Leisure Bay" to foster connectivity between coastal and inland wetland ecosystems; promote the development of urban and nature landscapes; and improve residential and economic districts through extensive implementation of blue and green infrastructure (Figure 11). This included 43 km of coastal green corridors and extensive estuary and seawater exchange systems.

This planning area included a 75 km^2 reclaimed district, constructed from 2008–16 on the tidal mudflats of Bohai Bay, which created a more diverse coastal landscape based on prevalent wind and

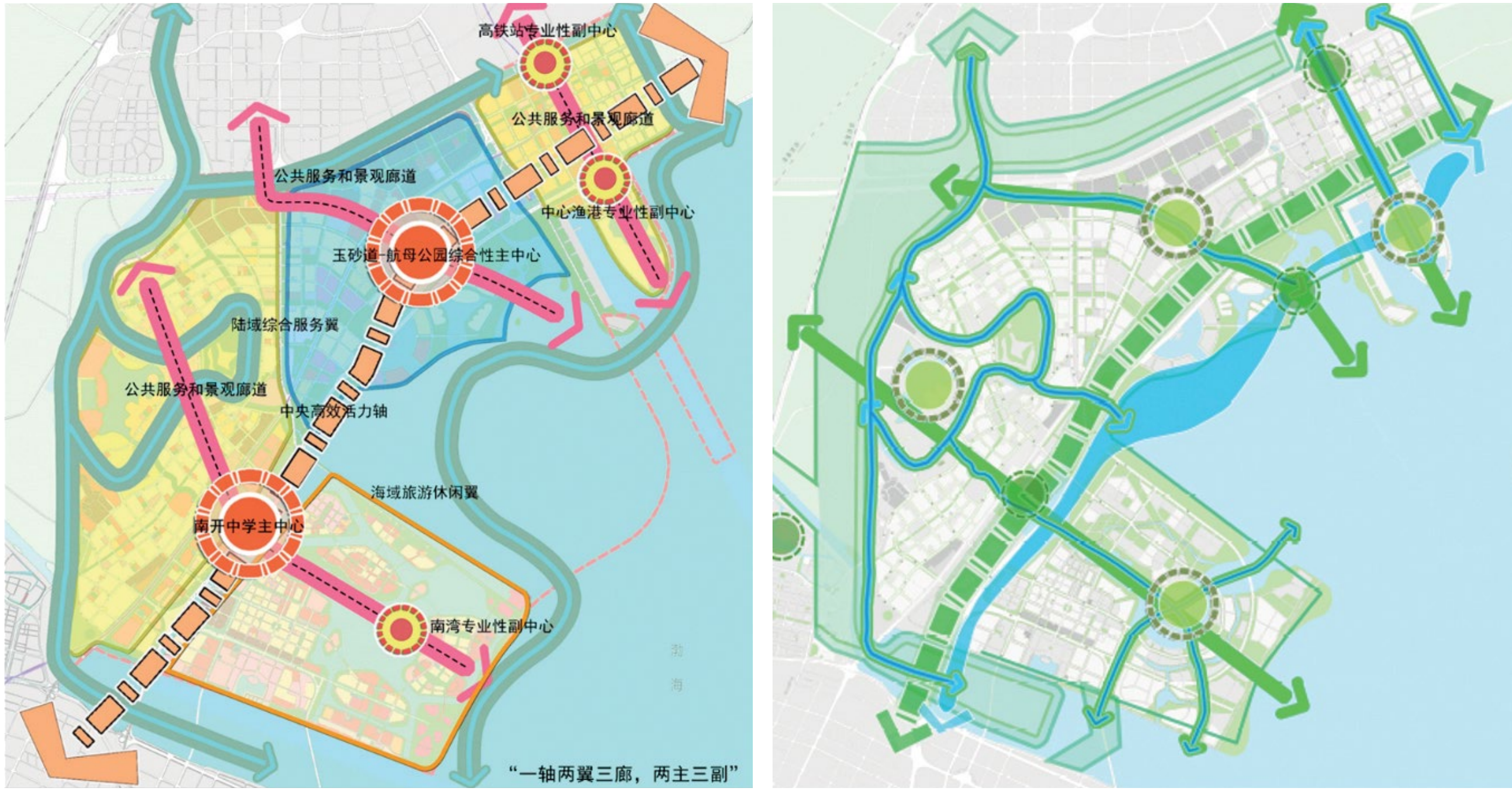


Fig 11. Sino-Singapore Tianjin Eco-City's coastal planning strategy, which integrates socio-economic networks with "Blue" and "Green" networks.
Image: Chinese Academy of Urban Planning and Design (CAUPD), Sino-Singapore Tianjin Eco-City Masterplan 2018

tidal conditions. The new coastline consists of a 20-km section of original tidal mudflats, a 7.5 km artificial rocky shoreline with clear water through wave breaking to prevent sediment suspension, and a 9 km tidal marsh shoreline with a rich ecosystem through creating conditions for organic sediment deposition at the Yongding River estuary.

Following the masterplan, the city commissioned a coastal urban design project for Sea Dike Park (Figure 12), aiming to unlock the social and tourism functions of the coastline with distinct design themes and typologies for every 3–4 km section befitting the landscape, ecology and local culture and heritage. It adopted a low impact, "Design with Nature" approach, following the new Chinese national standard on ecological sea dike construction, to enhance overall coastal resilience with a multi-layered methodology.

- The hard-concrete sea dike built initially as outer bund of the reclamation area was retrofitted to be embedded into the landscape as part of a wider coastal green corridor network for recreation and active mobility.
- In sections of the Eastern Sea Dike Park, a concrete seawall built to prevent wave-overtopping was removed and replaced with rock breakwaters extending 10–15 m offshore, achieving the same purpose, while allowing better recreational access to the waterfront.

Fig 12. East Sea Dike Park, which redeveloped coastal defence infrastructure into public space. *Source: AECOM Tianjin Engineering Consultants Co., Ltd*

- In the Northern Sea Dike Park, a low-lying tidal wetland belt was constructed behind the existing dike to act as a sponge area to absorb high tide overflowing the dike. Salinity resistant vegetation was also planted to further reduce the wave energy (Figure 13).
- A higher multifunctional dike was constructed further inland to protect the built-up urban area and transport network against extreme high tide events with a 200-year return period.

The design was drawn up in consultation with multidisciplinary experts, ensuring both engineering feasibility and robustness against projected climate change, accelerating rehabilitation of shoreline ecosystem post-reclamation, and an enhanced leisure experience for people to interact with nature.

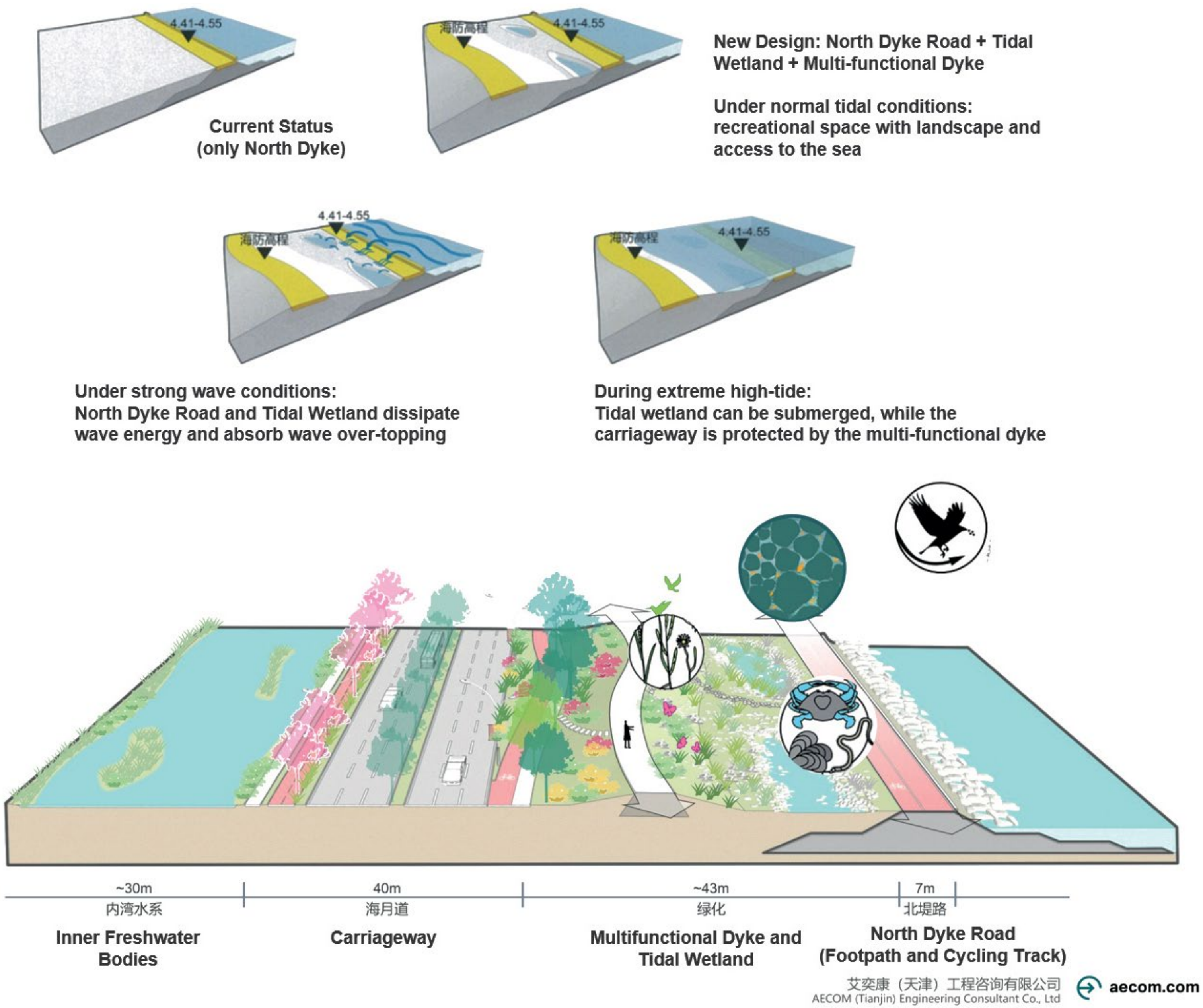


Fig 13. North Sea Dike Park – multi-layered coastal resilience with planning, engineering and Nature-based Solutions. *Source: AECOM Tianjin Engineering Consultants Co., Ltd*

Fig 14. Layered landscape (left) and soft edges (right) along the shoreline protect the Brooklyn Bridge Park against flood risks. *Images: Brooklyn Bridge Park*

Case Study: Brooklyn Bridge Park, the United States

When the City of New York planned to build a park on land that was previously occupied by warehouses on the waterfront next to the Brooklyn Bridge, it faced a shortage of funds needed to maintain the park. The city thus mandated that the site had to generate enough revenue, through taxes on residential and commercial developments, to maintain itself. By partnering with private developers to develop residential buildings at the project site, New York was able to build an 85 acre public park that helped protect the city against the impact of storms and major floods using NbS.

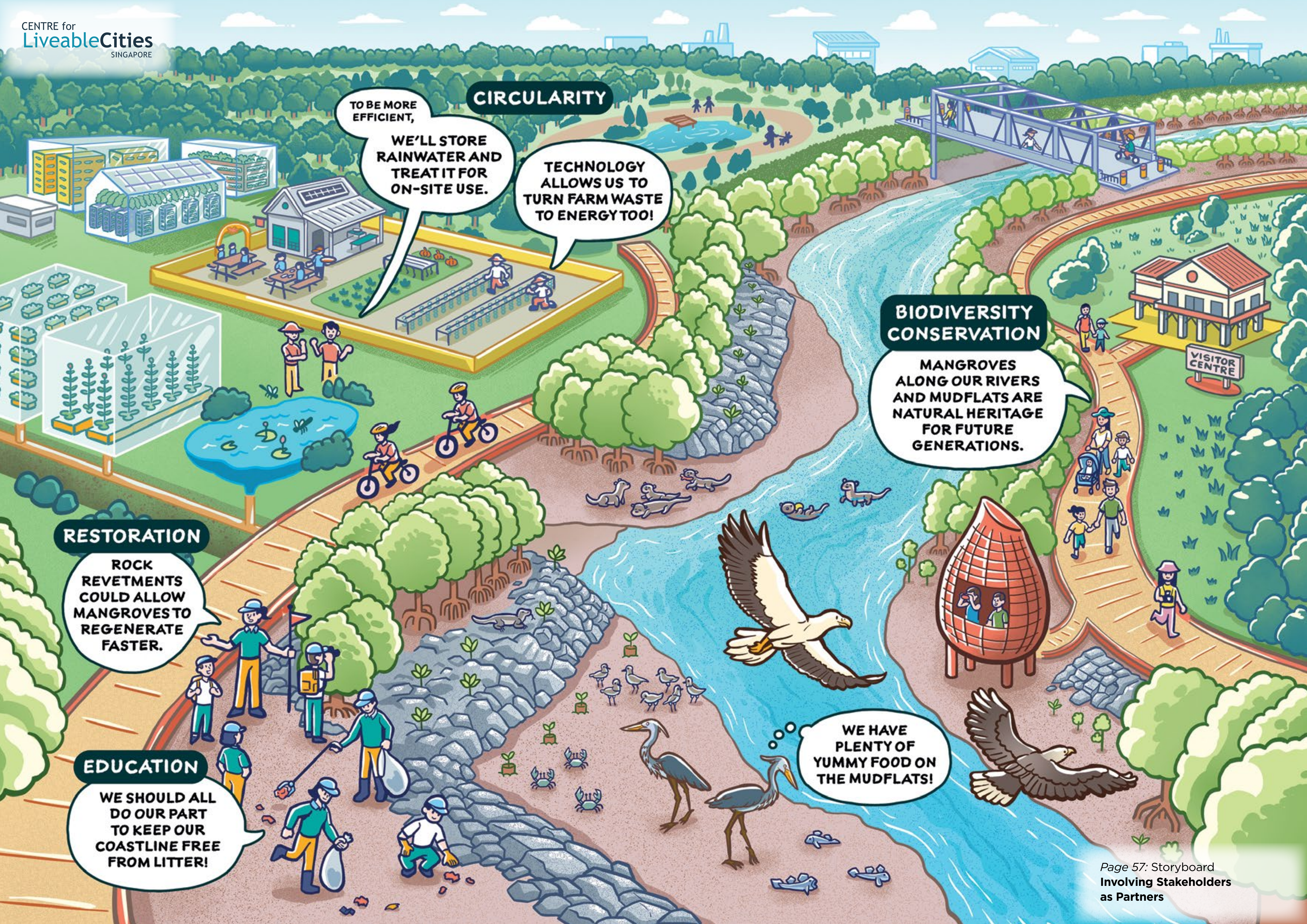
Taking into account future sea level rise and storm surges, the park's topography was raised, with parts of it rising as high as 30 ft (~9 m). The city created a layered landscape with multiple berms that would be able to block floodwaters. It also planted salt-tolerant plant species that would be able to survive flood waters, and used natural edges (salt marshes) in certain areas to protect against storm surges. These features were proven effective during Hurricane Sandy, when the park helped protect the surrounding residential developments against stormwater and debris, and the shoreline was able to withstand the effects of the storm.

The park is currently overseen by the non-profit Brooklyn Bridge Park Development Corporation, which ensures the park remains financially sustainable through investment in residential and retail spaces. The residential areas have also benefited from their proximity to this attractive park, in the form of dramatically increased property prices.

Nature-based Solutions deliver a multitude of social benefits, such as health and wellbeing, educational, recreational and community bonding opportunities. Moreover, they have the potential to offer a transformative approach to co-create sustainability efforts and strengthen community resilience

Left: The Ubin Living Lab (ULL) is a catalyst for community participation through outdoor learning and citizen science. The species recovery effort at the Mangrove Arboretum is part of community initiatives in conserving the biodiversity of Pulau Ubin for generations to come. *Source: NParks*

Right: Guided intertidal walks are regularly organised for the public to enjoy one of Singapore's richest coastal ecosystems in Chek Jawa Wetlands, Pulau Ubin. *Source: Alan Tan*



Page 57: Storyboard
Involving Stakeholders as Partners

Involving Stakeholders as Partners

Studies have shown that fostering resilience in both human and ecological systems are effective measures to deal with uncertain environmental changes, including climate change (Tompkins and Adger, 2004). Enhancing public knowledge and collaboration are vital to improving social resilience against myriad of future challenges, so practitioners should include a strong public engagement, education, and participation element in all stages of the process of developing NbS (Raymond et al., 2017). The concept and theory of regenerative design calls for the co-evolution of human and natural systems in partnered, symbiotic relationships, which must be achieved through an enduring responsibility of stewardship. (Cole, 2012)

Engagement can take many forms, from "transacting" and "informing", which have low levels of participation by relevant stakeholders, to "co-delivering" and "co-creating", which involves more upstream participation of, and collaboration between the various stakeholders (Figure 15).

Given the issue of climate change and associated coastal risks are often long-term and uncertain, a key barrier reflected is often a lack of common understanding of the risks and priorities for coastal adaptation. Furthermore, NbS come with greater uncertainty in risk reduction compared to typical engineered solutions, and may be purposely designed to accommodate, instead of prevent risks such as flooding.

As such, it is essential for NbS planning and development to adopt a more upstream and inclusive engagement approach, geared towards aligning stakeholders on "what are the challenges/risks we are facing", and "what are the values/targets we should strive for" as a society. Engagement for NbS should aim at high level of stakeholder participation, to enhance community resilience as a key objective of the development.

1. Co-create a shared vision with stakeholders through more people-centric, clear and balanced policy communications.
2. Plan systemically to address a wide range of impacts, and maximise co-benefits by understanding communities' needs and aspirations.
3. Develop better understanding of the benefits, costs and trade-offs of different solutions, and minimise non-acceptance through open dialogues.
4. Foster greater trust, risk preparedness and willingness to act across different sectors and stakeholders against climate change.

Based on the site profile and intended outcomes of development, NbS projects could also have different scales and complexities, and may require different modes of public participation ranging from more professionally-driven participation, such as public exhibitions and expert consultations, to more ground-up activities such as community stewardship. For example, when developing a mixed-use coastal area, the wider community (e.g., residents, recreational users, visitors, etc.) can be surveyed for their values and priorities for the area (e.g., aesthetics, recreational options, historical importance, etc.). It is possible to concurrently identify a smaller group of core stakeholders like schools, local businesses, sports and nature interest groups, and for resident committees to be involved to co-design the area, with the designs supported or informed by the survey results from the larger community.

The Centre for Liveable Cities (CLC)'s Building Community Resilience project showcased how a multi-stakeholder framework, involving community engagement and participatory design, can nurture citizen-initiated projects and strengthen social capital and community resilience through a co-creation journey (CLC, 2022).

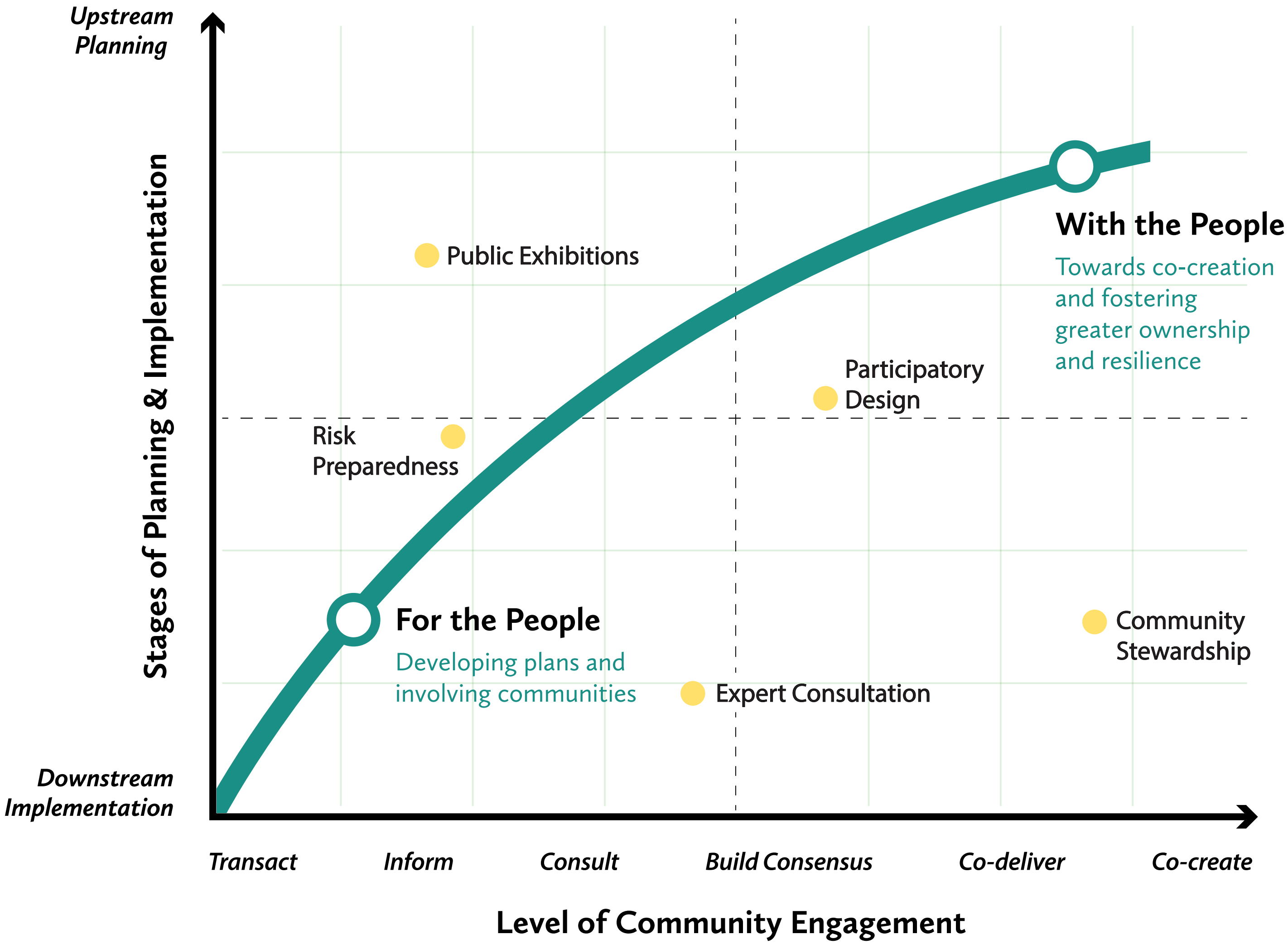


Fig 15. Illustration of the degrees of community engagement in Singapore at different stages of planning and implementation, and the value of incorporating greater co-creation in up-stream planning. *Source: CLC*

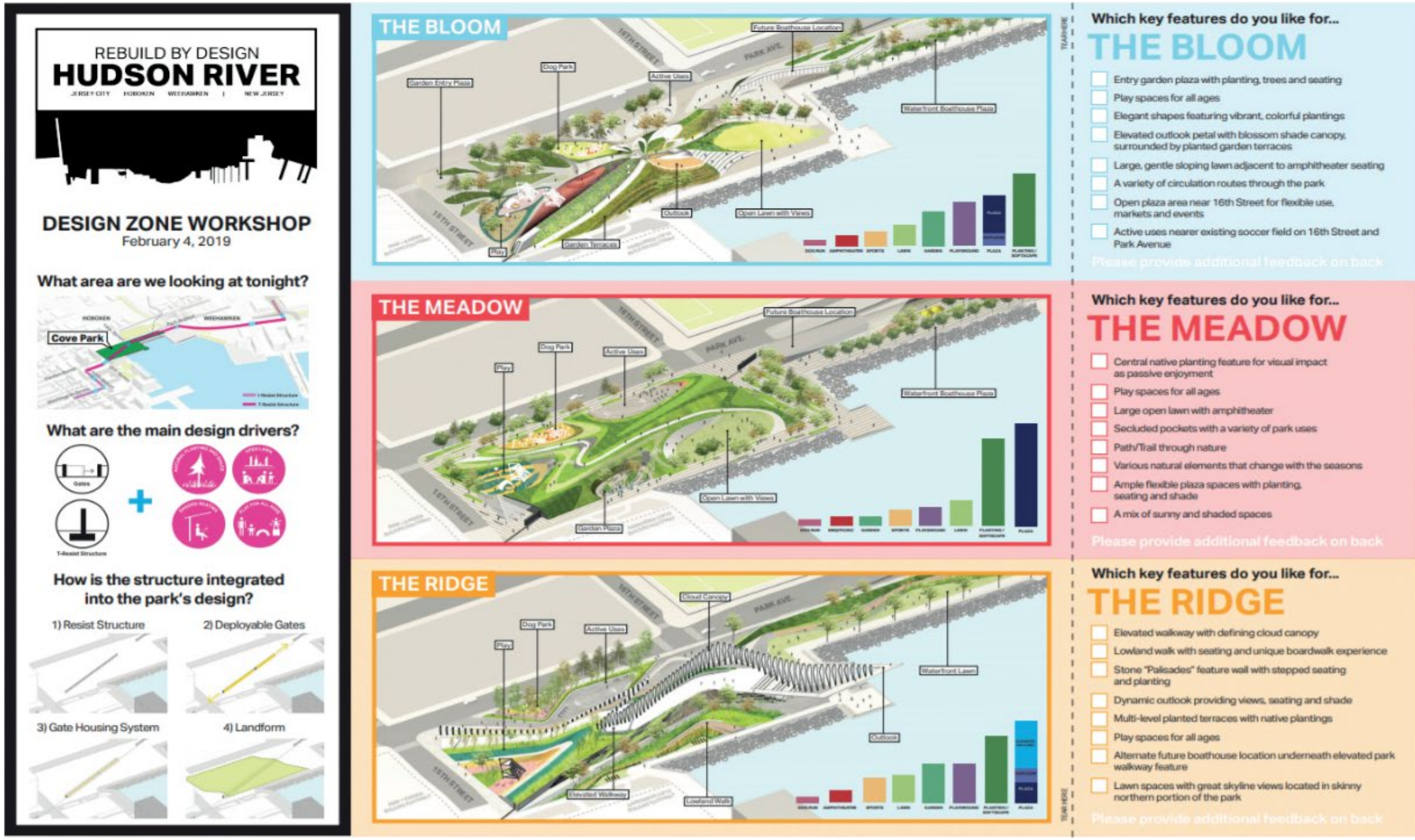


Fig 16. Example of a design form to get targeted feedback used in the Hudson River project of Rebuild by Design. *Image: New Jersey Department of Environmental Protection (NJDEP)*

The Rebuild by Design competition (see **Case Study**) has demonstrated effective community engagement across several projects, and has developed a Best Practice Guide for developing engagement strategies. Among its recommendations are making sharing inputs easy and intuitive, and the use of maps, models and visual aids to help stakeholders better understand the project and its outcomes. The Hudson River project uses well-designed handouts to solicit targeted feedback during their community design workshops, which are supported by detailed presentations and display boards (Figure 16). By including design consultants in the engagement process, both the quality of the information shared and feedback received can be enhanced.

Community engagement should also be timed to be more meaningful. Studies have shown that community engagement that takes place too early in the planning process can lead to excessive expectations by the community and frustrations when they are not accommodated. Conversely, there were also negative reactions and a higher chance of backlash when engagement takes place too late and designs can no longer be adjusted (Rijke et al., 2012). During engagement, stakeholders' expectations should be managed through more transparent and evidence-based information sharing, combined with people-centric communications (e.g., being upfront about what the boundaries are and why they are necessary).

Case Study: The Ubin Project, Singapore

The Ubin Project was launched in 2014 to seek ideas from members of the public on how Pulau Ubin's rustic charm, natural environment, biodiversity and heritage could be enjoyed by future generations of Singaporeans. More than 2,000 ideas, ranging from conservation of biodiversity and heritage, support for education, and opportunities for nature-based recreation and trials of sustainable technologies, were received by November 2014.

Friends of Ubin Network

Established in 2014 as part of The Ubin Project, the Friends of Ubin Network (FUN) is a diverse stakeholder network including members from youths, volunteers, nature groups, heritage groups, local villagers, fish farmers and academics. It has five key thrusts:

- Biodiversity Conservation
- Education & Research
- Community, Heritage & History
- Nature-based Recreation
- Sustainable Design & Practice

Several coastal nature-based solution projects have been enacted on Ubin in consultation with the community through FUN, listed below.

Restore Ubin Mangroves (R.U.M.)

R.U.M. is an initiative to carry out ecological mangrove restoration in abandoned aquaculture areas on Ubin by creating the appropriate hydrological conditions for natural recruitment to occur. This ground-up initiative comprises concerned groups that have a shared passion for Ubin's mangroves, and includes the Mangrove Lab of NUS, Marine Conservation Group of Nature Society (Singapore), Gamefish and Aquatic Rehabilitation Society (GARS), Sea Angel (representing fish farmers) and WildSingapore.

A key component of R.U.M. is its engagement of stakeholders at the planning and design stages. Through multiple engagement sessions, they were able to share their insights and value-add discussions, resulting in a more robust mangrove restoration plan. Volunteers are organised to help with mangrove surveys, propagule collection, test planting, restoration work, monitoring and outreach.

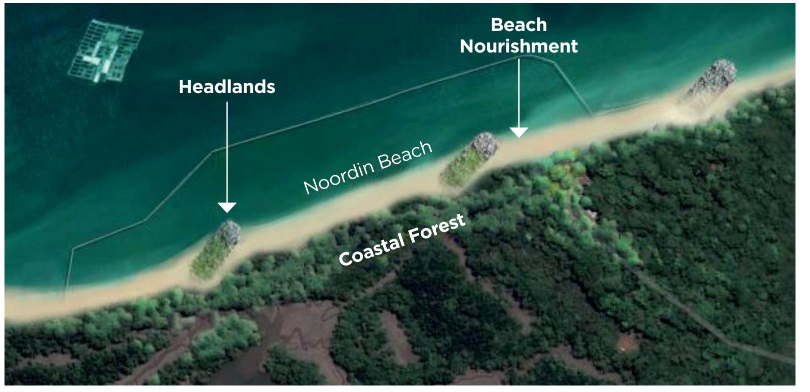
Through restoring mangroves, R.U.M. hopes to increase Ubin's level of biodiversity and its associated ecosystem services, such as seafood provision for local fishermen, good water quality for fish farmers, nature-based recreation for visitors and tourism income for residents.

A research collaboration between NParks and the NUS Geography Department (on behalf of R.U.M.) led to a feasibility study on using Ecological Mangrove Restoration (EMR) at Sungei Durian. Throughout the planning, design and implementation process, engagement with the community through R.U.M. will continue.

Ubin Shoreline Restoration Project

Shoreline restoration along northern Ubin was one of the earliest priorities of The Ubin Project. Severe erosion was observed at the mangroves and coast of Noordin Beach in the north (Figure 17). Feasibility studies were done in 2015–16:

- Collect baseline data (satellite imagery, hydrodynamics, ecology, land use, topography, sediment, vessel traffic). This enabled assessment of the degree of erosion and impact on natural habitats along the entire shoreline of Ubin.
- Conduct hydrodynamic and wave modelling to assess causes and effects of erosion, and identify areas for restoration (e.g., Noordin Beach).
- Identify and evaluate restoration/mitigation measures



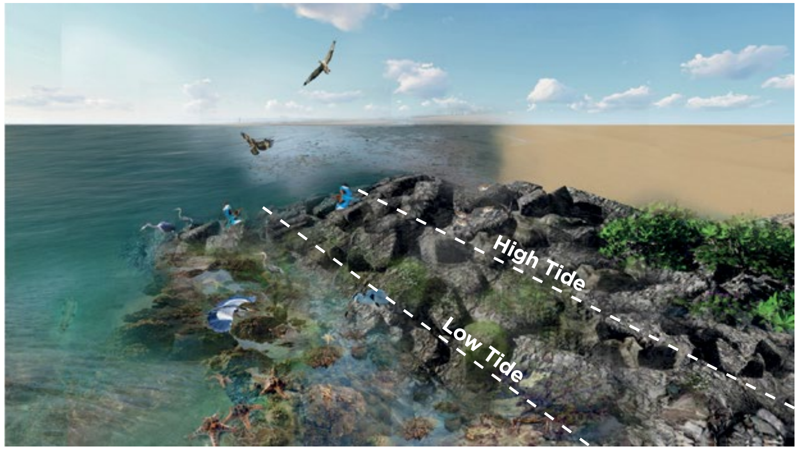


Fig 17. Layout of new headlands at Noordin Beach (top), with artist's impression of the new headland with habitat enhancement features (centre and bottom). *Images: NParks*

through testing via modelling.

- Consolidate measures in a holistic plan for long-term management and monitoring of the coastline.

Causes of erosion identified include changes in land use, where high water flows during ebb tide from abandoned aquaculture ponds cause erosion, and high vessel traffic, where ship wakes contribute to increased wave energy.

A combination of solutions was proposed based on modelling studies:

- Design headlands to include rock pools and crevices for intertidal fauna and coastal plants to promote biodiversity.
- Beach nourishment, coupled with the headlands, to widen the beach.
- Add rock revetment along the toe of the cliffs.
- Apply geotextiles with coastal plants to reinforce the cliff slope.

For the mangrove restoration for eroded mangroves at Sungei Besar, Mamam and Jelutong, the following measures were attempted (Figure 18):

- Mangrove toe protection involving suitable substrate to fill mangrove undercuts and rocks along the toe.
- Mangrove rehabilitation by filling in disused aquaculture ponds and limiting the flow volume of water from tidal cycles. With more sediment accumulation, mangroves can then regrow and arrest further erosion.
- Preserving existing natural rivulets in toe protection design to facilitate natural inundation of the mangroves.

It was important to incorporate community involvement in the early stages. As part of the design process, the ideas were shared with FUN and a smaller focus group to seek comments and input. This helped to incorporate insights and views of experts and stakeholders in the early stages of the project, which helped produce a robust and holistic design and implementation plan.

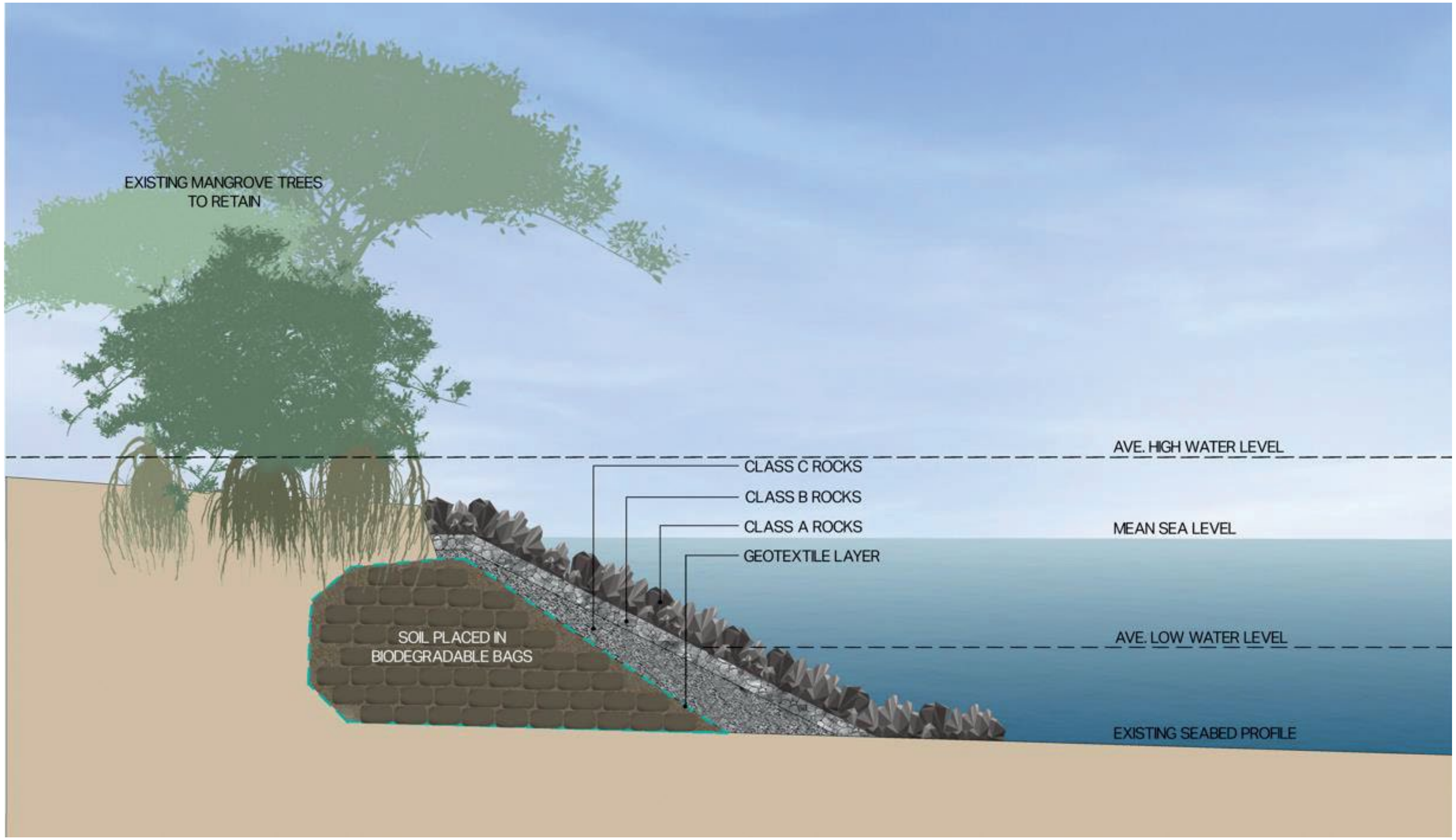


Fig 18. Typical cross-section of a mangrove shoreline toe protection measure. *Image: NParks*

With the world striving towards net zero carbon emissions, there is a growing business case for enterprises to research and develop innovative Nature-based Solutions integrated with engineering infrastructure and in turn, help cities mitigate and adapt to climate change at the same time.

Top: These ecologically-engineered BioBoss tiles on the seawalls at Pulau Hantu supplement coastal protection efforts and provide microhabitats that are attractive to various intertidal wildlife. *Source: Lynette Loke*

Bottom: Eight 10-metre artificial reef structures made of concrete and fiberglass are deployed at Small Sister's Island to not just promote coral growth, but also provide shelter for fish and other marine life. *Source: Nicholas Chew*

Page 65: Storyboard
Planning Adaptively, Learning by Doing

Planning Adaptively, Learning by Doing

A key concept of climate-resilient development is adaptive planning, which involves maintaining flexibility, with an iterative process of monitoring and re-evaluation to help account for long-term uncertainties. With stressors like sea level rise occurring over decadal to centurial scales, coupled with tidal or storm surges that are small probability but potentially high impact events, projection of future risks could be highly uncertain. Social, economic and technological changes may also render solutions less favoured or irrelevant over time.

Nonetheless, considering the gravity of the climate risks and the lead time for policy and infrastructure interventions, a concept of "Adaptative Pathway" has been increasingly recognised by policymakers and planners for coastal adaptation (Hasnoot et al. 2013), to adopt a long planning horizon, while maintain flexibility and allow solutions to be incrementally built as knowledge and technology evolve.

Once NbS are selected and implemented based on the intended goals and targets, they should be monitored regularly for their effectiveness. Practitioners can then make improvements or learn from the experience for future implementation. This exercise should be seen as a way to build long-term resilience through NbS rather than short-term outcomes.

The monitoring programme should be comprehensively designed, to include a range of parameters that cover both the key functions as well as co-benefits. For example, in the Sand Motor project conducted in the Netherlands to nourish a beach using local hydrodynamics, the five-year monitoring and evaluation programme examined not only the movement of sediment, but also included biodiversity and user surveys to quantify the benefit to humans and nature (Taal et al., 2016).

Assessments of NbS can be achieved through qualitative, quantitative and mixed methods, and can be done at various spatial and temporal scales, depending on the parameter being monitored. The EKLIPSE Expert Working Group on Nature-based Solutions (Raymond et al., 2017) recommends the following methods to objectively evaluate considerations/trade-offs commonly associated with coastal NbS:

- **Physical:** land-use and land cover changes, monitoring of physical parameters, number and extent of flooded areas, spatial analysis, GIS-based spatial analysis and modelling.
- **Economic:** cost-benefit analysis, price analysis, willingness to pay.
- **Social and educational:** surveys, estimates of the potential of NbS tourism, number of visitors, number and extent of research and education programs.
- **Biological:** estimated habitat suitability index and modelling, species census, spatial distribution of vegetation, normalised vegetation index, monitoring using citizen applications or programmes.
- **Chemical:** lab and field analysis of water quality, permanent monitoring systems.

For effective adaptive management, implementations should be treated as experiments, with proper replication and careful monitoring of responses (Nesshöver et al., 2017). Currently, one of the main barriers to implementing NbS is the lack of information to support interventions. Understanding the effectiveness and risks associated with NbS is necessary before solutions can be implemented on a broad scale. Solutions have worked elsewhere in the world, but it is not yet certain how they will function in a tropical island environment like Singapore. A common criticism

of NbS is the lack of data supporting the effectiveness or longevity of these solutions, hence planners may default to tried-and-tested conventional engineering solutions.
It is therefore necessary to invest early in pilot initiatives, with proper replication and careful monitoring of responses.

This allows practitioners to not only collect robust data on the effectiveness of the solutions, but also help identify the need for adjustments to the design, or help with scaling up and extend application to other areas. The key to this process is the strong emphasis on science-based decision making. The act of re-calibrating strategies, decisions and plans is predicated on the availability of new and better information, which is made possible by research. As such, adaptive management also needs to be supported by robust scientific research to better inform improvements to design and improve the accuracy of monitoring methods.

Since the implementation of a coastal protection and mangrove restoration project in 2010 at Pulau Tekong, NParks has continued to monitor and modify different NbS at various coastal areas, with a recently completed project at Kranji Coastal Nature Park. The next coastal protection project will be along Pulau Ubin's northern coastline, and will be complemented by mangrove restoration at Sungei Durian, along the island's southern coastline.

Case Study: **Pulau Tekong Mangrove Project, Singapore**

In 2010, NParks initiated a coastal protection and mangrove restoration project at Pulau Tekong to arrest the severe coastal erosion in the area while encouraging new mangroves to re-establish naturally. Using a combination of hard and soft engineering, low rock revetment and mud-filled geo-bags were deployed to slow down wave energy and encourage the accumulation of sediment. Mangrove saplings were also planted to test the survivability and growth of different species. The project successfully stopped coastal erosion as well as prevented further loss of the mangroves and degradation of habitat within the area over the last decade.

Fig 19. Toppling of mangrove trees as a result of shoreline erosion. *Images: NParks*

The coastal protection project at Pulau Tekong is one of the first nature-based hybrid eco-engineering applications in Singapore. NParks has since studied and adapted from this pilot for other coastal projects in other parts of Singapore.

The 92 ha of mangroves on the north-eastern coastline of Pulau Tekong represents the largest tract of pristine mangrove forest in Singapore. It supports a rich diversity of plants and animals, including one of the rarest mangroves in the world *Bruguiera hainesii*, the only natural population of *Bruguiera sexangula* in Singapore, and the Mangrove Pitta (*Pitta megarhyncha*), a critically endangered local bird. Due to its high biodiversity significance, it is designated a Nature Area under URA's Special and Detailed Controls Plan.

Unfortunately, studies conducted in 2009 and 2010 showed that erosion was causing a stretch of coastline to recede landwards between 1–9 m/yr, resulting in land loss of about 10,000 m^2. This led to the toppling of mature mangrove trees and habitat loss (Figure 19), and immediate action was deemed necessary.

Planning and Trials

Studies were conducted to quantify the severity and extent of erosion, and approximately 1.6 km of the 3 km coastline required urgent intervention. High wave energy in the area was identified as the root of the problem, but shipping traffic could not be redirected to alleviate the problem. NParks conceptualised a novel idea to restore the mangrove via sapling planting and coastal

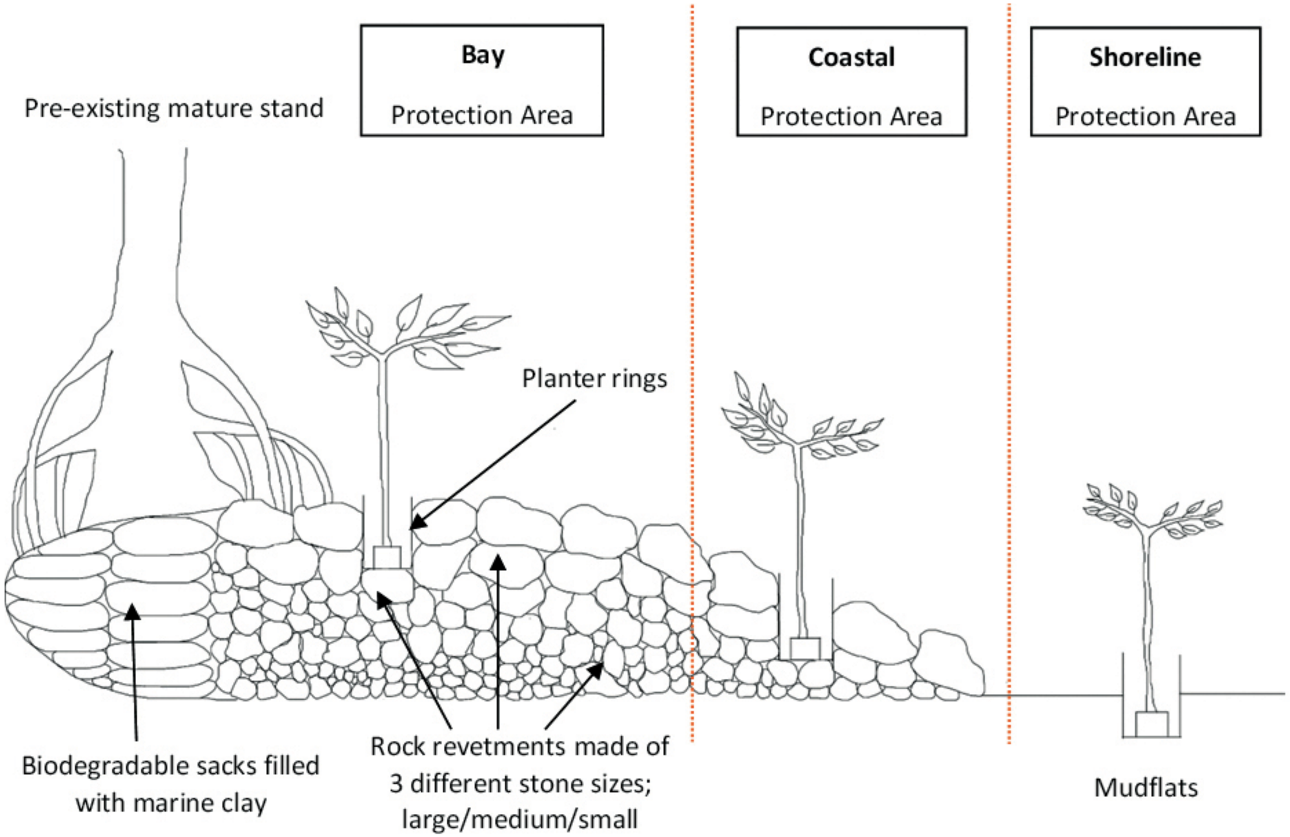


Fig 20. Diagram of the rehabilitation site layout. Erosion was arrested by using a combination of two strategies: 1) biodegradable sacks filled with marine clay placed under eroding berm, and 2) rock revetments made of three different stone class sizes were arranged to form a barrier against wave effects. Mangrove saplings were planted using biodegradable planter rings placed in between the rocks (bay protection area and coastal protection area) and in the mudflats (shoreline protection area).

protection. The agency took the lead by providing biological expertise and gathering multi-disciplinary expertise, including various public agencies and private consultants, to discuss possible solutions and considerations. The Housing Development Board (HDB) was appointed as the managing agent based on its experience in marine works, and carried out the works together with specialist marine consultants, horticulturists and contractors.

During the brainstorming period, many different options and potential solutions were tabled. To optimise the success rate of this project, a one-year pilot was carried out on these potential solutions and the conceptual design. This was followed by intense discussions between NParks, various experts and stakeholders from the nature community to review and re-design the project based on the findings from the field trial.

Hybrid solution for multiple benefits

The final design was an innovative approach using both hybrid solutions that combined hard and soft engineering solutions to achieve both engineering and biodiversity goals: the construction of rock revetments and the active transplanting of mangrove saplings into the rehabilitation site (Figure 20).

The hard solution, or coastal protection approach, aimed to address erosion caused by scouring waves by filling undercuts with biodegradable sacks of marine clay. The sacks were filled off-site, transported to the site, then placed beneath the eroding berm to support the overhang and provide a suitable substrate for the continued growth of the existing mangrove trees. Stones of various sizes were then placed along the coast to reduce the impact of breaking waves and arrest erosion.

The soft solution, or mangrove restoration approach, aimed to restore mangrove habitat and mitigate wave action by planting multiple species of native mangrove saplings, instead of conventional single species planting. All 13,500 saplings used in the project were grown from propagules collected in Singapore to retain the native gene pool. The selection of species was also based on findings from the field trial.

An Environmental Impact Assessment (EIA) was carried out to review the final design and works to be carried out on-site to ensure that the works would not cause a significant negative impact to the coastal and marine environment.

Monitoring for adaptive planning

Works were stringently supervised during the construction phase, which lasted from 11 October 2010 to 20 September 2011, to ensure minimal impact to the environment, with consultants from DHI tasked to do an Environmental Monitoring and Management Plan (EMMP), which would monitor the health of the mangroves throughout the project. The three main components of the EMMP included the monitoring of the physical and biological characteristics of existing mangroves, newly planted mangrove saplings and natural recruitments. After construction, another three rounds of monitoring were conducted in 2012, 2013 and 2016. Continuous monitoring of mangrove and sediment characteristics was essential to assess if the project objectives had been met.

The extensive monitoring revealed that the primary objective was fulfilled: shoreline erosion was arrested and the mature mangroves behind the revetment were safeguarded. The lowest bathymetry at which mangrove planting can work was also made apparent, as saplings planted beyond that point had a lower survival rate. Natural recruitment monitoring showed a number of recruits of various species in the project area, suggesting that the shoreline stabilisation structures provided a substrate for natural recruitment to occur. Some trends were apparent—for example, the existence of a cove-like bay facilitated greater levels of seedling recruitment and survival. Natural recruitment was not limited to mangrove saplings; in 2016, other marine organisms such as sponges were found inhabiting the planter rings.

An additional visual assessment was made in 2021, and the saplings growing from the rock revetment were found to be small (Figure 21), which may be a sign of stunting caused by the limited sediment and space between the rocks available for their root systems. Sapling growth was also limited to only a thin strip just in front of the original mangrove forest, which were not able to grow beyond the newly protected shoreline.

The monitoring results obtained were important as they can

Fig 21. Planted (left) and naturally recruited (right) mangrove saplings growing from the rock revetment, taken in 2021. Note the broad seaward zone where no saplings were able to survive/recruit. *Images: NParks*

be used by management agencies in planning future mangrove rehabilitation projects in Singapore or the immediate region. Key takeaways include:

1. Planting and rehabilitation works should focus on re-creating natural mangrove shorelines, and incorporating relatively flat and sheltered profiles at higher bathymetries to ensure greater survival of planted saplings and promote natural recruitment. If the goal is to not merely protect shorelines but also to facilitate the growth of healthy new mangroves, soft sediment at higher bathymetry is essential.
2. More localised studies are required to better understand different species' responses to the rehabilitated environment. Experimental planting studies with a larger sample size could also be conducted to assess optimum bathymetry for planting or natural recruitment of each species.
3. By combining lessons from multiple projects, new improved typologies can be derived.

The project successfully test-bedded a unique approach, the first of its kind in Singapore and possibly the world, to address the problems of eroding mangroves. It demonstrated a balanced approach towards development and environmental sustainability, showing that the protection of shorelines can involve more than just hard structures. Incorporating soft elements through planting not only creates an aesthetically pleasing and less intrusive appearance, but also enhances native biodiversity and potentially increases adaptive resilience to sea level rise. The lessons learnt from this project demonstrate that no solution should be seen as final, and adaptive planning strategies involving monitoring and iterative design will allow for continuous improvement to deal with changing conditions.

Mangrove Rock Revetment at Kranji Coastal Nature Park

Following the success of the Pulau Tekong nature-based approach, in 2018 NParks embarked on a similar project based on the lessons learnt. A 0.49 ha coastal belt with a similar rock revetment was constructed at Kranji Coastal Nature Park, a buffer park abutting Sungei Buloh Wetland Reserve.

This project refined the eco-engineering solution implemented at Pulau Tekong in several ways. A 400 m-long low rock revetment was located between heavily degraded secondary vegetation

Fig 22. As part of coastal protection efforts, a 400 m-long low rock revetment was built at Kranji Coastal Nature Park to slow down wave energy, promoting sediment accretion and natural recruitment of mangrove saplings. *Image: NParks*

and existing mangroves and seagrasses on mudflats, rather than in front of the mangroves. This hybrid solution provides multiple benefits: enhancing biodiversity, promoting long-term resilience of the ecosystems, and acts as a buffer for the coast against increased wave action as a result of rising sea levels and storm surges.

In addition to retaining the original mangroves, a gentler slope profile of the revetment was adopted to slow down wave energy and promote sediment accretion for natural mangrove recruitment. This was the key strategy used for the mangrove restoration portion of the project as modelling showed it to be a recipient site for dispersed propagules (NParks, unpublished). Two years post-implementation of the rock revetment, more than 300 mangrove saplings of at least four species have naturally recruited without mangrove planting required.

A coastal vegetation belt curated to emulate natural habitat zonation from terrestrial to coastal/mangrove forests was planted as part of the restoration plan. This provides additional habitats for biodiversity and creates a buffer area that can continue to absorb wave action as sea levels rise. As part of citizen stewardship, this

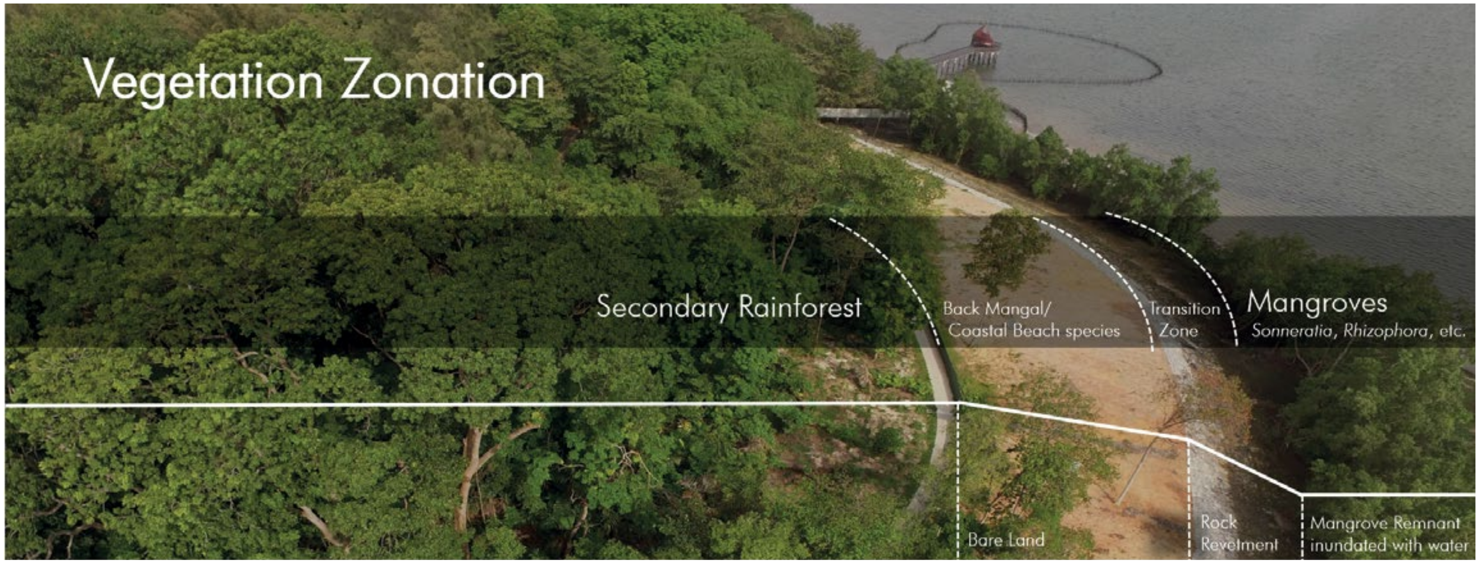


Fig 23. As part of coastal protection efforts, a vegetation belt that follows the natural zonation from terrestrial forests to coastal and mangrove forests was created at Kranji Coastal Nature Park. *Image: NParks*

Fig 24. Black-waisted Pronged-Nomia (*Nomia incerta*) pollinating *Ormocarpum cochinchinense*, a coastal tree species that is part of the NParks Species Recovery Programme, at Kranji Coastal Nature Park. *Image: NParks*

belt anchored a coastal forest restoration programme with the community. To date, a total of 58 tree and shrub species have been planted at the site, including four species that are part of NParks Species Recovery Programme – *Cocculus orbiculatus*, *Utania nervosa*, *Zingiber singapurense* and *Ormocarpum cochinchinense*. The *O. cochinchinense*, which was previously thought to be extinct in Singapore until it was rediscovered on Pulau Tekong and Pulau Ubin, is establishing well, with the trees flowering and producing seeds regularly, and are often visited by pollinators such as native solitary bees.

These habitat enhancement efforts were conducted as part of the OneMillionTrees movement and involved more than 250 participants, including National Development Minister Desmond Lee and individuals from various nature groups, Friends of the Parks volunteers, schools and other organisations.

Case Study: Building with Nature (BwN), the Netherlands

Initially promulgated by the Netherlands, Building with Nature (BwN) is a concept widely practised across the North Sea countries like Germany, Denmark and Belgium. The Netherlands' Delta Commission recommended in the report "Working together with water" in 2008 that 'developing with climate change and other ecological processes is the most sensible strategy to counter the effects of climate change' (Deltacommissie, 2008). BwN was thus adopted as a preferred strategy for coastal and water infrastructure projects to align with natural processes where possible, to achieve better cost efficiency in the long run.

To enable collaborative learning and quick scaling-up of pilot innovations, a 30 million Euro innovation programme was set up and managed by EcoShape, a research consortium consisting of government agencies, Institute of Higher Learning and Research Institutions, and private companies including coastal engineering consultants and dredging contractors. BwN research programme adopts a mantra of "learning by doing" with extensive pilot research, monitoring and evaluation conducted in "living laboratories" in the North Sea Region, to improve the understanding of NbS functions under different environmental conditions.

The reinforcement Houtribdijk (or Houtrib Dike) which was initially built in the 1960s by the Delta Works, is one notable project with BwN principles applied on the basis of both natural and recycled material selection and usage. The project combined engineering objective to meet the new flood safety requirement with the creation of nature and recreational opportunities.

The pilot dike reinforcement phase was constructed by EcoShape in 2014 at a 450 m section of the Houtribdijk. The pilot area consisted of a body of sand of approximately 70,000 cubic meters, implemented with varied height, width and vegetation cover. An extensive monitoring programme was conducted to study the morphodynamics of the foreshore, to test its effectiveness to wave attenuation and the stability of vegetation cover, over a monitoring period of four years in 2014–2018. The pilot project concluded with new knowledge on the design of soft hybrid dike and efficacy of different types of vegetation (Rijkswaterstaat-Ecoshape, 2016).

Subsequently, Houtribdijk was successfully reinforced in 2020 with 10 million cubic meters of sand dredged from the Markermeer at the north-western section to create a sandy foreshore; and 1.2

Fig 25. Vegetated Sandy Foreshore – Houtribdijk pilot reinforcement and monitoring project in 2016. *Image: Jurriaan Brobbel*

million tonnes of quarry stones and poured asphalt at the south-eastern section. A new nature reserve area, Trintelzand, with an area of more than 500 hectares was created through depositing excess sludge from the process of embankment dredging, which was deemed more cost-effective compared to sludge disposal.

BwN programme has proven that through transdisciplinary research and pilot testing involving researchers and companies, NbS innovations could become more viable technically, and make strong business case to be implemented at scale.

Fig 26. Houtribdijk Final Reinforcement in 2020. *Image: Frank Janssens*

Conclusion

NbS are a family of approaches that provide human well-being and biodiversity benefits, which have ecological, socio-cultural, environmental and economic value. Given their potential for immense and diverse values in the long run, we urge planners and developers to look to NbS as the first option to be considered in tandem with engineering solutions for mitigation and adaptation to achieve climate resilience and sustainable development objectives.

In this guide, we focused on NbS interventions for coastal adaptation, taking inspiration from international frameworks and successful case studies, and outlined key planning and design considerations which enable the adoption of NbS in coastal areas. The guide also documented a series of NbS typologies that have been implemented or occurred incidentally, which could be more intentionally pursued in Singapore's tropical urban context. These typologies offer different benefits and should be selected based on the characteristics of the site and desired outcomes of the development. Through both local and international case studies, this guide has demonstrated how NbS can be applied across a range of scales, and the importance of integrated design, stakeholder engagement and adaptive planning in their implementation.

To meet the current generation's needs, and to take proactive measures against future challenges, Singapore needs to carefully balance development and conservation to maintain and further enhance liveability, embodied by better human wellbeing, sustainable use of resources and more diverse opportunities for its citizens. As Singapore seeks to strengthen its resilience against both anticipated stresses and unforeseeable disruptions from climate change, NbS present a golden opportunity to create multipurpose, adaptable spaces and solutions that strengthen the long-term climate resilience of our city, safeguard our natural heritage and regenerate urban ecosystems services in harmony with human society and built environment.

With growing interest for NbS particularly in urban settings globally, there are potential first-mover advantages if Singapore were to invest early in the development of NbS through an "ecosystems" approach with the collaborative effort of the public, private and people sectors. There is no better time to spur new research and pilot bold solutions that are tailored to tropical urban context, while strengthening human and intellectual capital to become an innovation hub to support the resilient development of high-density coastal cities around the world.

Resources

Nature-based Solutions Planning and Implementation			
Title	**Authors/Editors**	**Year**	**Links**
ThinkNature Nature-Based Solutions Handbook	Somarakis G., Stagakis S., Chrysoulakis N.	2019	https://platform.think-nature.eu/system/files/thinknature_handbook_final_print_0.pdf
Guidance for Considering the Use of Living Shorelines	National Oceanic and Atmospheric Administration (NOAA) Living Shorelines Workgroup	2015	https://www.habitatblueprint.noaa.gov/wp-content/uploads/2018/01/NOAA-Guidance-for-Considering-the-Use-of-Living-Shorelines_2015.pdf
Building with Nature – Thinking, acting and interacting differently	EcoShape	2012	https://www.ecoshape.org/app/uploads/sites/2/2016/07/ECOSHAPE_BwN_WEB.pdf
Implementing Nature-Based Flood Protection: Principles and Implementation Guidance	World Bank	2017	http://documents.worldbank.org/curated/en/739421509427698706/pdf/120735-REVISED-PUBLIC-Brochure-Implementing-nature-based-flood-protection-web.pdf
Integrating Nature-Based Solutions for Climate Change Adaptation and Disaster Risk Management: A Practitioner's Guide	Asian Development Bank	2022	https://www.adb.org/publications/nature-based-solutions-climate-change-adaptation-disaster-risk-management
Use of Natural and Nature-Based Features (NNBF) for Coastal Resilience	U.S. Army Engineer Research and Development Center	–	https://ewn.el.erdc.dren.mil/pub/Pub_4_NNBF_Final_Report_v2.pdf
Engineering with Nature: An Atlas	U.S. Army Engineer Research and Development Center	2018	https://ewn.el.erdc.dren.mil/img/atlas/ERDC-EL_SR-18-8_Ebook_file.pdf
Ecosystem-Based Disaster Risk Reduction in Japan	Ministry of The Environment (Japan)	2016	https://www.preventionweb.net/files/48400_ecodrr.pdf
Directives for Ecological Sea Dyke Construction of Reclamation and Polder Projects	Ministry of Natural Resources (China)	2020	http://www.caoe.org.cn/upload/202001/20200115848142068495217.pdf
The Australian Guide to Nature-based Methods for Reducing Risk from Coastal Hazards	Earth Systems and Climate Change Hub, National Centre for Coasts and Climate (Australia)	2021	https://nespclimate.com.au/wp-content/uploads/2021/05/Nature-Based-Methods_Final_05052021.pdf

Monitoring and evaluation			
Title	Authors/Editors	Year	Links
An Impact Evaluation Framework to Support Planning and Evaluation of Nature-based Solutions Projects	EKLIPSE Expert Working Group on Nature-based Solutions to Promote Climate Resilience in Urban Areas	2017	https://ora.ox.ac.uk/objects/uuid:3ecfc907-1971-473a-87f3-63d1204120f0/download_file?file_format=pdf&safe_filename=EKLIPSE_Report1-NBS_FINAL_Complete-02022017_LowRes_4Web.pdf&type_of_work=Report

Community engagement			
Title	Authors/Editors	Year	Links
Elements of Effective Engagement	Rebuild by Design	–	http://www.rebuildbydesign.org/wp-content/uploads/2021/12/375.pdf
Friends of Ubin Network	National Parks Board	–	https://www.nparks.gov.sg/pulau-ubin/friends-of-ubin
Building Community Resilience	Centre for Liveable Cities	2022	https://go.gov.sg/building-community-resilience

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Marina @ Keppel Bay.
Image: Nathaniel Soon

A Guide to Implementing Coastal Nature-based Solutions for Singapore

Cities can leverage Nature-based Solutions to improve climate resilience, restore nature, and provide benefits to people. This guide was jointly developed through research convening a wide range of stakeholders and experts. It aims to document a shared understanding of the principles and enablers for Nature-based Solutions to be applied within an urban coastal context, to reduce climate risks, regenerate ecosystem services and deliver greater societal gains.