GREEN COASTAL PROTECTION AND FLOOD DEFENCE OPTIONS FOR WESTERN INDIAN OCEAN COUNTRIES

by
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Thesis presented in fulfilment of the requirements for the degree of Master of Engineering in Civil Engineering in the Faculty of Engineering at Stellenbosch University

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December 2022

DECLARATION

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ABSTRACT

Traditionally engineers have resorted to hard or grey infrastructure to defend vulnerable coastlines against the forces of coastal processes. However, there is growing interest and awareness in more sustainable or soft coastal defence approaches that work with the forces generated by coastal processes to achieve the same levels of coastal protection and gain the benefits of ecosystem services that hard infrastructure does not offer.

Countries bordering and within the Western Indian Ocean have a large collective coastal population of about sixty million people. These countries are also among the most under-resourced and most at risk to the effects of climate change and sea-level rise in the world. This study intended to investigate and propose green coastal protection infrastructure options that could be adopted in countries in the Western Indian Ocean.

A literature review was completed to understand the spectrum of coastal protection infrastructure including grey or hard infrastructure, eco-friendly infrastructure, hybrid infrastructure, and green or soft infrastructure. The advantages and disadvantages of each coastal protection type were discussed. Furthermore, the study explored a few examples of each coastal protection type.

Literature was also sourced on ways to quantitatively evaluate the vulnerability of coastlines in the Western Indian Ocean using variables that are easily obtainable for countries that may not have detailed coastal surveys or historical records of coastal data. Finally, quantitative comparative evaluation methods of coastal infrastructure were investigated to account for the ecosystem services provided by soft infrastructure which are often ignored in traditional evaluation approaches.

The information from the literature review informed the proposal of green and hybrid infrastructure strategies that could be adopted in countries in the Western Indian Ocean. Case studies were conducted in three Western Indian Ocean Countries to illustrate how green coastal infrastructure can be incorporated into coastal defence strategies. The case studies investigated were Mon Choisy, Albion, and Case Noyale in Mauritius, Ponta Gea and Praia Nova in Beria, Mozambique, and Richards Bay in South Africa.

OPSOMMING

In die verlede het ingenieurs meestal teruggeval op grys of harde infrastruktuur om kwesbare kuslyne te beskerm teen kusprosesse. Daar is egter toenemende belangstelling in en bewustheid van meer volhoubare of sagte kusbeskermingsbenaderings wat saamwerk met die kusprosesse en wat dieselfde vlakke van beskerming kan bied as tradisionele metodes, asook die voordele van ekosisteme kan benut.

Lande in die Westelike Indiese Oseaan het 'n groot kusbevolking van gesamentlik om en by sestig miljoen mense. Hierdie lande het ook 'n aansienlike tekort aan hulpbronne en is onder die wat mees blootgestel is aan die risiko van klimaatverandering soos wat seevlakke wêreldwyd styg. Hierdie studie het ondersoek ingestel na, en groen kus beskermings opsies voorgestel, wat deur lande in die Westelike Indiese Oseaan benut kan word.

'n Literatuuroorsig is voltooi om die omvang van kusbeskermings infrastruktuur, insluitend grys of harde infrastruktuur, eko-vriendelike infrastruktuur, gemengde infrastruktuur en groen of sagte infrastruktuur te kan verstaan. Die voordele en nadele van die verskillende benaderings word bespreek. Daar word ook voorbeelde van verskeie kusbeskermings tipes ondersoek.

'n Literatuuroorsig is ook gebruik om maniere te kry om die kwesbaarheid van kuslyne van die Westelike Indiese Oseaan kwantitatief te kan evalueer, deur middel van algemeen beskikbare veranderlikes wat maklik verkrygbaar is vir lande wat 'n tekort het aan gedetailleerde kusopnames of historiese data. Laastens is kwantitatiewe vergelykende evaluerings-metodes ondersoek om die nut van ekosisteem dienste gebied deur sagte infrastruktuur te bepaal, wat andersins dikwels deur bestaande evaluerings-metodes misgekyk word.

Die inligting voortspruitend uit die literatuuroorsig het aanleiding gegee tot voorstelle vir infrastruktuur strategieë wat deur lande in die Wes-Indiese Oseaan aangewend kan word. Gevallestudies is uitgevoer in drie Wes-Indiese Oseaan lande om te wys hoe groen kusinfrastruktuur in kusbeskermingsstrategieë opgeneem kan word. Die gevallestudies wat ondersoek is sluit in Mon Choisy, Albion, en Case Noyale in Mauritius, Ponta Gea en Praia Nova in Beira, Mosambiek, en Richardsbaai in Suid Afrika.

ACKNOWLEDGEMENTS

I would like to express my gratitude to Dr AK Theron for sparking my interest in coastal engineering and for proposing and guiding me through a stimulating thesis topic.

I offer special thanks to Ms RL Owen for her fresh energy and input that helped me finish.

I would also like to convey my appreciation to Mr D Janisch for proofreading my thesis.

Finally, I am indebted to my parents for their endless love, support, and encouragement throughout my educational journey.

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EQUATIONS

SYMBOLS

Symbol	Description
A	Dean's Equilibrium Constant
B	project benefit value (USD)
C	project cost value (USD)
D_{50}	mean grain size of sand sample (mm)
d_b	depth of wave breaking (m)
D_{n50}	average rock diameter (m)
FV	future value (USD)
g	gravitational acceleration on Earth's surface (9.81 m/s^2)
h	Height (m)
H_{is}	significant incident wave height (m)
H_s	significant wave height (m)
K_t	Wave transmission percentage for reef ball reef (%)
M_{50}	median rock mass (kg)
N	number of waves
N_S	stability number
PV	present value (USD)
R	risk of failure (%)
r	time-discount rate
$R_{u2\%}$	2 percent exceedance wave run-up (m)
t	time period or project life (years)
T	project life or wave period (years or s)
T_m	mean wave period (s)
T_p	peak wave period (s)
V_{se}	volume of semi-ellipsoid (m^3)
w	width (m)
α	slope of revetment
Δ	relative density
ξ_{0m}	surf similarity parameter
ρ_c / ρ_r / ρ_w	density of concrete/density of rock/density of seawater (kg/m^3)

ABBREVIATIONS

Abbreviation	Description
AFRC	Albion Fisheries research centre
BCR	benefit-cost ratio
CBA	cost-benefit analysis
CVI	coastal vulnerability index
ESWL	extreme still water level
IPCC	Intergovernmental Panel on Climate Change
IRR	internal rate of return
IUCN	International Union for Conservation of Nature
JICA	Japan International Cooperation Agency
MCDA	multi-criteria decision analysis
MOI	Mauritius Oceanography Institute
MSL	mean sea level
NPV	net present value
PIANC	World Association for Waterborne Transport Infrastructure
RPC	representative concentration pathway
SLR	sea level rise
TNPA	Transnet National Ports Authority
UNDP	United Nations Development Programme
UNEP	United Nations Environmental Program
WIO	Western Indian Ocean
WIOMSA	Western Indian Ocean Marine Science Association

1 BACKGROUND

The United Nations Environmental Program (UNEP, 2021) reports that nearly 40% of the human population lives within 100 km of the coast at twice the density of the global average, and this percentage is expected to increase. The effects of climate change such as sea levels rising are becoming greater threats to these coastal populations. Currently, USD 3 trillion of coastal assets are at risk of inundation in coastal cities, and this number is expected to increase tenfold over the next 50 years (Temmerman et al., 2013). Thus, researching and developing effective coastal protection techniques is possibly one of the most critical issues faced by coastal communities.

The conventional engineering approach to defending coastlines has been to construct hard infrastructure, such as breakwaters, seawalls, and groynes, to resist or obstruct forces of nature. These approaches, traditionally seen as the ultimate coastal defence techniques, are now being questioned because the cost of building hard infrastructure is becoming increasingly significant, and the maintenance of these structures will become unsustainable, especially in poorer under-resourced countries (Temmerman et al., 2013; Hinkel et al., 2014). In addition to this, questions are being raised about the environmental impacts of hard infrastructure which damages natural habitats and does not necessarily provide the ecosystem services of natural habitats (Morris et al., 2018).

This has led to growing interest in green coastal infrastructure which includes soft infrastructure solutions and hybrid infrastructure solutions which work with the forces of nature. Examples of soft infrastructure include a variety of natural coastal habitats such as dunes and beach nourishment, mangrove forests, wetlands and salt marshes, and coral reefs. Hybrid solutions are the combination of hard and soft infrastructure which may be done retroactively or simultaneously. Aside from protecting coastlines by attenuating waves and providing buffers against storm surges and sea-level rise, green infrastructure provides a variety of ecosystem services such as supporting biodiversity and habitat for fish nurseries, sequestering and storing carbon, filtering water, providing food and materials for residents, providing opportunities for ecotourism and job creation (IUCN, 2018). Additional benefits of green infrastructure include improved adaptability to sea level rise and lower construction and maintenance costs when compared to hard infrastructure.

Western Indian Ocean (WIO) countries are some of the most under-resourced and most at risk to the effects of climate change and sea-level rise especially considering their large collective population of about 60 million people living within 100 km of the coast (Groeneveld, 2015).

This study will investigate several types of green coastal infrastructure that can be adopted in WIO countries, focusing on case studies from three countries in this region: Mauritius, Mozambique, and South Africa.

The study will also investigate approaches to evaluating different hard and soft coastal infrastructure options that account for the ecosystem services provided by soft infrastructure.

Finally, the study will evaluate and propose options to be considered in the coastal protection strategies for the selected case studies in Mauritius, Mozambique, and South Africa.

2 OBJECTIVES

The objectives of this study are as follows:

1) Investigate several types of green coastal protection and flood defence infrastructure that can be adopted in WIO countries.
2) Develop a coastal vulnerability assessment tool that can identify vulnerable coastlines in WIO countries.
3) Identify quantitative evaluation methods that can be used to assess green coastal infrastructure and account for their associated ecosystem services.
4) Propose green infrastructure options for consideration in adopting coastal protection strategies in selected case studies from Mauritius, Mozambique, and South Africa.

3 LITERATURE STUDY

3.1 Coastal processes

Coastal processes is a general term covering the natural forces that act on and shape a coastline (Theron et al., 2012). These processes are driven by wind, waves, tides, storm surges, and sea-level rise.

Waves are one of the primary driving forces that shape our coastlines and drive sediment transport and erosion. Waves are generated by winds blowing over the ocean surface for long distances thereby transferring energy to the water and typically have a periodicity of 20 s or less. Waves can also be generated by tides and earthquakes, but these waves have periods in the order of minutes. When a wave approaches the surf zone, at a certain point, it becomes unstable triggering the wave to break. The area between the initial wave breaking point and the shore is the surf zone. In the surf zone, the wave height begins to attenuate due to the water depth, but the momentum of the wave causes the mean water level to rise above the mean still water level. This process is called wave setup.

Tides are the fluctuation in sea level produced mainly by the combined gravitational pull of the moon and sun whilst the Earth rotates. The water 'bulges' on the sides closest and furthest from the moon causing a local high tide. Thus, many coastlines experience two high tides each day. Twice during a lunar cycle (at new moon and full moon) the moon and sun align with the Earth. Their combined gravitational forces resulting in spring tides which are the highest and lowest tides that occur in the lunar cycle. Tidal drivers are well understood, and tidal levels can be modelled with high degrees of accuracy.

Storm surges are a rise of water level above normal water levels caused by zones of low barometric pressure and by storm winds driving water onshore. Climate change is increasing the frequency and severity of storm surges in many parts of the world (IPCC, 2014).

It is accepted that sea levels have been rising since the late 1800s after having remained at a stable height for the last 6000 years (Short, 2012; Reeve, Chadwick & Fleming, 2018). During the period between 1993 and 2007, it was observed that global sea levels were rising by 3.3 ± 0.4 mm per year, and this number is expected to increase throughout this century (Cazenave & Llovel, 2010). In its 2019 report on sea-level rise, the Intergovernmental Panel on Climate Change (IPCC) predicted that in a continued high emissions scenario, sea levels will rise from current levels to between 0.61 m and 1.10 m by 2100 (Oppenheimer et al., 2019).

3.1.1 Coastal Inundation

When these coastal processes act simultaneously, the likelihood and extent of shoreline affected by coastal inundation increase, as illustrated in Figure 3.1. In this case, a storm surge is occurring at the same time as a high tide, causing inundation. The red line indicates the potential future inundation level when accounting for sea-level rise. Thus, coastal habitats, populations, and developments are being increasingly threatened because of the effect of climate change on sea levels and storm surges.

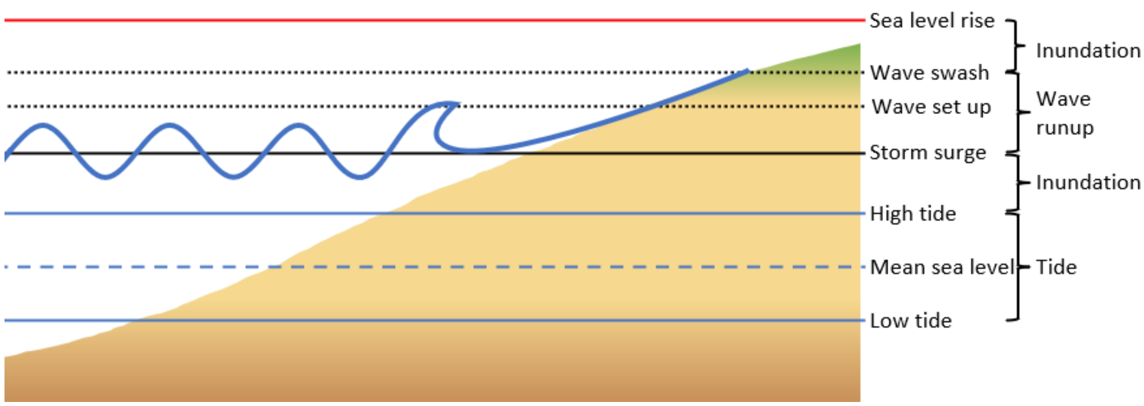

Figure 3.1 Coastal processes contributing to coastal inundation

(adapted from Theron, Rautenbach, Maherry, et al., 2015; Vitousek, Barnard, Fletcher, et al., 2017)

3.1.2 Coastal erosion

Coastal erosion is the loss or displacement of land along the coastline due to the effects of the above-mentioned coastal processes (waves, tides, storm surges, sea-level rise, and inundation) (O'Neill, 1985).

Erosion may also be triggered by anthropogenic causes such as interfering with longshore sediment transport processes by damming rivers, building groynes, breakwaters, and harbour entrances, and thus erosion is a widespread problem experienced on the downdrift side of breakwaters and groynes.

Erosion can occur rapidly, over a few days, because of a severe storm surge (as seen in Figure 3.2) or slowly, over the period of decades, caused by waves, currents and sea-level rise.

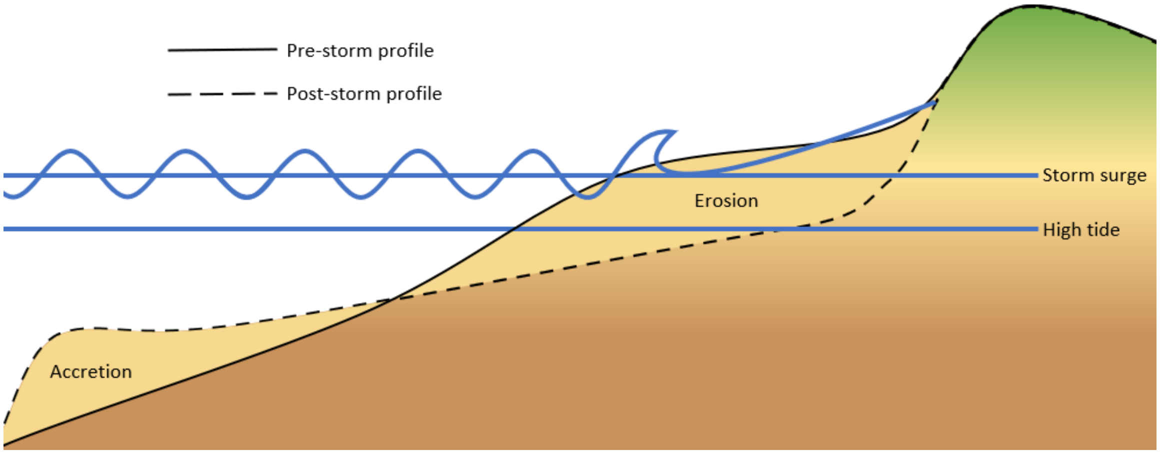

Figure 3.2 Process of rapid storm surge erosion (O'Neill, 1985; Theron, 2021)

3.1.3 Direct wave impacts

Waves lose some energy in the surf zone due to bed friction and turbulence when breaking (Chadwick, Morfett & Borthwick, 2013). The remaining energy is dissipated during the process of 'uprush' and 'hitting' against the coastline. This energy can be significant and cause damage to both natural coastlines and coastal infrastructure, for example, causing concrete seawalls to crack and break or even collapse.

3.2 Coastal management techniques

The previous section highlighted the primary hazards (direct wave impacts, inundation, and coastal erosion and under scour) threatening coastal infrastructure and resources (Theron et al., 2012). This section considers some of the approaches that can be taken to manage these hazards.

In 1992 the International Panel on Climate Change (IPCC), outlined three management responses to the rising sea levels, coastal erosion and inundation, and changing coastal environment:

- Protection or defence

The strategy behind the protection response is to design site-appropriate features to protect (or defend) the existing coastline from erosion or inundation. Consideration should be given to multiple development options. The best option is chosen and implemented with consideration given to, among other factors, coastal damage, cost-benefit, and efficacy of the design. Protecting and defending the coastline entails using either *green infrastructure* or *grey infrastructure* which is discussed in more detail in the following section.

- Accommodation

In this response, it is decided that no measures would be taken to protect the existing coastline but instead the existing infrastructure is made more resilient to coastal climate change. Examples of this response would include raising buildings on stilts, improving the integrity of existing buildings to withstand stronger and more frequent sea storm events, and changing from agriculture to pisciculture (fish farming) or farming salt-tolerant plants. Merely replacing the structure after being damaged should be avoided. An assessment should be undertaken to find ways to improve the resilience of the structure or defence protecting the structure.

- Retreat

In this case, it is accepted that coastal erosion or flooding is inevitable, and the best action is to reposition the compromised infrastructure and population away from the eroding or flooding coastline. It requires foresight from planning authorities to realise that not retreating would be more costly financially, socially, and environmentally.

The process requires long-term governmental planning, management, and oversight to implement the development of a safe setback zone from the coastline. Furthermore, governments need to facilitate the resettling of affected people and provide access to services. The setback zone becomes a coastal reserve in which no development is allowed. The challenge with this option is that it does not account for existing high-value infrastructure that is at risk, in which case it may, on closer analysis, prove to be more financially favourable to defend rather than relocate.

This management technique is considered to be best practice Internationally (Theron et al., 2012).

Other literature (Theron & Barwell, 2012, and others) offer a fourth default management response:

- Do nothing

In some cases, it may be favourable to accept the current situation and avoid acting rather than implementing poor measures to protect the infrastructure. This option should only be considered if changing the existing infrastructure may worsen the current situation and the risk of doing nothing does not threaten human life.

Theron & Barwell, (2012) also recommend as part of the coastal management process that the following indicators are monitored to identify trends which give authorities time to plan for future events and to reduce the associated risks appropriately.

- Monitor the annual changes in the wave regime and inshore water levels (continuous)
- Check integrity of coastal structures and natural defences (every three to five years or after major storms)
- Conduct topographic and bathymetric surveys to analyse the stability of the shoreline in terms of erosion (once a decade)

Future coastal developments should be cognisant of the above management techniques and predict the likely hazards that may threaten the development over its life cycle. Taking preventative steps, such as locating coastal developments safely away from erosion and inundation-prone areas can prevent the need to use one of the more intensive management techniques listed above. Documents such as Integrated Coastal Management plans are useful in this regard in ensuring that a unified approach is taken countrywide to reduce the risks of coastal hazards.

3.3 Grey vs Green coastal infrastructure

This study explores examples of *green infrastructure* that can be adopted by WIO countries in their response to coastal inundation, erosion, and sea-level rise. It is worth defining what is meant by *green infrastructure* in terms of coastal protection.

Coastal protection and defence refer to the schemes intended to protect coastlines from erosion and flooding due to coastal hazards (Reeve, Chadwick & Fleming, 2018). The U.S. Environmental Protection Agency (EPA) defines *green engineering* principles as those which reduce pollution and environmental risks and promote sustainability without sacrificing economic viability, efficiency, and human wellbeing. Consideration is given to ways in which developments can conserve and improve natural ecosystems and works with local geographies. *Green engineering* also aspires to make use of or invent new technologies rather than default to conventional design practices.

Reeve, *et al.* (2018) classify coastal protection or defence into two broad categories. The first, more conventional, category is *grey infrastructure* or *hard engineering* which aims to defend the coast by building hard coastal defence structures like seawalls and breakwaters (usually from rock and concrete) which resist or oppose natural coastal processes such as waves. The second category is *green infrastructure* which takes inspiration from defence mechanisms found in natural coastal habitats. G*reen infrastructur*e can be divided into a further three subcategories with increasing application of nature; eco-friendly hard infrastructure, hybrid infrastructure, and soft engineering (Morris et al., 2018; Schoonees et al., 2019).

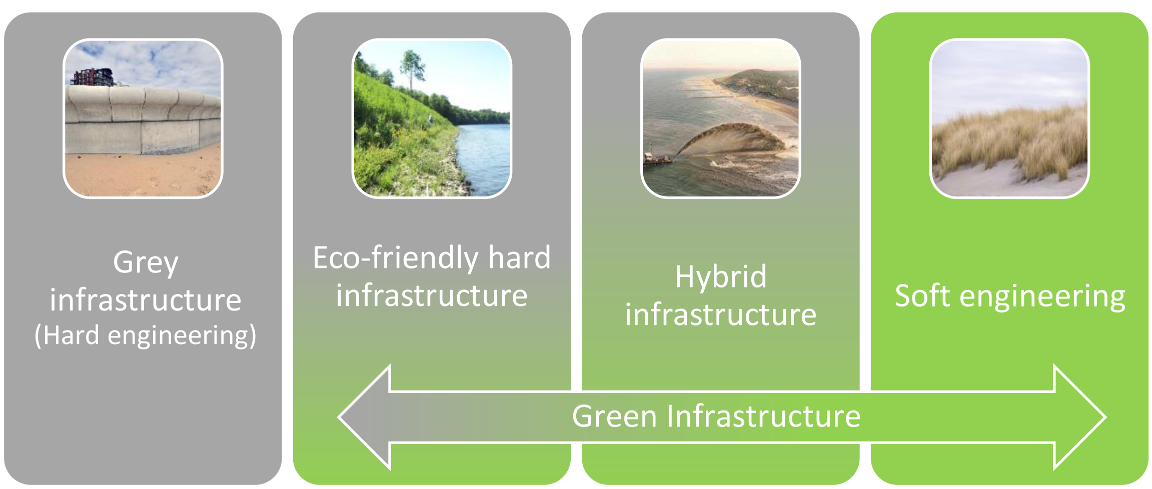

Figure 3.3 Defining the range of coastal infrastructure (adapted from Morris et al., 2018; Schoonees et al., 2019) From left: seawall (Beer, 2018), vegetated revetment (RSE, n.d.), beach nourishment and groynes (IAEA, 2014), and vegetated dune (TFG, 2022)

Eco-friendly hard infrastructure is designed to retrofit *hard infrastructure* to restore, conserve, or mitigate the loss of the original ecosystem services provided (Dafforn et al., 2015; Schoonees et al., 2019). Examples of eco-friendly hard infrastructure include encouraging shellfish reefs to develop on the infrastructure, and sheltering the structure from wave attack whilst providing the ecosystem services of shellfish like water filtration (Beck et al., 2009).

Sometimes the most favourable design will combine examples of both hard and soft engineering in a *hybrid infrastructure* project to capitalise on the benefits from both approaches, and may improve the resilience of the coastline against storm flooding (Sutton-Grier, Wowk & Bamford, 2015; Schoonees et al., 2019). An example of a hybrid structure would be the simultaneous installation of a flood gate and a salt marsh. During storm events, the flood gate can be closed to reduce the likelihood of flooding and erosion (Sutton-Grier, Wowk & Bamford, 2015).

Soft infrastructure has the same objective as that of *hard engineering* but differs structurally by incorporating natural habitats and processes in its design such as dunes, mangrove forests, and coral reefs. These structures work with or redirect the natural coastal processes and enhance the ecosystem services provided by natural habitats rather than hard infrastructure which resists the forces of nature without additional benefits (Theron et al., 2012).

Conventionally engineers have turned to *hard infrastructure* (like breakwaters, dykes, and seawalls) to defend the coastline from erosion and other coastal hazards (Morris et al., 2018). However, Hinkel *et al.*, (2014) predict that continuously relying on *hard infrastructure* like dykes until 2100 is going to result in a significant financial burden including annual investment, upgrade and maintenance costs when considering the scenario of sea-level rise.

This has prompted researchers to investigate alternative protective coastal infrastructure, for example, creating and restoring natural habitats or *soft engineering* (like dunes, salt marshes, and mangroves) (Morris et al., 2018). Some benefits of *soft infrastructure* include that they can provide a cheaper solution, become more resilient as they mature and can adapt and self-repair after storm events (Borsje et al., 2011; Gittman et al., 2014). It has been found that *soft engineering* can also serve additional functions beyond defending the coastline by offering a variety of ecosystem services.

Temmerman et al. (2013) and Pontee et al. (2016) divide ecosystem services into four categories of supporting (nutrient cycling and/or water filtration), provisioning (providing raw materials, supporting fish stocks and/or biodiversity), regulatory (coastal protection, carbon sequestration, and/or carbon storage), and cultural services (recreation, tourism and/or scientific opportunities). Over 40% of the total global value of ecosystem services originates from coastal environments like estuaries, seagrass beds, coral reefs, mangrove forests, and dunes (Costanza et al., 1997).

Despite growing awareness of the need for more sustainable solutions, research done on the protective capacity of *soft engineering* is limited when compared to *hard infrastructure* resulting in low enthusiasm for *soft engineering* in practice because it is seen as more 'risky' (Temmerman et al., 2013; Morris et al., 2018). Pontee et al. (2016) state that this assumption is incorrect by citing examples like the managed coastal dunes in the Netherlands which have achieved protection levels as high as *hard engineering* structures. Morris *et al.* (2018) argue that more research needs to be done comparing the different *soft engineering* and *hard infrastructure* options especially highlighting the protective capacity, instalment and long-term financial cost, and ecosystem services. This will encourage more engineers, clients, and authorities to adopt greener engineering solutions.

3.4 Green coastal protection techniques or soft infrastructure solutions

Table 3.1 summarises some of the benefits and disadvantages of soft engineering that are common to many of the techniques discussed in this section.

Table 3.1 Advantages and disadvantages of soft engineering

(Sutton-Grier, Wowk & Bamford, 2015; Schoonees et al., 2019)

Benefits	**Disadvantages**
Provide ecosystem services (habitats, water filtration, carbon sequestration, recreation)	Limited quantitative research available on best practice and extent of protective capacity
Habitat becomes stronger as it matures	Takes time to establish and mature
Ability to self-recover after storm damage	Requires more space than hard infrastructure
Often comparatively cheaper	Difficult to quantify cost-benefit

A challenge with soft engineering is that it does not have the same set of established guidelines as those developed over the last century for conventional grey or hard infrastructure. Due to a lack of established guidelines soft engineering solutions are not well understood leading to engineers shying away from utilising them and thus not developing the experience needed to create soft engineering guidelines in the first place (Pontee et al., 2016). Pontee et al., (2016) call for more soft engineering studies to focus on the following three factors which will inform the understanding of the effectiveness of different soft engineering solutions and can, in turn, aid the development of guidelines:

- Habitat type: what are the appropriate environmental conditions (like wave energy, nutrient availability, or tidal range) for different soft engineering solutions.
- Wave energy dissipation: how and what determines the dissipation of wave energy moving through different habitats.
- Habitat characteristics: what characteristics should be focused on or enhanced to make the soft engineering option a more effective solution (perhaps increased density of mangrove forests or increased reef crest heights).

Another challenge with soft infrastructure projects is that they are dynamic systems that change over the project life thus carrying additional uncertainty (PIANC, 2011; Morris et al., 2018). Seasonal and long-term variability makes it difficult to evaluate the viability of soft engineering over a life span of 30 to 50 years (usually the design life for seawalls and revetments) or up to 100 to 200 years (the design life for breakwaters). Coastal modellers are beginning to accurately predict some dynamic coastal systems, but more data needs to be gathered to better understand some of the associated uncertainties with coastal systems (PIANC, 2011). Morris *et al.* (2018) point out that the variability of a natural system is what may enable it to adapt to environmental changes such as sea-level rise unlike the rigid design of hard engineering options. Borsje et al., (2011) illustrate this concept in Figure 3.4 with a conceptual project addressing sea-level rise with two different approaches. The first approach is to use grey infrastructure or "traditional engineering" (dotted line) whilst the second is to use green coastal defence (solid line). The shaded area indicates the expected range of sea level rise. Traditional engineering initially has an overdesigned capacity that does not respond to environmental changes. On the other hand, the green defence has uncertain seasonal variability but matures with time responding appropriately to environmental changes. Furthermore, after a hypothetical extreme event, like in 2060, the green coastal protection recovers and continues to improve in its protective capacity.

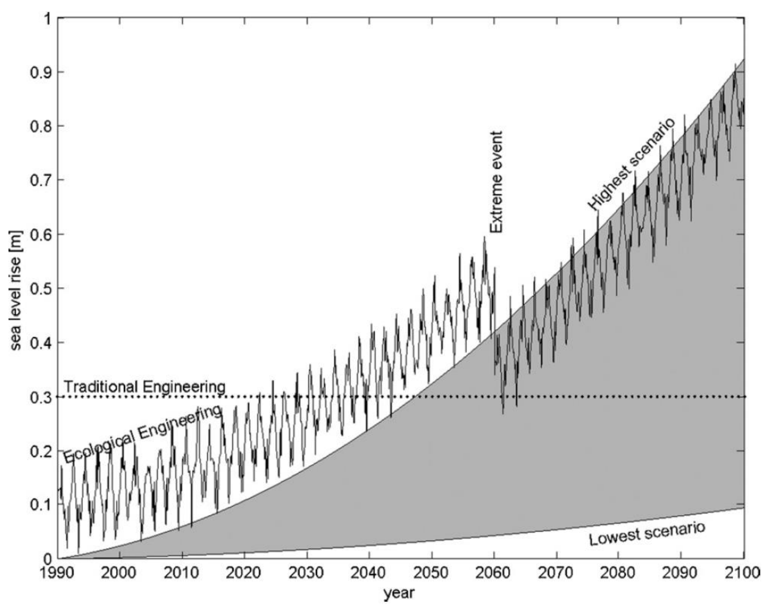

Figure 3.4 Conceptual project framework comparing traditional grey infrastructure to green ecological engineering
(Borsje et al., 2011)

Morris, Graham, Kelvin, *et al.* (2020) indicate that there is also an imbalance in research focus given to the various soft engineering options with more studies on coral reefs, dunes, and salt marshes than on kelp beds, sea grasses, and oyster reefs.

3.4.1 Shore nourishment

Shore nourishment, also known as beach nourishment, aims to combat the effects of coastal erosion and inundation by adding sediment to the budget and widening the beach. This provides coastal infrastructure protection by moving the shoreline and coastal hazards away from the threatened hinterland. The widened beach may also increase tourism and nearby property values and can appear natural to most users (Morris et al., 2021). Depending on the project outcomes shore nourishment could be a once-off project (called capital nourishment), a periodic maintenance program, or a continuous maintenance nourishment program.

The imported sediment must have similar properties (especially grain size but also the colour for aesthetic reasons) to the receiving beach (Reeve, Chadwick & Fleming, 2018). However, one should also be mindful of the environment where the source sediment is coming from as one should avoid creating a sediment imbalance elsewhere. Reeve *et al.* (2018) point out that it would be beneficial if the source of sediment can come from dredging waste from other projects.

The newly placed sediment will continue to erode and will require a program of routine re-nourishment every 5 to 15 years depending on the erosion rate (Theron et al., 2012; Morris et al., 2021). Deciding on the sand volume to be placed is the summation of a 'storm demand' estimation (the likely volume of sand that will be lost during storm surges), the ongoing beach erosion due to wave and current action and sea-level rise over the design period (Morris et al., 2021).

A challenge with shore nourishment is that it is an expensive option with high dredger mobilisation costs (Theron et al., 2012). Another limiting factor, as previously mentioned, is that a source of similar sand needs to be near the destination beach for it to be a practical option. It should be noted that whilst shore nourishment is seen as a soft engineering solution, it is not without its environmental impacts causing considerable disturbance to the borrow and deposit sites, suspending fine sediments in the surrounding aquatic environment, and use of heavy equipment (Chadwick, Morfett & Borthwick, 2013).

Shore nourishment is often used in conjunction with a hard engineering solution especially groynes, artificial headlands, and detached breakwaters.

3.4.2 Dune Management (vegetated and/or reinforced)

Dunes form when windblown sand from the foreshore accumulates in the backshore above the high-water level. The sand can then be colonised by vegetation which in turn accelerates the rate of sand deposition and accumulation allowing the sand mass to eventually form a dune. The protective value of a dune is twofold, firstly, it can serve as a reservoir of sand that feeds the beach in periods of erosion and, secondly, it can protect the inshore areas from temporary inundation acting as a barrier. Thus dunes can be used as an affordable solution for coastal protection (Theron et al., 2012). Rock gabions can be used to form the core of the dune preventing extreme erosion and serving as a structure to accelerate dune development. Sand fences can also be used as a cheap way to accumulate sand faster.

Unvegetated dunes are very dynamic and can be unstable. Thus, it is recommended that a planting program be undertaken quickly after dune construction to ensure that the dune is stabilised (against wind, waves and people walking on the dune) and to increase the rate of sediment accumulation (Queensland Beach Protection Authority, 2003a). Root structures increase soil cohesion whilst above soil material can attenuate wave energy during wave overtopping (Morris et al., 2021). The Queensland Beach Protection Authority recommends planting robust salt-tolerant pioneers that can creep and grow through accumulations of sand such as spinifex grass, *Ipomoea imperati* (beach morning-glory or *strandpatat*), and sea purslane. These species have naturalised along sandy coastlines worldwide if they are not already indigenous. To avoid erosion whilst the pioneers are establishing, brush or coir matting can be laid over the sand. Once the dune has been stabilised, secondary plants like shrubs can be planted followed by tertiary plants such as trees. In addition to accumulating sediment, vegetated dunes protect nearby developments from corrosive sea spray and sand inundation (Morris et al., 2021).

Artificial dunes should be constructed from a material with a median grain size equal to or greater than that of the natural sediment. Sediment that is too small will erode quickly whilst sediment that is too big will not retain nutrients and water making it harder for vegetation to colonise. Source material should be free of clay or other materials that may affect drainage. (Queensland Beach Protection Authority, 2003b)

A challenge with designing dunes is the complexity of factors that determine the extent of the protection such as the design storm, dune dynamism, sediment characteristics, extent of vegetation and morphology of the beach (Morris et al., 2021). However, Queensland Beach

Protection Authority (2003b) and Theron & Barwell (2012) propose that the ideal dune volume can be estimated by examining erosion from pre- and post-storm surveys and other healthy dunes in the region with similar conditions. Generally, dunes should have a crest height between 6 m and 10 m above sea level (sufficiently high to prevent overtopping or breaching and allow for sea-level rise) with a seaward slope of about 1:5 and landward slope of 1:3 (Queensland Beach Protection Authority, 2003a; Theron et al., 2012). Figure 3.5 shows the design dune profile described.

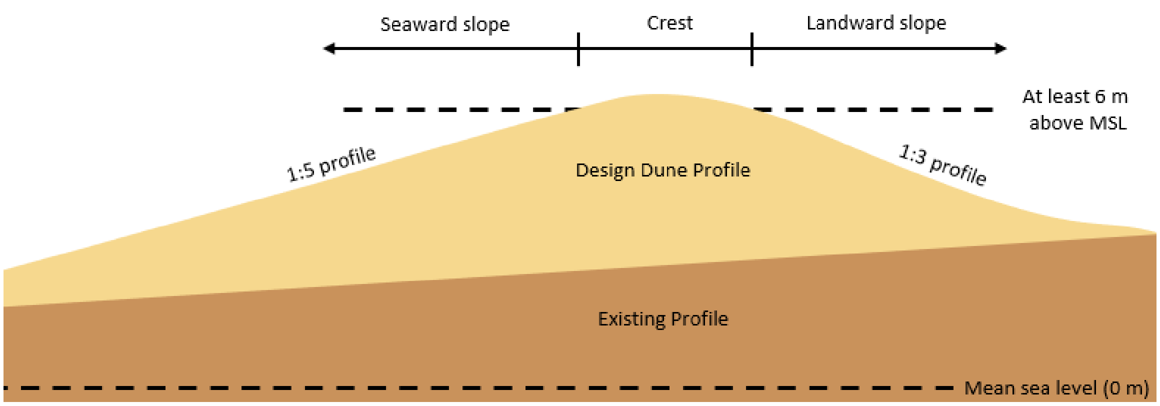

Figure 3.5 Typical artificial dune profile (adapted from Queensland Beach Protection Authority, 2003a)

The cost of dune construction will depend on the size of the designed dune and the length of the coastline. Some factors to consider when constructing dunes include site establishment, bulk earthworks, planting, fertilising, and irrigating the pioneer vegetation, fencing, footpaths, and signage. Reinforced dunes have the additional cost of reinforcement and the associated additional costs such as labour (Theron et al., 2012). Coastlines tend to revert to their natural states, so dunes may require regular nourishment to maintain their desired shape, especially after storm events (Queensland Beach Protection Authority, 2003a).

3.4.3 Salt marshes and wetlands

Salt marshes or coastal wetlands (Figure 3.6) are low-lying coastal areas that are formed by the accumulation of fine sediment. They are tidally dynamic regions regularly flooded and drained with salt water and thus are only vegetated by salt-tolerant plant species. Salt marshes are the temperate equivalent of mangrove forests, and increase in diversity of plant species as one progressively moves further from the equator to coastal waters with mean temperatures of 8 °C (Morris et al., 2020).

Salt marshes form in areas with some wave protection starting with accumulation of muddy sediment in tidal flats which builds outwards towards the sea. Once sufficient sediment has accumulated in a tidal flat, vegetation colonises the accumulated mud from the landward side and gradually stabilises the mud as the rate of tidal inundation decreases on the landward side. Once pioneer vegetation like grasses (*Poaceae*) and rushes (*Juncaceae*) have been established tidal water is attenuated decreasing the velocity and increasing the rate of sedimentation (Reeve, Chadwick & Fleming, 2018).

Figure 3.6 Salt marshes and tidal wetlands in West Coast National Park, South Africa (Prokosch, 2012)

Salt marshes are also lost due to interrupted sediment supply, exposure to harmful chemicals causing vegetation loss, rising sea levels inundating marshes, and farmland reclamation (Department of the Army, 2003; Reeve, Chadwick & Fleming, 2018). Reeve *et al.* (2018) indicate that in the UK, farmland reclaimed from salt marshes is erosion-prone and often needs hard engineering defences to be sufficiently protected. Initiatives are being undertaken in some UK communities to restore these reclaimed environments to their natural state and gradually remove the grey infrastructure (Reeve, Chadwick & Fleming, 2018). The Coastal Engineering Manual states that salt marshes can be easily created or restored by placing dredged fine material and propagating salt-tolerant species on this material. Another approach to salt marsh restoration, common in the US, includes the use of rocky sills that allows for tidal inundation but lowers the approaching wave energy, increasing sediment deposition (Morris et al., 2020).

Salt marshes are efficient at dissipating wave and tidal energy with one study estimating that salt marshes reduce wave heights by 72% in sheltered environments (Narayan et al., 2016). Another study found that artificial salt marshes increase protective capacity over time, reducing 7% of wave energy immediately after installation and 30% of wave energy after one year of establishment (Manis et al., 2015). Salt marshes are resilient to periodic extreme storms; however, they typically flourish in sheltered environments.

The Coastal Engineering Manual indicates that salt marshes provide many additional ecosystem services to shoreline protection including shoreline stabilisation, retaining water, and providing habitat and refuge for a variety of marine, bird, and animal life.

3.4.4 Mangroves

Mangroves are a variety of seventy-two shrubby tree species that fall within the Rhizophoraceae family and are the sub-tropical and tropical equivalent of tidal flats. Mangroves tend to grow in the zone between mean sea level and the highest astronomical tide although this depends on the particular species' tolerance to inundation periods (Morris et al., 2020). Mangroves do not grow well in sandy soils with low humus or organic matter content (David, Schulz & Schlurmann, 2016).

Figure 3.7 Mangrove forests in Mozambique (left) and Tanzania (right) (UNEP-Nairobi Convention & WIOMSA, 2015)

Mangroves are effective natural tools for dissipating wave energy by creating drag and low-energy environments that act as sediment traps due to their branching root structures which can be seen in Figure 3.7 (Morris et al., 2020). These semi-permeable barriers can also attenuate flood water in storm events and reduce wave heights by 20% for every 100 m the wave travels through the established forest (Mazda et al., 1997). Mangroves are two to five times more cost-effective than submerged breakwaters in attenuating waves with heights of half a metre (Narayan et al., 2016). Narayan et al. further report that this cost-effectiveness improves with increasing wave height within the natural limits of the plant.

Mangrove habitat loss can be attributed to land clearing for industrial or agricultural use and wood harvesting (Department of the Army, 2003). The Coastal Engineering Manual states that restoration of mangroves can be done by dredging and placing fine-grained material within a temporary dyke much like with salt marsh restoration. The sediment is then vegetated with mangrove seeds or nursery-grown seedlings. Once these mangroves have been established the dyke is breached to form a tidal channel. Erftemeijer, Ito & Yamamoto (2021) also experienced that mangrove forests need a protected environment in which to establish before they become effective in protecting the coastline. Care should be taken to ensure the mangroves are planted at the right tidal depth for each species to manage inundation (Erftemeijer, Ito & Yamamoto, 2021).

Because mangrove forests can accumulate sediments, they can adapt to moderate sea-level rise by building sediment upwards and landwards (David, Schulz & Schlurmann, 2016). Aside from shoreline stabilisation, protection against wave action, and preventing inundation mangroves provide important nursery and foraging environments for a variety of aquatic life, birds, and insects. Mangroves also filter and maintain water quality by absorbing excess nutrients and organic materials from upstream (Morris et al., 2021). Additionally, mangrove trees are important carbon sinks absorbing about 1.5 tonnes of atmospheric carbon per hectare per year (David, Schulz & Schlurmann, 2016).

In their 2007 study Chatenoux and Peduzzi, found literature indicating that mangrove forests can help reduce tsunami impacts. However, Chatenoux and Peduzzi did not identify any mangrove forest in continental India, Indonesia, Maldives, Sri Lanka, or Thailand that provided protection during the 2004 Indian Ocean tsunami. It was suggested that for mangrove seedlings to establish, protection from wind and wave activity is required. Hence, sites that have mangrove forest cover are already protected from the impacts of tsunamis to some extent (Chatenoux & Peduzzi, 2007). David, Schulz and Schlurmann (2016) report that there is a correlation between mangrove trunk diameter and survival rates during tsunami events, and that mangrove forests can re-establish fully within 15 to 30 years after the event.

3.4.5 Coral reef rehabilitation and protection

Found in warm (20 – 30^{o}C) tropical waters within 22.5^{o} north and south of the equator, coral reefs are one of the Earth's most diverse ecosystems providing a habitat for nearly 25% of marine species (Mulhall, 2009). Reefs offer many ecosystem services such as recreational and commercial fishing, tourism and materials for pharmaceutical products (Department of the Army, 2003; Mulhall, 2009). Coral reef restoration efforts and research primarily centres on habitat creation. However, Narayan *et al.* (2016) draw attention to the coastal protection potential of coral reefs. Upon reviewing multiple studies Narayan *et al.* (2016) estimate that coral reefs can reduce wave heights by 70% and have the greatest potential (of all soft infrastructure options) for coastal protection in high-energy environments.

Coral reefs are classified into three categories: fringing, barrier and, atoll reefs. *Fringing reefs* are shallow coral reefs that lie just below the low water level along the coasts of tropical countries and islands. This category of coral is the most widespread around the world and in the WIO. The reef grows towards the low water level surface and gradually spreads towards the open ocean. *Barrier reefs* develop parallel to the coastline separated by a lagoon. Initially, barrier reefs may begin as fringing reefs that have gradually extended to the edge of the continental shelf. Alternatively, barrier reefs may establish on an offshore shelf in shallow waters that are conducive to coral growth. Barrier reefs protect shorelines by causing waves to break offshore as can be seen in Blue Bay Marine Park in Mauritius (Figure 3.8). *Atoll reefs* are reefs that exist upon submarine mountains that were once volcanoes. The reefs may have once been fringing reefs that continued to grow and accrete towards the sea surface as the former volcano became subsided due to sinking or rising sea levels. The atoll usually encircles small islands or shallow lagoons consisting of sand and coral rubble. (Zubi, 2007)

Figure 3.8 Fringing coral reef in Blue Bay Marine Park, Mauritius that causes waves to break offshore protecting the shoreline (Google Earth, 2022a)

Coral structures are formed by a symbiotic relationship between soft tissue coral polyps and a brown alga called zooxanthellae, which lives on the calcium carbonate structure, giving the coral its colour. The zooxanthellae photosynthesise producing sugars and oxygen which the polyp uses to build its calcium carbonate structure. When environmental conditions change such as a rise in sea temperature or salinity the polyps expel the zooxanthellae which may result in the death of the coral polyp. This phenomenon is known as coral bleaching as the coral turns white when the zooxanthellae have been expel. This has resulted in corals being negatively affected worldwide by the effects of global warming.

In addition to warming oceans, corals face many threats including overfishing, destructive fishing techniques, pollution from coastal populations, irresponsible tourism, reef mining for limestone, dredging, and ocean acidification (Mulhall, 2009). This has led to a 50% reduction in coral reef cover globally since the 1950s (Eddy et al., 2021).

The US Army Corp Coastal Engineering Manual (2003) breaks down the process of coral reef restoration into two phases. The first phase is achieving the correct water quality for reefs. Factors that need consideration include salinity, temperature, water clarity, and hydrological conditions. Some actions that could achieve this are diverting sewage runoff and restoring natural flow regimes. Once the parameters have been met in the first phase, the second phase can begin with the reconstruction of the limestone substrate, if needed, and seeding of the reef with mature coral attached with cement, stainless steel wire, or nylon cable ties. Gradually small fish and crustaceans begin to occupy the reef followed by larger predatory fish. Seeding of artificial reefs with living corals has been used around the world as a method of accelerating the establishment of reefs, and it can be expected that artificial reefs reach their equilibrium state between one to five years after placement (Bohnsack & Sutherland, 1985).

Summarising the findings of previous studies Narayan *et al.* (2016) listed the two main factors that determine the efficiency of a coral reef in reducing wave height, and which should be considered in restoration projects:

- Reef width: The reef should be at least twice the width of the incident wavelength.
- Reef depth: The reef should not lie deeper than that of half of the incident wavelength.

3.4.6 Shellfish reefs

Described as 'ecosystem engineers', oysters and mussels form shellfish reefs that provide many ecosystem services (including water filtration, nutrient removal, and providing nursery habitats), and create conditions that can allow for aquatic plants and animals to thrive in temperate waters (Beck et al., 2009). Additionally, these shellfish reefs could be used as a food source and provide coastal protection against erosion for coastal communities.

Little research attention has been given to the coastal protection value of shellfish reefs when compared with dunes, salt marshes, and coral reefs (Morris et al., 2018). Beck *et al.* (2009) attribute this partly to so few natural oyster reefs remaining having lost 85% of their original habitat in the last 200 years due to destructive fishing practices, translocation of exotic shellfish, and diseases, land reclamation and dredging activities, and upstream agricultural pollution in watersheds.

One study by Piazza, Banks & La Peyre (2005) found that oyster reefs were only effective in reducing shoreline retreat in low-energy environments, although it was noted that if the studied reefs were larger they may have provided more protection in the high-energy environments. Other studies found that oyster reefs adjacent to marsh vegetation in strong periodic wave conditions like boat wakes and storms can attenuate 67% of wave energy, thus reducing the erosion and stabilising the sediment within the marsh by up to 40% (Meyer, Townsend & Thayer, 1997; Manis et al., 2015). The study by Manis *et al.* (2015) also indicated that after one year the height of the placed reef increased by 8.1 cm (due to new oyster larvae attaching to the placed oysters and the placed oysters growing larger) and attenuated more than twice as much wave energy as the original bed. This may suggest that oysters will be well suited to adapt to the effects of sea-level rise.

Oysters and mussels reproduce by releasing spawn and eggs into the water which fertilise and form larvae. The larvae remain suspended for a period before sinking to the sea floor and attaching to a hard substrate. Oysters are sessile (unable to move after settling) unlike mussels (which have some limited and slow movement) and the larvae will die if they settle on soft material. The Coastal Engineering Manual says that the primary method of encouraging oyster population growth is to increase the area of hard substrate. Appropriate substrate material includes old oyster shells, concrete, and rubble. The Coastal Engineering Manual also says that dredged material can be capped with an appropriate substrate to establish a reef that will stabilise the dredged material.

3.4.7 Seagrass

Seagrasses are flowering plants that have adapted to shallow marine and brackish estuarine environments around the world in both temperate and tropical conditions. As flowering plants or angiosperms, seagrasses reproduce sexually by producing fruit and seeds, but can also reproduce asexually from fragments of the parent plant. Seagrasses root in and draw nutrients from sea surfaces ranging from muddy to sandy. Reliant on sunlight for photosynthesis, seagrasses are typically found in water depths less than 10 m (Morris et al., 2021). When single or multiple seagrass species cover an area, an underwater ecosystem is formed called a seagrass bed or a seagrass meadow.

Depending on the density and height of seagrasses in a seagrass meadow, the seagrasses can attenuate wave energy and reduce wave run-up. Seagrass meadows also stabilise the seabed with their root structures reducing coastal erosion, and can promote sediment accretion. It was found that sites (located in continental India, Indonesia, Maldives, Sri Lanka, and Thailand) leeward of seagrass beds experienced significantly less coastal flooding during the 2004 December tsunami (Chatenoux & Peduzzi, 2007). However, the authors were not able to establish whether this was because of seagrasses dampening the wave energy or because of the bathymetry in which seagrasses occur limiting the build-up of wave energy.

Morris et al. (2021) mention that in temperate regions seagrasses senesce, or ‘die back’, during cold seasons, which may mean that the protective capacity of seagrass meadows is lost in regions in which the colder seasons coincide with stormy periods.

There are three methods of seagrass bed restoration proposed by Morris et al., (2021). The first is gathering fragments of three to eight shoots from a healthy donor site and anchoring the fragments to the seafloor at the new site. To improve the survival rate of the first method, plugs can be grown in controlled calm environments and planted at the restoration site. This method limits stress on the plant and allows for quicker colonisation due to roots structure having formed already. This method is considerably more expensive. The final method recommended for large areas requiring restoration is harvesting seed from donor sites and sowing the restoration area.

The restoration methods discussed here can be complemented with wave reduction methods by using a temporary biodegradable structure such as coir bags.

3.4.8 Kelp forests

In temperate intertidal and subtidal waters, kelp forests often form the dominant habitat which makes kelp a candidate worth investigating for natural coastal protection, especially for South Africa's temperate waters (Steneck et al., 2002). Kelps are best suited to moderate wave energy environments with adequate flow of nutrients across the fronds, but can become easily dislodged in environments with high wave energy. Research indicates that aquatic plants such as kelp may alleviate coastal erosion and flooding by creating drag-altering wave motion and reducing wave velocities in a water column in some cases (Smale et al., 2013; Morris et al., 2020).

Smale *et al.* (2013) indicate whilst there is much research into the ecosystem services of kelp forests (such as biodiversity 'engineers', primary food sources, and human products) there is limited understanding of the degree of coastal protection provided by these habitats. Dubi and Torum (1997) found that in waters less than 10 m deep, up to half of the wave energy can be dissipated if the density is 12 plants per m^2. One study found that one species of kelp (*Ecklonia Radiata*) had a negligible effect on wave attenuation and has appeared to have evolved to move passively with the wave cycles and minimises overall water column drag (Morris et al., 2020). It was noted in this study however that the kelp investigated was in water depths of at least 10 m and that the proportion of kelp made up less than 10% of the water column. Another study proposed that kelp has higher wave attenuation and drag in shallow waters where it constitutes a greater proportion of the water column (Mork, 1996). Furthermore, the density and extent of kelp affect the degree of wave attenuation by kelp forests (Gaylord, Rosman, Reed, et al., 2007; Jackson, 1984).

The best practice of establishing a kelp forest has not been established although success has been achieved by transplanting juvenile or mature kelps from donor sites. In one case study, a locally extinct species was reintroduced to Sydney Harbour, becoming self-sustaining in one generation (Morris et al., 2021). Kelp plants can also be propagated sexually or asexually in situ or in laboratories and released to the environment being restored.

3.5 Grey coastal defence techniques or hard engineering solutions

Table 3.2 summarises some of the benefits and disadvantages of hard engineering that are common to many of the techniques discussed in this section.

Table 3.2 Advantages and disadvantages of hard engineering

(Sutton-Grier, Wowk & Bamford, 2015; Morris et al., 2018; Schoonees et al., 2019)

Benefits	**Disadvantages**
Comprehensive guidelines developed over decades	Does not adapt to change (needs to be modified)
Comprehensive understanding of all the functions and applications	Generally, more expensive than soft engineering over the long term
Defends immediately after completion	Strength weakens over lifecycle
Uses less space than soft engineering	Can provide a false sense of security
Easy to quantify cost-benefit (if only considering financial cost-benefit and ignoring social and environmental cost-benefits)	Habitat loss and negative ecosystem changes
	No benefits accrued during mild weather

Although grey infrastructure is often the conventional option, there are substantial social and ecological costs with hard engineering solutions which are not always considered in project planning (Morris et al., 2018).

The following examples of hard engineering structures are summarised from the Coastal Engineering textbook by Reeve *et al.* (2018) unless noted otherwise.

3.5.1 Breakwaters

Breakwaters are nearshore structures that shelter coastlines from wave energy and thus limit erosion effects or create protected conditions for harbours (Elsafti et al., 2019). The structures are usually constructed of rock or armour units which need heavy equipment to transport and place the materials, making the process expensive. Breakwaters can be useful in dissipating wave energy in all wave energy environments, but they are not efficient in combatting rising sea levels and are costly in terms of installation and maintenance. Two types of breakwaters are classified depending on their connection to the coastline.

a) Attached breakwaters

Attached breakwaters differ from groynes (refer to Section 3.5.5) in that they are lone structures that usually stretch out much further into the sea. Thus, breakwaters have a larger effect on waves, currents, and longshore transport than groynes. Attached breakwaters are used to create sheltered bays for harbours as seen in Figure 3.9 for Coega Port in South Africa.

Figure 3.9 Coega Port breakwater (Google Earth, 2022b)

b) Detached breakwaters

Detached breakwaters are offshore structures designed to break waves away from the shoreline but allow gentle currents and sediment to move between the breakwater and shoreline. Thus, sediment tends to collect on the lee side forming a tombolo (when sediment extends and attaches the land to the breakwater) or a salient (when sediment extends from the land but does not connect to the breakwater, as seen in Figure 3.10).

Figure 3.10 Detached breakwater at Norfolk Beach (Virginia, US) with salients forming leeward of the breakwater (Google Earth, 2019)

Another type of detached breakwater is an artificial reef which is a submerged breakwater that causes waves to break and disperse energy offshore and decrease the wave height thus protecting the shoreline. Finally, there are floating breakwaters which are low-cost structures that float and thus accommodate tidal changes but are only appropriate in low-energy environments.

3.5.2 Sea walls and revetments

Seen as the last defence, sea walls and revetments are hard structures that form a barrier separating the sea and land thus preventing erosion and flooding. Sea walls should ideally be located as far back from the sea as possible to allow the coast to change and adjust naturally. These structures must be designed to dissipate as much wave energy as possible. Depending on desired structural characteristics (such as longevity, cost, and environmental impact) sea walls and revetments can be constructed using a variety of materials including stone, concrete, and timber. The cost of rock structures is dependent on proximity of, and access to the available rock.

In emergencies, revetments are often constructed with geotextile sand containers (or sandbags) and gabions, being affordable and quickly implemented coastal protection responses that are easily reversible. Sandbags and gabions can also be incorporated in hybrid coastal infrastructure as a ‘sleeping defence’ revetment within a dune. If during extreme storms the dune ‘shell’ erodes, the sleeping defence can mitigate further erosion. Both materials have a limited lifespan of a few decades at most, due to not being suited to the corrosive sea environment, but they can last longer in a ‘sleeping defence’ structure.

3.5.3 Perched beach structures

A perched beach is an uncommon defence structure consisting of a submerged or emergent sill that is constructed in the intertidal or beach zone and is intended to increase the beach profile by retaining more sediment than would be naturally retained on the landward side of the sill. Figure 3.11 illustrates an example of a submerged concrete sill retaining a perched beach which extends the beach profile seawards. Sills may also disperse wave energy by reducing the wave depth against a hard structure away from the shoreline. Challenges with sills include that they can create dangerous swimming conditions, and may not be effective in treating all cases of coastal erosion.

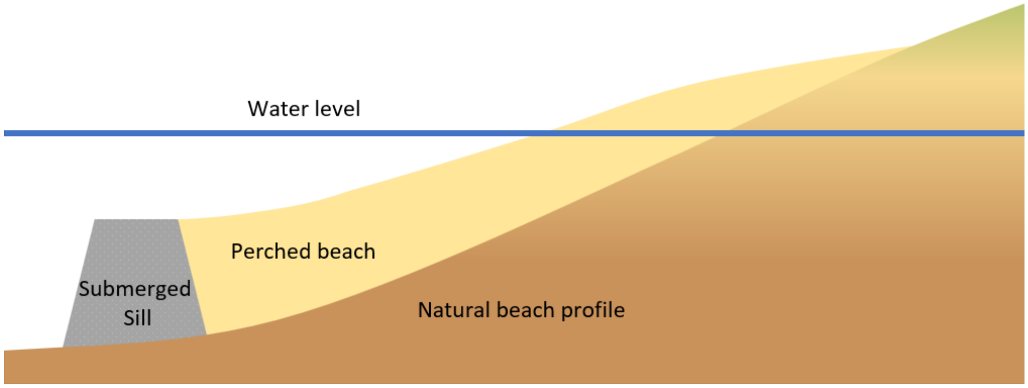

Figure 3.11 Profile of a submerged sill retaining a perched beach

3.5.4 Dykes

(Adapted from Coastal Engineering Manual and Theron & Barwell, 2012)

Dykes are large earthen mounds that form the barrier between the sea and the land to protect low-lying areas from inundation. Usually, dykes have sandy cores with a watertight outer layer. Depending on the design, dykes can include armouring on the seaward side and/or vegetation. Due to their size and volume dykes are expensive and not easily integrated into existing built-up environments. Dykes need to be continuous to effectively defend infrastructure, and allowance should be made for removing trapped water that has breached the dyke or has flooded on the landward side (i.e., rainwater flooding). Figure 3.12 shows a dyke along the Nederrijn River (part of the Rhine) in the Netherlands protecting low-lying land.

Figure 3.12 Nederrijn River dyke in the Netherlands (Cormont, 1995)

3.5.5 Groynes

Groynes are impermeable or semi-permeable structures built at intervals perpendicular to or at an angle to the shore, to trap sediment (cause accretion) on the updrift side of the groyne thereby reducing wave energy. Groynes indirectly protect coastlines by trapping sediment which is what buffers land from the sea. A small area of erosion can occur on the downdrift side of the groyne as illustrated by Figure 3.13 of the groynes in Richards Bay. By extending groynes beach areas can be widened. Some disadvantages of groynes include strong rip tides parallel to the groynes and loss of cross-shore sediment.

Groynes are typically made from concrete, stone, or wood.

Usually, groynes are implemented with either a once off or a regular beach nourishment program. Thus, whilst groynes themselves are considered to constitute grey infrastructure solutions; they are often used in a hybrid infrastructure project with beach nourishment. Additionally, of the grey infrastructure options, groynes are among the more economically and environmentally inexpensive options.

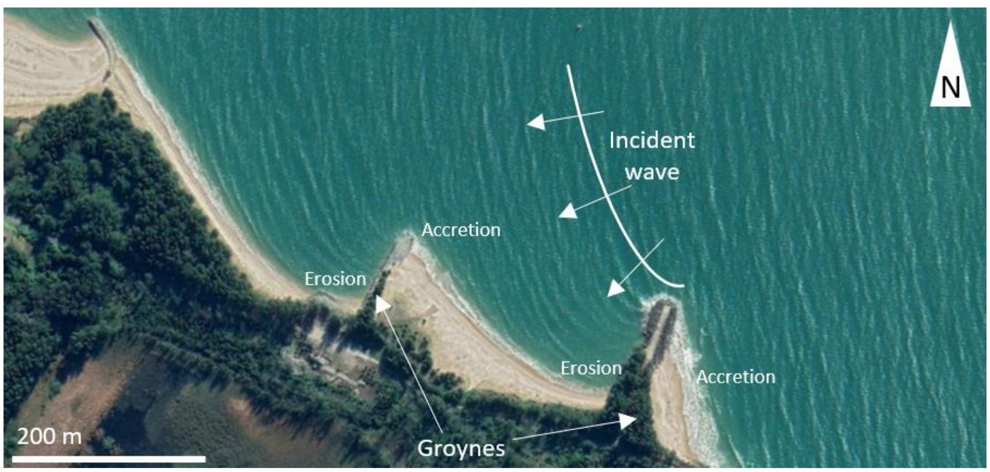

Figure 3.13 Groynes in Richards Bay South Africa (Google Earth, 2020a)

3.6 Eco-friendly hard infrastructure

Eco-friendly hard infrastructure entails hard infrastructure that incorporates solutions to improve biodiversity and improve natural habitats to make them "greener." This includes existing hard infrastructure that is retrofitted, or new hard infrastructure projects that include habitat enhancement in their design. Whilst the additional natural solution may provide some defensive capacity, the underlying hard infrastructure usually is not reliant on it as it should be designed to adequately defend the coastline on its own. (Section 3.7 discusses hybrid coastal infrastructure that combines the defensive capacity of both hard and soft infrastructure). Hence, the focus of this approach is to create more sustainable marine built environments especially when the grey infrastructure cannot be completely replaced with green solutions (due to space constraints, for example) (O'Shaughnessy et al., 2020). Furthermore, the objective is to add to the defensive functionality by improving the ecological value of hard infrastructure (O'Shaughnessy et al., 2020).

Greening existing grey infrastructure is a relatively new concept, and more experimentation needs to be done, shared, and critically evaluated before eco-friendly hard infrastructure can be considered for mainstream solutions (Firth et al., 2020; O'Shaughnessy et al., 2020). However, most current examples of eco-friendly infrastructure take inspiration from rock pools and reefs, and try to mimic these habitats on otherwise barren grey defence infrastructure with little marine biodiversity, so that the defence structures can then offer additional benefits other than just storm protection (Sutton-Grier, Wowk & Bamford, 2015).

Many examples of eco-friendly hard infrastructure have been experimented with and studied in the literature. However, only a few examples are briefly explored in this study in order to illustrate the concept of eco-friendly hard infrastructure.

3.6.1 Water retaining "flowerpots"

An example of eco-friendly hard infrastructure is the addition of water-retaining features by attaching "flowerpots" to seawalls. The 30 cm deep "flowerpots" are attached to the seawall with stainless-steel brackets as seen in Figure 3.14. The design intends to simulate rock pools by being submerged at high tide and retaining water during low tide providing refuge for species that could not otherwise colonise the seawall (Strain, Morris & Bishop, 2017).

A study by Browne & Chapman (2011) found that over seven months the pots provided habitat for 25 new species (including species typically found in rock pools like fish, starfish, and algae) not found living along the seawall before the pots were installed. During experiments by Strain, Morris & Bishop (2017) in sheltered areas, the "flowerpots" filled with and retained a lot of sediment, and it was not clear if this was of positive value. Other challenges included the loss of pots in high-energy wave areas due to difficulty attaching the pots to seawalls. Hence, it would be better to build the pots into seawalls from the planning stages. Furthermore, the metal straps may be prone to theft and vandalism.

Figure 3.14 "Flowerpots" attached to a seawall in Sydney Harbour (Strain, Morris & Bishop, 2017)

3.6.2 Living Seawall panels

Another example of seawall habitat enhancement is Living Seawalls by Reef Design Lab. Living Seawalls are "modular habitat panels" that are attached to otherwise flat seawalls creating a complex surface that increases natural biodiversity and creates novel micro habitats like those found in crevices in a rockpool (Strain, Morris & Bishop, 2017). The concrete panels are cast from 3D printed moulds and come in ten different designs which are attached by bolting to the seawall as seen in Figure 3.15. More information can be found at www.livingseawalls.com.au.

Strain, Morris & Bishop, (2017) found that oysters have a better rate of survival on the complex and creviced surfaces of the Living Seawall than on flat seawalls due to being able to retreat from predatory fish. Furthermore, the crevices were cooler and retained moisture resulting in more colonisation of both sessile and mobile invertebrates.

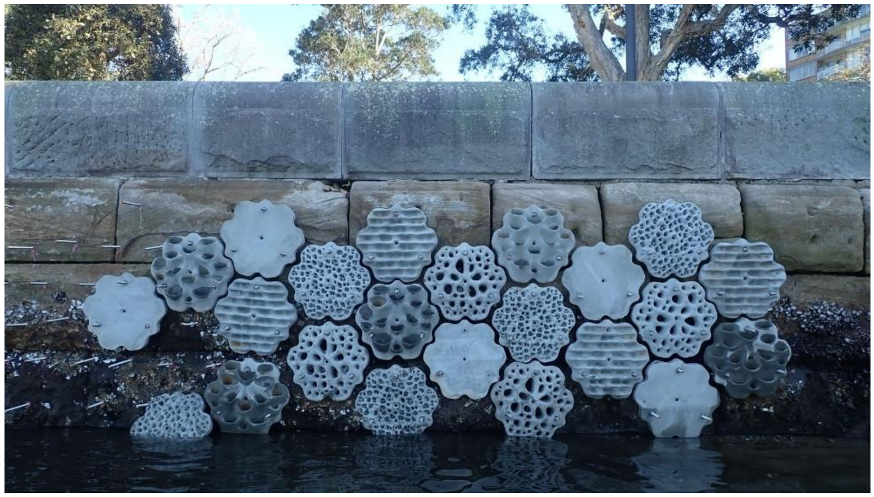

Figure 3.15 Living Seawall panels in Rushcutters Bay, Sydney (City of Sydney, 2020)

Borsje et al. (2011) found comparable results when experimenting with the textures of concrete surfaces in the intertidal zone. In their experiment, grooved and holed surfaces that retained water during low tides were colonised by green algae and eventually mussels, periwinkles, and barnacles. Thus, the study concluded that modifying the surface textures of grey infrastructure like revetments, seawalls, and groynes can result in improved productivity and biodiversity without compromising hinterland safety.

3.6.3 Seashell-shaped artificial armour units

In 2019, Elsafti et al. investigated an innovative design of large seashell-shaped units, called *SeashellBreakwater*, for placement on top of rubble mound breakwaters. The units were an enlarged form of the *Cerastoderma edule* or common cockle which has evolved to have a hydrodynamically streamlined shell with low wave drag. The study found that the shape and regular layout of the units dissipated wave energy effectively by causing wave breaking as well as diverging and converging the flow between units. Additionally, the authors said that the semi-spherical shape contributed to unit stability and thus mitigated the need to make the units interlocking which is required in many other rubble mound structures. This reportedly also made the installation and maintenance of the units easier and quicker than interlocking units (like dolosse). The study concluded that the units were able to reduce wave drag by 2.5 times with a two-deep shell arrangement as seen in Figure 3.16.

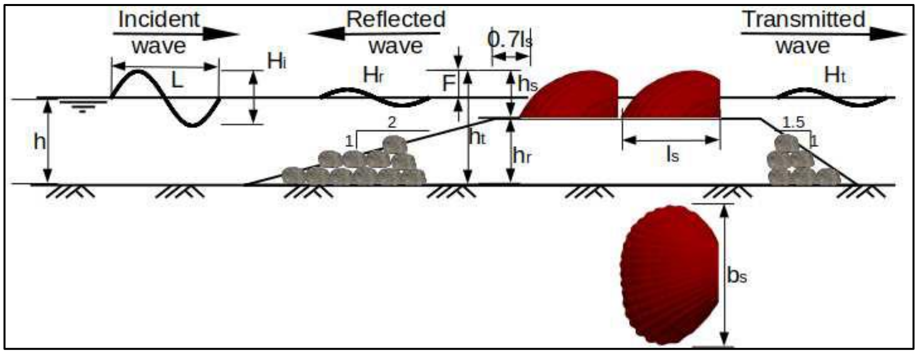

Figure 3.16 Cross-section of rubble mound topped with SeashellBreakwater (Elsafti et al., 2019)

This design is an example of biomimicry (which uses nature as inspiration for the design) rather than eco-friendly engineering. Due to the wave-energy-dispersive shape of the seashell units, the rubble mound height needed is less. This reduces the volume of the rubble mound and its environmental impact.

3.6.4 Modular coral-shaped artificial reef

Traditional detached breakwaters are effective at damping offshore wave energy, thus protecting and stabilising beaches. However, detached breakwaters are ineffective in providing ecosystem services, and often have negative environmental impacts (Mendoza et al., 2019). Thus, Mendoza et al. (2019) investigated another example of biomimicry, the development of modular coral-shaped units that can be incorporated into the design of detached breakwaters so that the hydrodynamic and ecological performance of coral reefs can be replicated on breakwaters.

The researchers took a modular coastal protection element previously developed at UNAM, Mexico, digitally added, and 3D printed three designs of *Acropora palmata* coral shape. The three designs were developed to suit on the location of the breakwater. The seaward elements had short branches, the crest elements had longer branches and the leeward elements had the longest branches. Figure 3.17 shows a model of the breakwater using the original element shape and the three new coral element shapes.

Mendoza et al. (2019) found the structure to be effective in dissipating wave energy by bottom friction and triggering wave breaking. Comparing the laboratory models with natural corals Mendoza et al. (2019) found that the breakwater had similar if not higher damping potential.

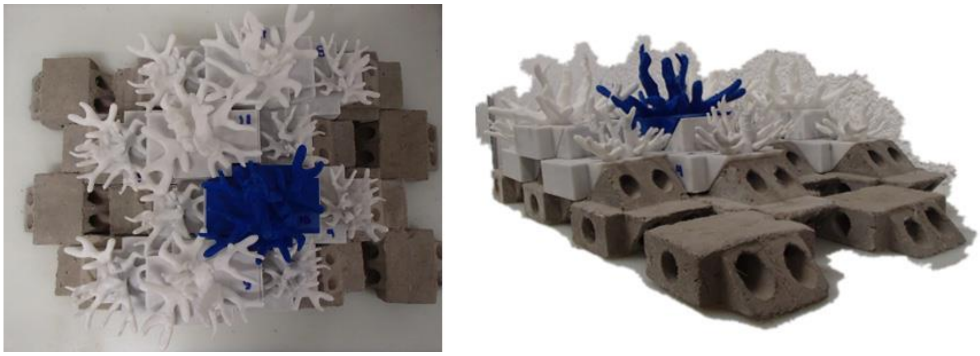

Figure 3.17 Modular coral shaped artificial reef (Mendoza et al., 2019)

The study did not investigate the habitat potential of the artificial coral reef units, but the researchers envisaged that the structure would provide a habitat that would be readily colonised by native marine organisms. It was not clear from the study whether the slender arms made use of internal reinforcement and how this may affect the longevity of the solution. This longevity will need to be evaluated before the artificial coral reef can be used on a large scale.

3.6.5 Reef balls

Reef balls, as seen in Figure 3.18, are modular concrete units shaped as hollow hemispheres with several holes in their walls. The hollows and holes mimic the natural refuge and habitat of marine life in natural coral reefs (David, Schulz & Schlurmann, 2016). When placed in multiple parallel rows, the units form submerged breakwaters that also function as artificial reefs thus providing coastal protection with the biological benefits of reef habitats. However, the units need to be spaced close to one another in tight offset rows with the crest of the units near the surface so as to sufficiently disperse wave energy. Otherwise, wave energy will simply move through the interspaces or above the units without much dispersion.

Figure 3.18 Reef Ball units in-situ and artificially colonised (photos from www.reefball.org)

The surface of the units provides a substrate to which benthic organisms can attach and colonise. This enables corals to develop in locations that they would not ordinarily grow, like abrasive sandy seafloors (Meesters, Smith & Becking, 2015). As corals do not usually grow in the locations where the reef balls are used, Meesters, Smith & Becking (2015) propose that coral colonisation is encouraged by re-stabilising (where broken matured corals are attached to the units) or by propagating (harvesting of small fragments of coral and attaching them to the units).

On their website (at www.reefball.org) it is said that suitable locations should meet the following criteria:

- Tidal variation should be less than 2 m.
- The reef crest should be below the biological tide line (the shallowest depth that permanently submerged marine life grows).
- The reef should be placed in shallow waters to minimise the reef width (deeper waters are possible but will require greater reef widths to provide the same level of protection)
- The units need to be suitably anchored for at least 1 in 50 storm events.

3.7 Hybrid coastal defence infrastructure

Hybrid coastal defence infrastructure is an approach in which both green and grey infrastructure are incorporated simultaneously in the design phase of coastal defence. It differs from eco-friendly hard infrastructure in that it is not a retrofitted solution, or an ecologically friendly 'shell' added to green hard infrastructure but rather an incorporation of the defensive capabilities of both grey and green infrastructure.

Hybrid infrastructure offers potential for innovation to combine existing green and grey infrastructure approaches in new ways to maximise coastal protection (Gedan et al., 2011). The combination of approaches allows coastal communities to gain the positive characteristics of both approaches such as the defence service provided by the hard coastal infrastructure and additional benefits of ecosystem services and self-maintenance (Gedan et al., 2011; Sutton-Grier, Wowk & Bamford, 2015).

Another benefit of hybrid infrastructure is that the grey infrastructure provides immediate short-term protection whilst the green infrastructure matures (Bouma et al., 2014). Conversely from a long-term perspective, green infrastructure can provide adaptive protection to changing conditions like sea-level rise which grey infrastructure cannot.

Table 3.3 summarises some advantages and disadvantages that are often associated with hybrid coastal infrastructure projects.

Table 3.3 Advantages and disadvantages of hybrid engineering

(Sutton-Grier, Wowk & Bamford, 2015)

Benefits	**Disadvantages**
Combine the best characteristics of grey and green infrastructure	Limited examples and data of previous performance
Allows for innovation in coastal protection	Limited expertise to implement
Benefits additional to coastal protection like ecosystem services	Limited information for cost-benefit analysis
Provides greater confidence than just natural defences	Does not provide all the ecosystem services of green infrastructure
Smaller footprint than just natural defences	More challenging to motivate clients and/or authorities

Sutton-Grier, Wowk & Bamford (2015) explains that hybrid infrastructure intends to use natural infrastructure as the first defence to lessen the overall defensive capacity need for grey infrastructure as the second defence. Because the green protection absorbs some of the storm energy, the capacity of grey infrastructure can be smaller.

The greatest challenge with hybrid defence is that it is a novel approach with only a few recently implemented projects. The result is that not much data exists on the long-term effectiveness or the cost-to-benefit ratio. Yet, there is a growing appetite from cities and communities to adopt examples of hybrid defences due to the novel approaches to adapting to climate change and rising sea levels whilst enjoying co-benefits like recreational opportunities and greener urban living options (Sutton-Grier, Wowk & Bamford, 2015). This is especially the case in regions where green infrastructure alone is not an appropriate option (Morris et al., 2018).

The rest of this section illustrates some examples of combinations of hybrid infrastructure projects.

3.7.1 Oyster reefs and seawalls

In New York, the Billion Oyster Project has had widespread success in installing oyster reefs around grey infrastructure (like bulkheads and gabions) at 14 sites (Firth et al., 2020). The Billion Oyster Project is also currently involved in the Living Breakwaters project found off the south of Staten Island which aims to reduce coastal risk and create and restore marine habitat by integrating breeding oyster reefs into the design of new offshore breakwaters. More information can be found at www.billionoysterproject.org.

Morris et al. (2018) also propose shellfish reef placement in front of a seawall as a hybrid defence. The oysters would be the first line of defence prolonging the seawall lifespan. If the oyster reef is damaged by a storm the seawalls serve to protect landward infrastructure after the reef re-establishes.

Sutton-Grier, Wowk & Bamford (2015) illustrate two theoretical examples of hybrid coastal infrastructure of relocating: a seawall and incorporating oyster reefs for defence as seen in Figure 3.19. The first option involves moving the seawall and establishing a salt marsh and oyster bed. The second option suggested is to move the seawall inland and include a flood gate which can be closed during extreme storm events. Natural defences, moving seawards, include a salt marsh, an oyster bed, and an offshore barrier island. In both cases, the green coastal defence should be sufficient to protect against small and medium storms whilst, for large storms the grey infrastructure offers more protection necessary for extreme storm events.

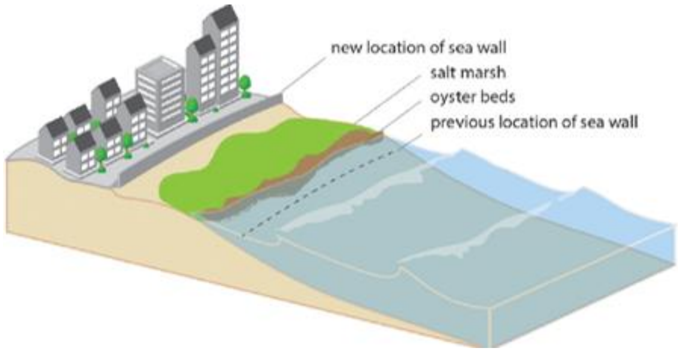

Figure 3.19 Hybrid defence with seawall, salt marsh, and oyster beds (Sutton-Grier, Wowk & Bamford, 2015)

After hurricane Sandy coastal communities in New York, like Howard Beach, are considering using the hybrid approaches, outlined by Sutton-Grier, Wowk & Bamford, using berms, salt marsh restoration, and oyster reefs with moveable flood gates that are only utilised when extreme storms are likely to overwhelm green protection (UWAS, 2013; Schoonees et al., 2019).

Oyster domes, seen in Figure 3.20, are another example of prefabricated concrete units that can be used in breakwater structures, berms and, salt marsh edges to aid wave dispersal and create a benthic habitat which further increases the protective capacity of breakwaters (Gedan et al., 2011; UWAS, 2013).

Figure 3.20 Oyster domes placed along a coastline in Florida (Parsons, 2017)

3.7.2 Salt marshes and seawalls or dykes

Sutton-Grier, Wowk & Bamford (2015) also reported that some communities in the UK are moving their grey coastal defences, like seawalls or dykes, inland after cases of failure. The land, usually agricultural, seaward of the new wall is acquired and converted into natural coastal ecosystems like salt marshes which buffer the new defences from the sea. The outcome is that coastal erosion is acknowledged, and communities are retreating enough to create natural buffers that complement the new grey infrastructure. This is seen as a more cost-effective and sustainable way of dealing with sea-level rise as opposed to rebuilding or raising the level of the old grey infrastructure (Chadwick, Morfett & Borthwick, 2013; Sutton-Grier, Wowk & Bamford, 2015). Due to the perception that this method is 'giving up' valuable land to the sea, it is often met with public resistance, and thus for projects to be successful public and stakeholder engagement is very important (Waryszak et al., 2021). Whilst some land has been sacrificed, habitats have been enlarged, thereby increasing natural coastal biodiversity in these communities (Chadwick, Morfett & Borthwick, 2013).

Figure 3.21 Examples of salt marsh with a seawall in the United Kingdom (left by Chadwick, 2012) and salt marsh with a dyke in the Netherland (right by van Belzen, 2017)

3.7.3 Vegetated revetments

UWAS (2013) advocates creating "living shorelines" in which hard infrastructure elements like breakwaters, berms, and revetments are vegetated. Vegetation stabilises banks, provides some defence, and improves the urban environment creating valuable natural habitats. The benefit of this hybrid approach is especially clear in urban environments, like New York, where space is limited, preventing full natural restoration but still gaining the benefit of coastal defence as well as some of the ecosystem services associated with green infrastructure.

3.7.4 Mangroves with permeable walls

Juvenile mangrove plants are vulnerable to the forces of the sea and often require more protection initially to allow the plants to reach maturity. Therefore, mangrove restoration projects often use a hybrid approach whereby a permeable seawall is placed seaward of newly planted mangroves. The seawall controls the hydrodynamic conditions of the contained area and improves the conditions for the development of juvenile mangrove plants (Waryszak et al., 2021). Figure 3.22 shows such a project in Vietnam where a permeable bamboo wall was built to attenuate high wave energies and promote sediment accumulation in the newly planted area (Thieu Quang & Mai Trong, 2020). Once the bamboo fence begins deteriorating the mangroves will have matured enough to withstand the forces of the sea.

Figure 3.22 Permeable bamboo fence protecting a newly planted mangrove forest in Vietnam
(Thieu Quang & Mai Trong, 2020)

Another variation of the Reef Ball, discussed in Section 3.6.5, also created by the same organisation is the Mangrove Reef Ball. The units have a similar shape to Reef Ball units, and they are filled with material in which mangrove propagules are planted. The structure is intended to protect the roots of propagules in harsh environments and improve the survival rates of the plants. Once the mangroves have matured, they no longer need the protection provided by the Mangrove Reef Ball and therefore there is also a possibility to make the reef ball structure with a biodegradable material that will 'wash away' as the mangrove matures.

Figure 3.23 Mangrove Reef Ball in the Cayman Islands (photo from www.mangrovesolutions.com)

The Mangrove Reef Ball also allows for a larger planting area as the mangrove propagules can be planted in deeper waters (about 2.5 m below high tide). According to the Mangrove Reef Ball website (www.mangrovesolutions.com), they are useful in locations where natural mangrove recolonization has been compromised due to hydrological changes.

3.7.5 Groynes and shore nourishment

One of the most common hybrid coastal defence combinations is that of groynes and shore nourishment. The combination is a good one as groynes are intended to slow the longshore transport of sediment causing net accretion which means that nourished sediment (i.e. additional artificially placed or pumped sand) will be retained for a longer period (Corbella & Stretch, 2012). This reduces the frequency needed for maintenance nourishment along beaches that require regular artificial placement of sand. Figure 3.24 shows a frame from a video by TNPA of a targeted beach renourishment project in the Durban groyne field.

Figure 3.24 Example of beach nourishment along a groyne field in Durban (extracted from video by TNPA, 2018)

3.7.6 Sleeping defence

One final example of a hybrid coastal defence is building a dune over a hard engineering structure like a revetment or seawall as illustrated in Figure 3.25. The intention is that the dune will respond to coastal processes like feeding the beach during erosional periods or accumulating excess beach sediment during periods of accretion. However, in an extreme erosion event when the dune sediment is depleted the "sleeping" structure within the dune is exposed and prevents further inland erosion of the coastline. "Sleeping" revetments can use materials that usually perish in the coastal environment like geotextile sandbags (that perish from UV exposure or are damaged by vandalism) or rock-filled gabions (that are prone to corrosion due to sea spray) because the materials are only exposed for short periods before being covered again after the storm. Visually, this combination appears natural as the revetment is hidden by the dune most of the time.

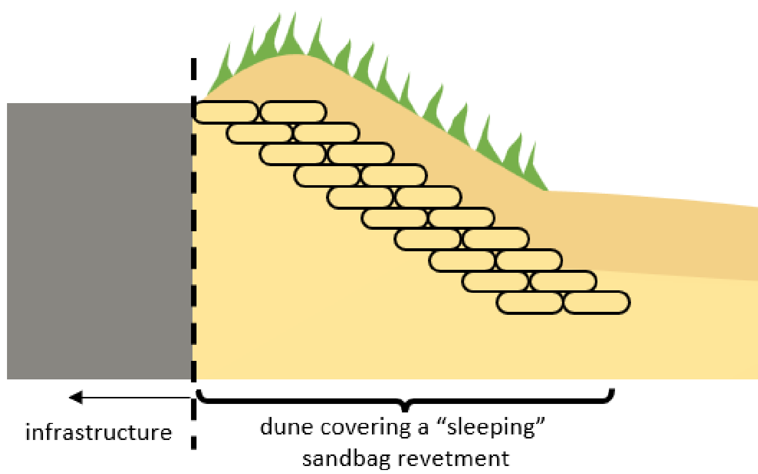

Figure 3.25 Cross-section of a geotextile sandbag revetment acting in a "sleeping" defence under a vegetated dune

3.8 Method of Evaluating Coastal Defence and Protection

3.8.1 Identifying vulnerable coastlines - Coastal Vulnerability Index

A Coastal Vulnerability Index, CVI, is a method of quantifying the relative tendency of a coastline to be affected or damaged by coastal hazards on a regional to national scale due to the properties of a coastline that have been identified as indicators of vulnerability (Thieler & Hammar-Klose, 1999; Palmer et al., 2011). The vulnerability indicators of the CVI also serve as a useful and objective tool for identifying and monitoring vulnerability changes over time which can help develop and evaluate protection strategies (Rygel, O'Sullivan & Yarnal, 2006). Each variable is ranked in its extent towards coastal vulnerability usually on a scale from one (very low vulnerability) to five (very high vulnerability). Many practical applications of CVI exist in the literature being a method that has been refined and adapted in terms of parameters specific to the applied coastal regions.

Gornitz & White (1992) compiled a database for the eastern coast of the US of seven coastal risk variables which they had identified as contributors to coastal vulnerability: elevation, geology, geomorphology, sea-level rise trends, shoreline erosion, tidal ranges, and maximum wave heights.

This database was used by Thieler & Hammar-Klose (1999) in devising one of the first examples of a ranked coastal vulnerability index. In their study of the coastal vulnerability of the US coast along the Gulf of Mexico, Thieler & Hammar-Klose (1999), considered the following criteria; geomorphology, relative sea-level change, rates of erosion (or accretion), mean tidal range and mean wave height. From Gornitz & White's database, Thieler & Hammar-Klose changed coastal elevation to coastal slope and omitted the variable considering geology. Each variable is assigned a vulnerability ranking from one to five based on increasing vulnerability. The complete CVI can be found in Table A.1.

Thieler & Hammar-Klose used the following equation to calculate the net CVI value by taking the square root of the multiple of the six rankings divided by six.

Equation 3.1 Net CVI (Gornitz & White,1992)

$$CVI = \sqrt{\frac{a \cdot b \cdot c \cdot d \cdot e \cdot f}{6}}$$

Where a to f are each a variable.

The range of CVI values is determined for the sections of coastline studied and then divided into four quartile ranges of relative vulnerability: low (>8.7), moderate (8.7-15.6), high (15.6-20), and very high vulnerability (<20). This study stresses that the CVI values cannot be directly equated to a physical effect, but are rather an indication of which areas are relatively more vulnerable than others.

Coelho et al. (2006) performed a coastal vulnerability analysis of the Portuguese coastline considering the following six parameters from Gornitz & White (1992): elevation above chart datum, tidal range, maximum wave heights, erosion and accretion, geology, geomorphology. To these six parameters, Coelho et al. added distance to shoreline, ground cover, and anthropogenic shoreline interventions. Table 3.4 summarises the vulnerability ranking used by Coelho et al. (2006). The study by Coelho et al. (2006) also experiments with the relative importance of each vulnerability by applying a weighting factor to account for variables that may have a greater or lesser impact than others on overall vulnerability. In the first weighting case, all parameters are considered equally with a multiplication coefficient of 1. The net CVI is divided by the sum of the coefficients, 9 in this case. In the second weighting case, ground cover and tidal range are halved in importance (by multiplying the vulnerability with a coefficient of 0.5). Distance to shore and geology are doubled in importance (by multiplying the vulnerability with a coefficient of 2). The net CVI is divided by the sum of the coefficients, 10 in this case. In the final weighting case, all the parameters are ranked in terms of importance and assigned a corresponding weighting coefficient 1 to 9. The net CVI in this case is divided by 45 (sum of 1 to 9).

Table 3.4 CVI weighting parameters by Coelho et al. (2006)

Vulnerability	Weighting of Vulnerability		
	Case 1	Case 2	Case 3
Elevation	1	1	7
Distance to shore	1	2	8
Tidal range	1	0.5	2
Max wave height	1	1	5
Erosion and accretion	1	1	3
Geology	1	2	9
Geomorphology	1	1	4
Ground cover	1	0.5	1
Anthropogenic actions	1	2	6
Total	9	10	45

In their coastal vulnerability study of the Southern African coastline, Theron et al. (2010) and Theron (2016) chose to work with the Coelho et al. (2006) study as it is well suited to the Southern

African context. However, three additional variables relevant to the Southern African coast were added; degree of protection from prevailing waves, sea-level rise (in terms of erosion potential determined by Bruun's rule), and relative height and volume of the foredune. Furthermore, in tropical regions like Mozambique, the vulnerability to cyclones (number per year), and coral and fringing reefs (percentage of shore length) are also included. The complete CVI is found in Appendix A.

One will notice that the greater the percentage of coastline that is reef the greater the risk score. Initially, this may appear counter-intuitive, however, Theron (2016) explains that this 'inverse' scoring of fringing reefs is because coral reefs in Mozambique are likely to deteriorate with climate change, and thus locations currently 'reliant' on their protection are at greater risk once the fringing reef is lost.

In 2011, Palmer et al. conducted a CVI study of the KwaZulu-Natal coast. To limit the scope of the study the vulnerability parameters were limited to five easily measurable parameters (which could be determined from 'geometrically corrected' aerial photographs) including beach width, dune width, rocky outcrop percentage, vegetation width behind the beach, and distance from the 20 m isobath. The variable characteristics were ranked by the extent of their associated level of risk from one (extremely low) to four (high) as seen in Table A.6.

An additional vulnerability score was given to estuarine environments. If environments scored high vulnerability for multiple variables, they are also assigned an additional vulnerability score. The relative CVI is simply the sum of each of the vulnerability rank scores. The benefit of the approach by Palmer et al. (2011) is that it is not reliant on detailed records and surveys which may be challenging to source for some regions that have not kept such records. Palmer's method can use satellite imagery if that is all that is available. This makes the method useful in developing nations that do not have access to long-term records of data and extensive coastal surveys.

Musekiwa et al. (2015) combined CVI variables from various sources including Thieler & Hammar-Klose (1999), Coelho et al. (2006), and Palmer et al. (2011) in their study of the South African coastal vulnerability. Beach geomorphology was adapted from a study by Harris, Nel & Schoeman (2011) examining the resilience different beach forms have against wave energy. Table A.4 shows the variables and their vulnerability ranges used by Musekiwa et al. (2015).

Zhu et al. (2019) proposed a multi-criteria index when assessing the Xiamen city coastline in Southeast China. The index is made up of twelve indices including seven natural vulnerabilities and five socio-economic vulnerabilities. The grouping of natural disasters is subdivided into coastal characteristic vulnerabilities (geomorphology, elevation, slope, habitat type, and buffer ability) and extreme event vulnerabilities (storms, and significant wave height). The socio-economic vulnerabilities are divided into coastal infrastructure (population activity, building value, and road value) and capacity to respond to disasters (GDP per capita, and fiscal revenue). This breakdown of vulnerabilities allowed the researchers to determine a more refined and comprehensive vulnerability score for each subcategory (like coastal characteristics or infrastructure), the natural and socio-economic groupings, or a global vulnerability score when all the subcategories were added together. This required some complex weighting factors to be applied for each permutation which will not be covered in this study. Readers can refer to Zhu et al. (2019) if interested in the weightings used.

Additional Considerations of CVI

Visual presentation of the CVI on a map helps to show the relative potential vulnerability of segments to sea level rise (SLR) along a coastline, and can be a useful tool for guiding coastal policy (Hamid et al., 2019).

The coastal vulnerabilities considered in the CVI analysis depend on what data is available in a region rather than what would ideally be available (Hamid et al., 2019). This may be a challenge in developing countries that may not have access to resources to collect coastal data and records of historical aerial photography such as Mozambique (Theron, 2016). To address this challenge the vulnerability parameters used can be adapted like in the case of Palmer et al. (2011) which only relies on satellite images of the study region.

While Landsat records may be freely available, a spatial resolution of greater than 30 m is not accurate enough to measure shoreline characteristics and changes like erosion and accretion (Theron, 2016). Only high-resolution historic aerial photography and/or LIDAR with enough resolution and consecutive images are sufficient to accurately determine the erosion rate. This should be complemented or verified with in-situ investigations or inspections.

Identifying the erosion and accretion rate requires more input than the other vulnerability indicators. The procedure in determining the erosion and accretion rate requires the image to firstly, be geo-referenced. The high-water levels can then be plotted from consecutive images over time. A line drawn perpendicularly through the plotted highwater levels gives the erosion or accretion rate.

In some regions, it is worth considering additional vulnerability indicators that are pertinent to the region as Theron (2016) did with the Mozambican region including cyclones and coral reefs as vulnerability indicators. Conversely, indicators should be excluded from CVI if they are not present in the entire region being assessed. For example, a study focusing on the South African west coast would not consider a cyclone indicator as cyclones do not occur in this region. However, a study of the entire South African coastline may include a cyclone indicator as they are present along the north-eastern coast.

'Double counting' of the vulnerabilities from similar indicators should be avoided such as when considering the distance from shore, elevation, and slope (Theron et al., 2012). These indicators all account for the vulnerability due to the degree of the landward slope so, including them all will affect the overall vulnerability score by collectively attributing a greater total weighting to the landward slope vulnerability than other considered vulnerabilities.

3.8.2 Choosing a protection approach with cost-benefit analysis

Project Implementation Framework – be aware of how selection fits into the design process

Once a section of coastline has been identified in need of coastal protection, Chadwick, Morfett & Borthwick (2013) and Morris et al. (2021) recommend that a four-stage project implementation framework (Figure 3.26) be setup to ensure optimal project results. Firstly, during *Initiation*, the project managers gather relevant information about the problem and begin defining the project scope and the objectives. This requires consultation from multiple disciplines to develop a holistic understanding of all the project aspects. Key stakeholders are also identified and involved at each stage throughout the project life.

After *Initiation,* the iterative *Design and Planning* process begins with the development of a few design options. Through a process of stakeholder consultation and cost-benefit analysis, a shortlist of preferred project options is created which can then advance to a detailed design phase. Sometimes it may be necessary to iterate this phase to refine the final design. Shortlisting nature-based solutions can be challenging as it is not easy to quantify the benefits of ecosystem services provided by nature-based solutions. This is discussed in more detail in the following section.

Once a design is chosen, the project is tendered, and the *construction* phase begins. After the project is constructed and implemented the *operation and maintenance phase* begins with periodic monitoring of the project to ensure that the objectives are being met and that environmental changes can be mitigated, or that infrastructure can be adapted timeously if necessary.

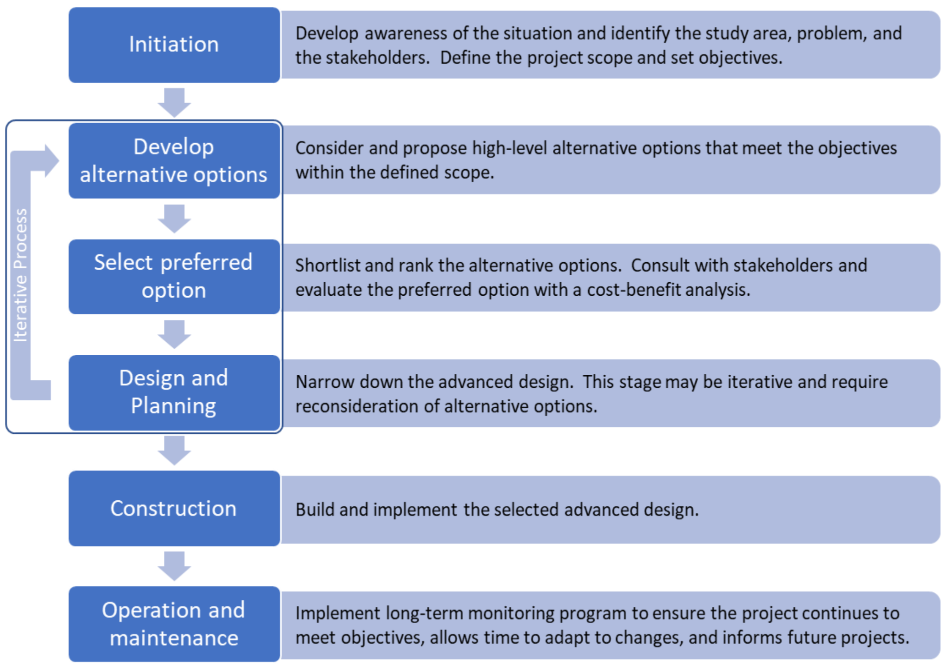

Figure 3.26 Project Implementation Framework

(adapted from Chadwick, Morfett & Borthwick, 2013; Morris et al., 2021)

Green infrastructure cost-benefit analysis within the Design and Planning phase

This section unpacks the selection of preferred options within the design and planning phase. The primary evaluation tool used is a cost-benefit analysis (CBA).

A CBA is used to evaluate the return on investment of resources spent on a particular project. This is done by adding the rewards or gains (such as hazard reduction and improved recreation) arising from investing in a particular project and subtracting the associated costs (such as construction and long-term maintenance) or losses (such as reduced natural habitat) of the project. The tool highlights the trade-offs between project options when compared with one another and the net impact the project will have (Martino & Amos, 2015). Furthermore, if resources such as municipal funding are limited, the tool can also help decision-makers allocate the resources to where they will have the most impact or return on investment.

The following six steps are an adapted summary mostly from Morris et al. (2021) recommending the process of performing the CBA.

1. Define proposed projects

Most of the information gathered in the initiation phase is considered in the development of project options.

Firstly, a baseline scenario is modelled whereby the case of 'doing nothing' is defined to establish the benefits and costs (consequences) if nothing is done. The baseline is compared with the consequences of the proposed project options.

Then alternative project options are developed, defined, and scoped for all the associated consequences including those from ecosystem services in the case of green coastal protection. The scoping process should identify and involve all stakeholders relevant to the project and the responsibilities they bear for each project.

A suitable timeframe needs to be chosen. Longer timeframes are appropriate for green coastal protection methods as they 'mature' with time and become increasingly resilient to coastal hazards. However, timeframes beyond 50 years are not worth considering (as the effect of the discounting principle in step four becomes negligible).

2. Identify biophysical impacts

All impacts, positive or negative, arising from each project need to be identified and assessed for magnitude (such as tonnes of carbon dioxide released or hectares of habitat restored). This also requires an understanding of how each proposed green coastal protection method impacts the biophysical processes.

The timeframe of each impact should be determined as well. Some actions have immediate impacts and others take longer to be realised. This is important for step four.

3. Valuing impacts and ecosystem services

CBA requires monetising the gains or losses of the previously identified biophysical impacts on coastal assets. The total economic value of coastal assets is divided into two broad categories of values namely market-based and non-market-based. If a good or service is traded for money it has market-based value. Goods or services that are not directly traded for money or have no monetary value are non-market based. (Rogers & Burton, 2019; Morris et al., 2021)

Valuing non-market-based ecosystem services can be complex (Costanza et al., 1997). The restoration of coral reefs illustrates this challenge. Some ecosystem services of coral reef restoration are easy to monetise such as the increased fish yield due to increased habitat for fish nurseries. This is direct market valuation (the value is calculated as the increased number of fish multiplied by the sale price of each fish). However, Costanza et al. (1997) indicate that most ecosystem services provided by coral reef restoration are non-market benefits such as wave protection and nutrient cycling which cannot clearly be monetarily valued but still contribute to environmental and human wellbeing. These ecosystem services require more involved indirect methods of valuation to produce a 'price tag' equivalent.

Various approaches to valuing ecosystem services are available in the literature and the following six are the most widely used.

a. Direct Market Prices

As already discussed, some ecosystem services or goods already have market values that are used directly in cost-benefit analysis. Examples include fishing stocks in which each kilogram of fish can be sold for a fixed market price, or sand mining which has a fixed market price as a building material.

b. Market Alternative

Daily et al. (2000) outline one approach to value ecosystem services as the 'cost of avoidance' or 'cost of replacement' by equating the cost of an equivalent technological alternative to the value of an ecosystem service. An example could be equating the value of a natural filtration system to that of a filtration plant. It is cautioned that this method may estimate a lower or partial value because manmade solutions are not always adequate, make poor substitutes for complex ecosystem services, and/or do not account for all benefits (Daily et al., 2000; Laing, Schleyer & Turpie, 2020). Thus Laing, Schleyer & Turpie (2020), summarise three criteria that should be applied to the replacement cost method to improve valuations: (i) the scale and quality of the services should be the same as the alternative, (ii) the most affordable alternative should be considered, and (iii) the affected individuals should be willing to pay for the alternative services if the ecosystem services were lost. To ensure these criteria are properly applied, it is recommended that coastal engineers are involved in finding the most affordable alternative solution and a stakeholder willingness-to-pay (see the following paragraph) survey is conducted (Laing, Schleyer & Turpie, 2020).

c. Surrogate Markets

Market values could be derived from preferences, use and actions in related or surrogate markets. This includes Hedonic pricing which uses existing markets to reveal non-market characteristics (Morris et al., 2021). An example of Hedonic is comparing the difference in property values between a beach front house boasting a scenic view to a similar house without a scenic view. The price differential can derive a 'willingness-to-pay' value for particular ecosystem services (Hussain & Gundimeda, 2010). The Hedonic price method is only useful when the price difference depends on a direct correlation with the ecosystem service and is not affected by non-environmental factors (such as local crime rates and access to public services) (Hussain & Gundimeda, 2010). The advantages of hedonistic pricing include that it is derived from data that already exists and is accessible (property prices) and it is a conservative lower-bound estimate of value (Rogers & Burton, 2019).

Alternatively, another method of determining values from surrogate markets is the travel cost method. The travel cost of recreational users to get to a recreational environment can be translated into the minimum amount that people are willing to pay to use a recreational benefit (Morris et al., 2021). Surveying the users of a facility can determine a supply-demand curve for the facility. Hussain and Gundimeda (2010) caution that defining the value of travel time can be a challenge. For example, the wear and tear cost on cars and the forgone income cost included in the travel cost. Furthermore, the model requires complex statistical input with a large data set, and is limited to recreational ecosystem services. Rogers and Burton (2019) note an advantage of the travel cost method is that it uses basic surveys that are easy to complete and generate conservative value estimates. Disadvantages include that values derived are limited to users (does not include non-use values) and multi-stop visits become challenging to attribute value to.

d. Stated Preference

Stated preference valuation is one of the more common approaches to ecosystem service valuation (King & Mazzotta, 2000). People are surveyed using either the contingent valuation method or the choice modelling method.

Contingent valuation is where respondents are presented with hypothetical environmental changes and are asked either what they are willing to pay to prevent the change or what compensation they would accept for the loss of ecosystem service (Costanza et al., 1997; Morris et al., 2021). The question could also ask how much the respondent is willing to pay for a hypothetical nature-based solution with a particular benefit. The willingness-to-pay method of evaluation could be limited if individuals are not fully aware of the ecological differences and what someone is likely willing to pay versus hypothetically willing to pay may differ (Costanza et al., 1997; Hussain & Gundimeda, 2010).

Choice modelling is where respondents are presented with various project options with varying ecosystem service levels and associated costs (Morris et al., 2021). The respondents are then asked to choose their preferred option or to rank the options. The information gathered from the process of trading-off different options and project attributes can be used to estimate how much someone is willing to pay for certain services. Hussain & Gundimeda (2010) point out that choice modelling is complex in terms of data collection and analysis.

The advantages of stated preference valuation are that it accounts for use and non-use values and the surveys are simple to design (Rogers & Burton, 2019). Whilst a disadvantage of these surveys is that, if poorly constructed, respondents may be subject to hypothetical bias. Furthermore, it becomes difficult to separate use and non-use values from answers which may lead to double counting (Rogers & Burton, 2019).

e. Participatory Valuation

The participatory valuation exercise is whereby stakeholders are allowed to voice concerns with project options to establish relative value indirectly. Hussain & Gundimeda (2010) give an example whereby respondents are given counters (like rice grains) to represent the relative importance of different factors related to the project. For example, food security may be given six rice grains whilst the cost of transport may be given four rice grains. This may appear to yield limited information, but the method can highlight relative importance from respondents who are not literate or not used to financially valuing different factors (Hussain & Gundimeda, 2010).

f. Benefit Transfer

Mendoza-González et al. (2012) describe another valuation technique, the benefits transfer method, whereby the monetary value of ecosystem services in an existing similar location (which has been studied previously) is used to infer the potential value in the study area. McComb et al., (2006) have reviewed some databases that provide information on environmental valuation useful for the benefit transfer method such as the two seen in Table 3.5**.**

Table 3.5 Two databases valuing ecosystem services (adapted from McComb et al., 2006)

Database	**Purpose and number of studies**	**Website**
Environmental Valuation Reference Inventory	Source of quickly searchable summaries of over 4000 peer-reviewed valuation studies	http://www.evri.ca
Ecosystem Services Valuation Database	Summarises over 5000 studies to a common set of units (international dollar/hectare/year in 2020)	https://www.esvd.info/

To apply the benefit transfer method, care should be taken to ensure that the parameters of the study site are similar to the site where the ecosystem value is being estimated (Mendoza-González et al., 2012). For example, in evaluating an ecosystem service on the island of Mauritius the studies from the abovementioned databases should be filtered to island nations preferably in the WIO region with similar economic circumstances to Mauritius. This will provide more meaningful information than a study from another region with different circumstances such as a North American or European country. Another possibility of valuing an ecosystem service is by using direct market price values. This could be done for environmental services that form part of the market such as access fees to a park, or the rental prices of recreational equipment such as surfboards or quadbikes.

Benefit transfer models are easy, cheap, and straightforward to apply especially if there is a strongly matching case study. However, one should account for a greater margin of error as no case study will be a perfect match. (Rogers & Burton, 2019)

Importance of including non-monetary factors

Tonmoy et al. (2015) illustrate the importance of including both monetary and non-monetary factors in decision-making using a Multi-Criteria Decision Analysis (MCDA) tool that combines both factors. This is compared to the traditional monetary-based CBA approach. Firstly, multiple project options are proposed, and the respective monetary and non-monetary factors are identified for each project. The monetary-based factors are then quantified with a probabilistic flood damage estimation which informs the Cost-Benefit Analysis whilst the non-monetary factors are identified and scored by consulting the local community and stakeholders. Both monetary and non-monetary factors are combined using MCDA which ranks the multiple adaptation options in order of favourability.

When non-monetary benefits (such as ecosystem services) are omitted in decision-making techniques, hard structures like seawalls rank favourably. However, when MCDA is used, accounting for factors such as community preference, aesthetics, and environment, hard structures feature less favourably compared to hybrid options such as groynes and a nourishment program (Tonmoy et al., 2015). Omitting ecosystem services from project valuation exercises results in construction projects ignoring or undervaluing non-market services or the social costs associated with projects which may change the decision of the most appropriate project (Costanza et al., 1997; Daily et al., 2000). Furthermore, failing to properly evaluate the non-market-based services means that the ecosystems will continue to be inclined to exploitation and degradation (Hussain & Gundimeda, 2010).

Other considerations in ecosystem service valuation

Care should be taken to correctly identify costs and benefits. Positive outcomes relative to the project baseline should be assigned as benefits. For example, the damage costs avoided by protecting assets from coastal hazards are benefits. Costs usually include items such as capital investment cost, project operating cost, negative consequences (like loss of recreational facilities), and opportunity costs of investing in one project over another.

Not everyone values the same services equally. For example, Rogers and Burton (2019) point out that swimmers may highly value a structure that reduces wave energy and improves their safety, whilst surfers would be resistant to this. Another example, owners of residential properties on a beachfront may react positively to a seawall being built protecting their assets whilst beachgoers may react negatively.

Morris et al. (2021) recommend accounting for risks of the project only partially delivering or failing to deliver its benefits. This may be attributed to design phase faults such as assumptions made or incomplete information, construction and maintenance faults such as implementation failures, or faults beyond the project control such as macroeconomic factors. Risks are included in CBA by determining a risk factor, R, from available data or expert consultation (Morris et al., 2021). R is a number between 0 and 1. For example, a project with a risk of failure of 20% has an R value of 0.2. The expected benefit is multiplied by R subtracted from 1.

$$\text{i.e., } True\ benefit\ =\ Expected\ benefit\ \times (1 -\ R)$$

4. Discounting

The value of benefits and costs determined in Step 3 is discounted to find an equivalent present value. This helps in determining how much is worth investing now to limit future impacts, and it accounts for the assumption that money will be worth less in the future due to inflation. This is an important consideration, especially when evaluating coastal protection projects which usually have high upfront capital costs and only realise benefits over a longer period. Using a higher discount rate results in a greater discounting of future values, and thus places a lower weighting on future values in today's terms and vice versa. As a result, Morris et al. (2021) suggest that one should test the discount rate sensitivity to check the effect on the present value.

Discount rates fluctuate over time (due to interest rates) and vary from country to country (for example the UK uses 3.5%, most Australian state governments use 7%, and the rate is estimated to be 8% for South African road infrastructure projects) (Morris et al., 2021; Pienaar, 2021).

Assuming a constant discount rate, *r*, the following discounting formula is used to find the present values of future benefits and costs:

$$PV = \sum_{t=0}^{T} \frac{FV_t}{(1+r)^t}$$

Where, present value, PV, and future values, FV, being discounted, r is the time-discount rate, t is the time, and T is the project life.

The London School of Economics and Political Science (2018) recommends that discount rates be reduced over time giving greater weight to future benefits and costs, especially in the context of the environment and climate change. Morris et al., (2021) also suggest that an argument can be made for reducing the discount rate over time due to the uncertainty of the true discount rate.

5. Decision metrics

Two approaches:

The first approach is to find the Net Present Value or NPV. The NPV determines the worthwhileness of a project, especially when comparing the opportunity cost between multiple possible projects. Especially important for green infrastructure with significant upfront investment cost and gradual realisation of the long-term benefits.

Equation 3.2 Net Present Value

$$NPV = \sum_{t=0}^{T} \frac{B_t}{(1+r)^t} - \sum_{t=0}^{T} \frac{C_t}{(1+r)^t}$$

Where B and C are benefits and costs respectively, r is the time-discounting rate and, t is the time from the present.

An NPV greater than zero (in other words the benefits exceed the costs) is considered to be a project worth investing in. Another similar metric is to set the NPV to zero in Equation 3.2 and find the internal rate of return, IRR, in place of *r* as set in Equation 3.3. In this equation, an IRR value greater than, *r*, is considered to make a project worth investing in.

Equation 3.3 Internal Rate of Return

$$\sum_{t=0}^{T} \frac{B_t}{(1+IRR)^t} = \sum_{t=0}^{T} \frac{C_t}{(1+IRR)^t}$$

Where B and C are benefits and costs respectively, IRR is the internal rate of return and, t is the time from the present.

The second approach is to find the Benefit-Cost Ratio or BCR. The BCR indicates how much benefit is gained per unit cost or invested as seen in Equation 3.2. Like NPV, BCR determines and compares the worthwhileness of a project against other possible projects. The higher the BCR, the greater the return on investment is.

Equation 3.4 Benefit-Cost Ratio

$$BCR = \frac{\sum_{t=0}^{T} \frac{B_t}{(1+r)^t}}{\sum_{t=0}^{T} \frac{C_t}{(1+r)^t}}$$

Where B and C are benefits and costs respectively, r is the time-discounting rate and, t is the time from the present.

Morris et al., (2021) stress that it is important to correctly assign benefits and costs in the BCR. The denominator should only include costs that are paid from the resource pool funding the project such as capital costs. Other costs associated with the project borne by other parties, such as businesses and individuals, should be subtracted in the numerator as a 'negative benefit'.

To illustrate this point made by Morris et al. (2021), consider a R20 million seawall is proposal (capital cost) to protect R80 million worth of beach front properties (benefit), but this will cause the loss of beach access worth R20 million to local tourism ('negative benefit'). The tourism loss is accounted for in the numerator of Equation 3.4 and the correct BCR is (80 – 20) / 20 = 3 as opposed to in the denominator with an incorrect BCR of 80 / (20 + 20) = 2.

(Pannell, 2019a,b) sets out the following three rules that should be applied when choosing a suitable decision metric for the project scenario.

i. Unlimited budget: Use either NPV or BCR and implement all projects with an NPV greater than zero or a BCR greater than one. In this case, NPV and BCR indicate the same thing – which of the projects has a net benefit.
ii. Limited budget and unrelated (not mutually exclusive) projects: Use BCR to rank the project options and select the project with the greatest BCR within the budget.
iii. Limited budget and mutually exclusive projects (one project precludes another project option): Use NPV to rank the projects and select the highest NPV project within the budget.

6. Sensitivity test.

Due to possible uncertainties of the variables used in the CBA (such as appropriate discount rates, confidence in non-market cost and benefit values, or biases that may overrate benefits and underrate costs), it is worth testing the range of the variables to determine the impact on the CBA output (Morris et al., 2021). Projects with greater sensitivity to variables (resulting in a more variable range of NPV outcomes) carry greater risk than projects that have less sensitivity to variables (resulting in a small range of NPV outcomes). Thus, it may be worth considering a project that has less variable sensitivity (small NPV range) and less risk over a project with high variable sensitivity (large NPV range) even if the initial NPV calculation favoured the sensitive project.

4 ADAPTING THE COASTAL VULNERABILITY INDEX

In the case of this study, the CVI by Palmer et al. (2011) was selected as primary inspiration for creating a CVI tool suitable for the WIO region. This is because it only requires aerial photography for its measurements. Using coarser segments (intervals of 250 m as opposed to the 50 m segments used by Palmer et al. (2011)) allows for quick manual data collection and data processing. This method is also affordable making use of free pre-existing satellite image services like Google Earth.

However, Theron (2016) points out two limitations of Palmer's CVI. Firstly, the method does not account for elevation above sea level, which is an important criterion, especially with sea-level rise. Secondly, the method does not account for the degree of wave exposure attacking the coastline. These two variables cannot be determined from satellite images which is probably why Palmer et al. (2011) excluded them. However, it is worth noting that the method has its limitations when these variables are not considered.

In addition to the limitations outlined by Theron (2016), and important in the context of the Western Indian Ocean, Palmer et al. (2011) do not account for cyclone vulnerability or coral reef vulnerability. To address this, these two vulnerabilities were removed from the CVI by Theron et al. (2010) and Theron (2016), and the ranges were adjusted to fit into the 'four-level' vulnerability system used by Palmer et al. (2011).

Table 4.1 CVI by Palmer et al. (2011) adapted to include fringing coral reefs and cyclones

Variable	**Ranking of Variable Vulnerability**			
	Extremely low	**Low**	**Moderate**	**High**
	1	2	3	4
Beach width (A)	> 150 m	100 – 150 m	50 – 100 m	< 50 m
Dune width (B)	> 150 m	50 – 100 m	25 – 50 m	< 25 m
Rocky outcrop percentage (C)	> 50%	20 – 50%	10 – 20%	< 10%
Distance to 20 m isobath	< 4 km	2 – 4 km	1 – 2 km	< 1 km
Vegetation distance behind beach	> 600 m	200 – 600 m	100 – 200 m	< 100 m
Estuarine mouth	No	No	No	Yes
Fringing coral percentage	< 10%	10 – 30%	30 - 50%	> 50%
Cyclones per annum	< 1	1 - 2	2 - 3	> 3
High vulnerability for A, B, and C	No	No	No	Yes

The description of how Palmer et al. (2011) took their four distance measurements (vegetation distance, dune width, beach width, and distance to 20 m isobath) is somewhat vague. Thus, it is important to define these distances as indicated in **Error! Reference source not found.** for this s tudy. The vegetation distance is taken as the distance from the start of the seaward-most infrastructure (such as roads, or buildings) and the landward-most back toe of the dune. The dune width is taken as the distance between the back and front toes of the dune. The beach width is taken as the distance between the dune front toe and the water's edge in the satellite image. (NB: The tidal level in the satellite image can be ignored because the CVI is a relative comparison of segments in the same image and thus will not affect the relative scores of the segments). The distance to the 20 m isobath is taken as the distance between the water's edge in the satellite image and the 20 m isobath.

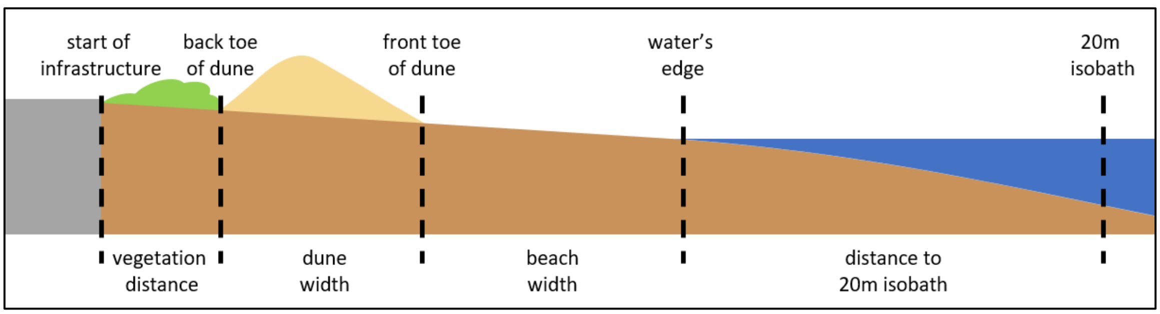

Figure 4.1 Defining the distance variables in the CVI

Should a variable not be present in the satellite image it is assigned 0 m. For example, a segment where there is no vegetation (the infrastructure immediately backs the back toe of the dune) is assigned 0 m of vegetation distance. Variables that are not present along the whole study area, such as fringing coral percentage in South Africa, are omitted as they do not contribute additional information to the CVI. This is because the CVI determines the relative vulnerability risk of segments within the section being studied and, thus variables absent for the whole study area do not add information. This is also the case for variables that are present but do not differ for the entire length of the section. For example, the number of cyclones experienced annually by all the segments in a region are the same and thus, it is not worth including in a CVI comparing segments within the same region.

Should the first three variables, beach width, dune width, and rocky outcrop percentage, all score a high vulnerability each, i.e., a score of 4, then an additional "high vulnerability" variable (refer to last row of Table 4.1) is applied. This is to make the distinction between especially vulnerable and less vulnerable locations clear.

Process used in applying the CVI used in this study

The following is the step-by-step process that was used in applying the adapted CVI in this study.

1. The coastlines of interest are divided into 250 m segments on Google Earth using the most recent satellite image available for the region.
2. Each segment of the coast has its vulnerabilities measured for the worst case as defined by **Error! Reference source not found.** (i.e., if part of the segment has no dunes the whole s egment receives a dune width of 0 m even if dunes are present elsewhere in the segment). Note that this yields a more conservative or higher than average score for the entire segment.
3. The gathered measurements are captured in Microsoft Excel where basic functions automatically assign the relevant vulnerability score.
4. The scores are summed and given the associated colour code for the risk score (low risk – yellow, moderate risk – amber, and high risk – red).
5. Returning to Google Earth the segment has its associated risk colour applied before moving on to the next segment.
6. The result is a visual image of the CVI overlaying the original satellite image.

5 WIO CASE STUDIES AND PROPOSED PROTECTION

5.1 Western Indian Ocean Countries

Western Indian Ocean (WIO) countries, as seen in Figure 4.2, span the eastern length of the African continent encompassing tropical, subtropical, and temperate coastlines. The countries can be divided into two categories: small island nations and large continental nations. There are five small island nations in the WIO: Seychelles, Comoros, Mauritius and, Mayotte and Reunion (the latter both French territories). The continental countries from the north are Somalia, Kenya, Tanzania, Mozambique, and South Africa. Madagascar is an outlier that has characteristics of both an island and a continental country. Collectively these countries have around 60 million people living within 100 km of the coast, usually in dense urban centres like Maputo, Dar es Salaam, and on the islands (Francis & Torell, 2004; Groeneveld, 2015).

The coastal environment of WIO includes a variety of habitats including salt marshes and deltas, sandy beaches, rocky shores, sea grasses, coral and shellfish reefs, and mangroves (UNEP-Nairobi Convention & WIOMSA, 2015). These environments provide ecological and economic importance to the coastal communities (Francis & Torell, 2004).

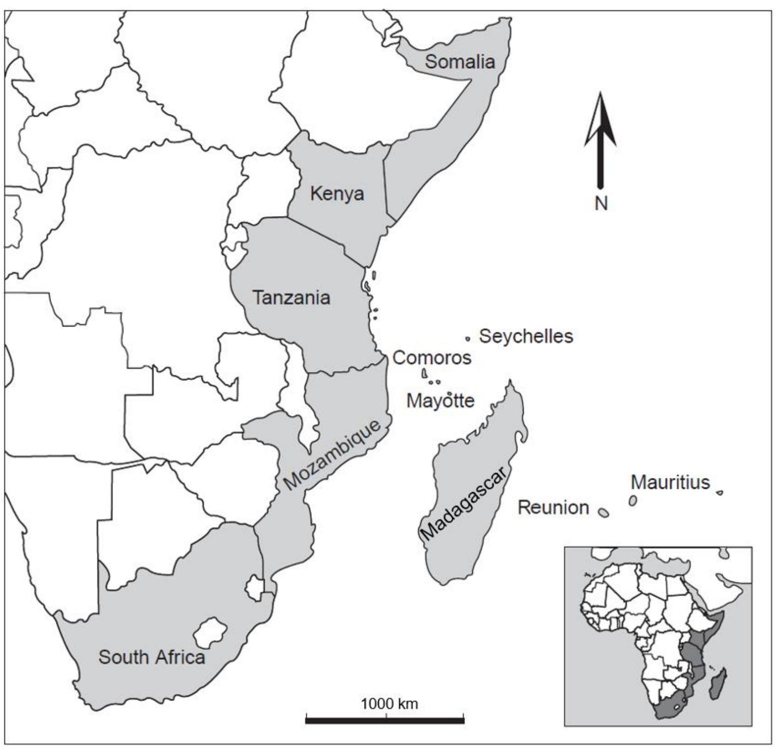

Figure 4.2 Western Indian Ocean region (adapted from Francis & Torell, 2004)

The coastal environments of the WIO are at risk and are threatened by the effects of climate change and the coastal processes discussed in Section 3.1 such as sea-level rise, erosion, and inundation as well as anthropogenic degradation causes such as resource exploitation and growing dense coastal populations (UNEP-Nairobi Convention & WIOMSA, 2015).

Despite being among the most at risk to the effects of climate change and sea-level rise, WIO countries have little 'adaptive capacity' to prevent coastal climate change and impacts on a large scale due to few economic resources and lack of access to technology (Theron et al., 2012). Thus, investigation is needed to look at appropriate adaptation and protection measures that are sustainable and promote the ecological richness found in this region.

In containing the scope of the study, the following three countries are focused on and explored in the next three sub-sections:

1. Mauritius
2. Mozambique
3. South Africa

5.2 Mauritius

5.2.1 Overview

The Republic of Mauritius is a nation made up of two main volcanic islands namely, Rodrigues and Mauritius, which are surrounded by several small volcanic and coral islets. Rodrigues, 560 km east of Mauritius, is not included in this study. Mauritius has a 2019 population estimate of about 1.265 million people and a GDP per capita of about USD 11 100 (The World Bank, 2021a,b).

Coastal conditions and weather

Mauritius has a tropical climate due to its location in the southwest Indian Ocean with a warm humid summer from November to April and dry winter from June to September. The following three climatic processes generate waves in Mauritius (Lalouviere, 2018):

- Consistent trade winds from the south-east year-round with speeds between 5 m/s and up to 25 m/s in the cooler months generating waves with periods of about 12 s.
- Storms affect the island as low-pressure systems move east from southern Africa. The ensuing waves have high periods and wave heights because of long unobstructed fetches.
- Three to four cyclones pass Mauritius annually during the summer months bringing heavy rains. Usually, every 10-15 years a cyclone makes landfall on one of the islands causing widespread flooding of low-lying areas and erosion of the sandy beaches.

The mean significant wave heights are found to be largest along the south-eastern coastline at around 2.2 m during summer and 2.6 m during winter (UWA, 2017). Waves on the north-western shores diffract around the island and the mean significant wave is about 1 m less than the southern shore due to the shadowing effect of the island (UWA, 2017). The mean sea-level rise over 30 years measured at Port Louis, the main port, is 3.9 mm per year (JICA, 2015).

Coastal area

The island of Mauritius covers an area of 1 865 km^2 and a coastline of 330 km. The island is 65 km long and 45 km wide. About 70% of the Mauritian coastline consists of sandy beaches of coral origin protected by fringing coral reefs enclosing shallow lagoons with widths of a few hundred metres in the north, and up to 4 km in the south (Onaka et al., 2015). Beach widths range from 20 m to 60 m and are up to thousands of metres long. About half of the beaches are bordered by residential or tourist developments (Duvat, 2009). The remaining shoreline composition alternates between rocky shores and cliffs of volcanic origin, and mangrove forests.

Once covering large parts of the Mauritian coastline, mangroves are mostly limited to estuaries and river mouths (Bhikajee, 2004). The current extent of mangroves on the island of Mauritius is not clear with one source indicating less than 1.5 km^2 (UNEP-Nairobi Convention & WIOMSA, 2015) whilst another indicates a more likely cover of 20 km^2 on the east coast (Appadoo, 2003). Mangrove forests are now protected and the government is encouraging replanting programs in former mangrove areas (Bhikajee, 2004). A study found that six sea grass species cover an area of 45 km^2 in Mauritius (Turner & Klaus, 2005). The World Atlas of Coral Reefs lists the reef area of Mauritius as 870 km^2. These corals are not in good condition largely due to direct and indirect anthropogenic actions like trampling, poor water quality and coral bleaching caused by rising sea temperatures (Turner & Klaus, 2005).

Importance of coastline

Mauritius relies on its sandy beaches, warm and calm inshore waters, and coral reefs for tourism. The island is a popular destination with nearly 1.4 million tourists travelling to Mauritius in 2019 generating nearly USD 1.5 billion, about 8.5% of the Mauritian GDP (Statistics Mauritius, 2019).

Current coastal status

Duvat (2009) and Onaka et al. (2015) indicate that on a geological scale Mauritius is losing sediment due to waves from storms and cyclones moving sediment beyond the coral reef area. Using aerial photographs and satellite images over a period from the 1960s to the early 2010s, JICA (2015) estimated that coastlines are eroding between 0.2 m to 0.4 m each year. Typically, during calmer periods the waves are of low energy and sandy beaches accrete. However, these periods are not long enough to replenish the sediment volumes lost during storm and cyclone events (Onaka et al., 2015). Duvat (2009) further attributes some anthropogenic causes of Mauritius's erosion to sand extraction and dune levelling for coastal developments, illegal jetties and groynes disrupting sand transport, and uncontrolled dredging for boat channels and sand renourishment schemes.

Mauritius appears to favour hard-engineered solutions in response to coastal risks and hazards. This is evident from the study by Duvat, Anisimov & Magnan (2020) who summarise and map the coastal risk reduction responses in 60 locations around Mauritius. More than 75% of the responses have used hard engineering solutions such as groynes, revetments, seawalls, and breakwaters. In some cases, these hard responses have not been well implemented, and have accelerated environmental degradation and coastal erosion, decreasing the tourism appeal of these locations (Onaka et al., 2015).

In the late 1990s and early 2000s, the Mauritian government embarked on a country-wide project of building gabions and seawalls along about 50% of the length of its beaches with little consideration being given to the strategic and environmental factors (Duvat, 2009; Onaka et al., 2015). This project was unsuccessful, in some cases accelerating coastal erosion and posed risk to beach usage, such as gabions breaking and spilling rock contents, decreasing the tourism appeal of some areas (Onaka et al., 2015). Duvat (2009) attributes this failure to a lack of national expertise in coastal management and defence. Some private hotels have also made inappropriate use of hard engineering, thereby accelerating erosion.

In Mauritius, coastal developments like homes and hotels have a 30 m setback from the high water line (before 2004 this was 15 m) which JICA (2015) points out is not much considering the rate of erosion they found. It would take 75 years for the high-water level to reach this set back assuming an erosion rate of 0.4 m and not accounting for sea-level rise.

Three sites in Mauritius were selected as case studies, namely, Albion, Case Noyale, and Mon Choisy. Albion was selected because it is still relatively undefended despite the erosion that it has experienced. Case Noyale was chosen because it is an example of a location where grey infrastructure has been implemented where a green infrastructure project would have been just as, if not more successful. Finally, Mon Choisy was selected as an example of a location where green infrastructure has been implemented successfully and has the potential to be extended. Figure 4.3 shows the relative locations of these sites on the island.

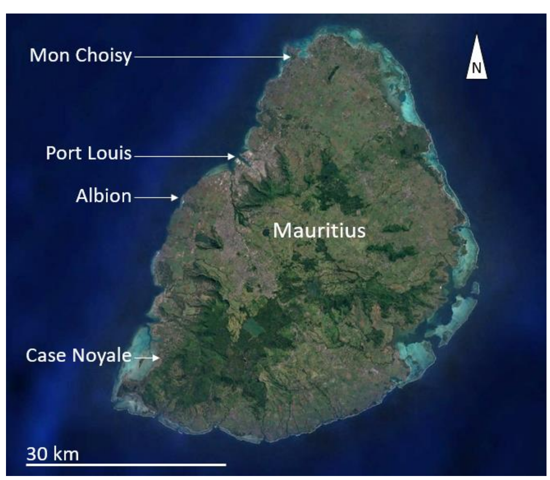

Figure 4.3 Island of Mauritius with the locations of Port Louis, Mon Choisy, Albion, and Case Noyale

5.2.2 Albion Beach

The town of Albion is on the west coast of Mauritius about eight kilometres southwest of Port Louis. As seen in Figure 4.4, the town surrounds the Albion Lagoon which extends inland from the deep-sea boundary covering an area of about 800 000 m^2. Other than the lagoon, which has a barrier coral reef on the seaward side, the coastline on the north and south sides comprises volcanic cliffs with no offshore reefs (unlike most of the Mauritius coast). The barrier reef shelters the lagoon by causing offshore waves to break as they pass, as can be seen in Figure 4.4. The lagoon forms a fringing coral reef and a sandy shoreline of about 2 400 m extending from the Club Med Albion Hotel in the south to the residential area to the north of the lagoon. Albion is also home to the Albion Fisheries Research Centre, AFRC, and the Mauritius Oceanography Institute, MOI. Built-up areas on the northern and southern shorelines are within 30 m of the high water mark despite the Mauritius Policy Planning Guidelines (JICA, 2016). Further inland from Albion is farmland, most likely sugarcane.

Figure 4.4 Satellite image of Albion, Mauritius (Google Earth, 2022c)

Onaka et al. (2015) highlight Albion Beach as an example of what effect deteriorating coral reefs is having on the shorelines of Mauritius. Figure 4.5, adapted from Onaka et al. (2015), compares two satellite images of the southern end of Albion Beach from 1967 and 2008. Three differences are noticeable in this figure; the seagrass bed cover near the beach has reduced significantly, the regular contrasting 'line' pattern (an indication of a healthy reef) of the coral reef has deteriorated, and the beach shoreline has retreated. Onaka et al. (2015) estimate that 10 000 m^3 of beach sediment was lost over the 40 years between images. JICA reported in 2016 from surveys conducted that the Albion Lagoon then experienced an annual sediment deficit of 170 m^3 meaning that this volume was lost from the lagoon area. This is a relatively small volume, but it has an ongoing effect. A survey from 2012 compared with the results from a 1994 study by the ARFC showed that seagrass beds were affected in the lagoon, disappearing from the central part; however, the extent of seagrass beds increased in the northern part of the lagoon (JICA, 2015).

JICA (2015) and Onaka et al. (2015) attribute coral and seagrass degradation and subsequent coastal erosion to strong cyclone-generated waves, destructive fishing practices in the lagoon with large nets, and unregulated recreational or tourism activities causing coral and seagrass trampling, and rising sea temperatures. The compromised coral reef and seagrass bed offer less protection to the sandy beaches resulting in sand erosion which is either lost from the lagoon or buries the seagrasses and the reef in some areas, further increasing the rate of degradation (Onaka et al., 2015). The AFRC also reported coral bleaching events in 2003, 2004 and 2009. The described coral degradation and subsequent erosion experienced at Albion are not unique and are found at sites around the island.

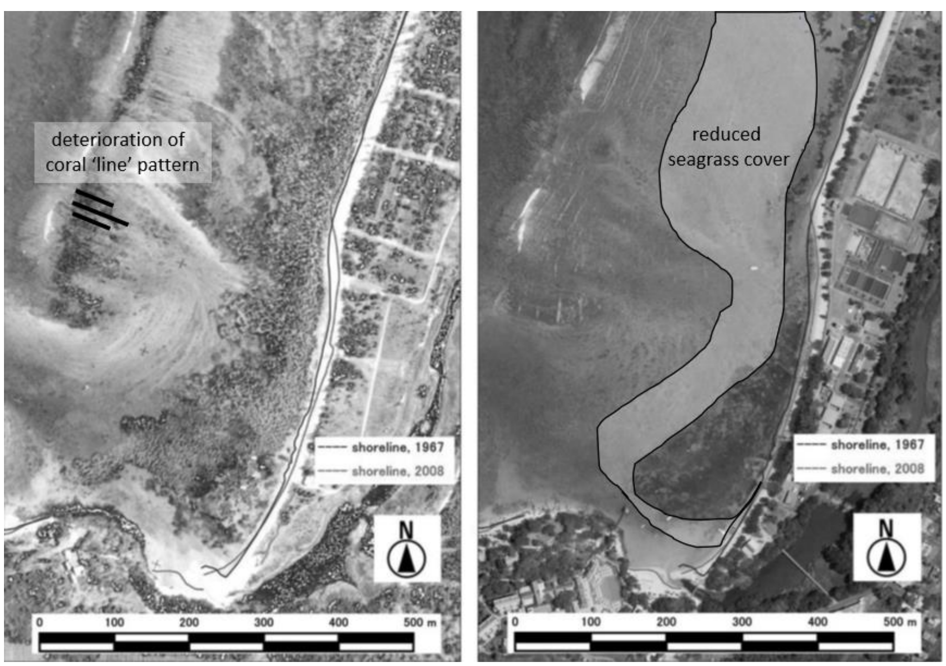

Figure 4.5 Deterioration of Albion Beach fringing coral reef and subsequent seagrass cover reduction and beach erosion between 1967 and 2008 (adapted from Onaka et al., 2015)

Despite the increasingly compromised long-term condition of the lagoon at Albion, no adaptation or protection responses have been implemented at the site (Duvat, Anisimov & Magnan, 2020b). However, the AFRC and MOI have experimented with coral farming in nurseries contained in the lagoon since 2008 (MoFR, 2010; MOI, 2021). Metal mesh tables were placed in the lagoon to which coral fragments were attached and left to develop naturally. Eventually, these fragments and newly settled coral larvae formed an artificial reef which attracted an abundance of fish (MoFR, 2011). The Ministry of Fisheries (2010) indicated that they intended to extend the project to other locations in the lagoon. However, the project in Albion was not mentioned again in their annual reports after 2011. The MOI (2021) reports that the method has been successfully adapted for the restoration of degraded coral reefs at three sites namely, Blue Bay Marine Park, Balaclava Marine Park and Trou aux Biches.

5.2.3 Case Noyale

Case Noyale is found on the south-western coast of Mauritius between Grande Riviere Noire and Le Morne on the B9 road. This site was identified as vulnerable and has had a hard coastal defence solution implemented late in 2018. It is included in this study as an example where a soft engineering approach may have been as, if not more, effective than the hard defence built.

On either side (north and south) of the site are two healthy native mangrove stands as shown on the left of Figure 4.6, and low tides reveal a gravelly mud flat that extends 50 m from the road embankment (Diospyros, 2017). Between the mangrove stands, there was a narrow 100-metre-long grassy embankment separating the road from the sea (see left of Figure 4.6). Diospyros (2017) reports that along the embankment there were twenty-one alien trees of five species and only one indigenous tree.

The 100-metre stretch was identified as a vulnerable area prone to erosion risk threatening public infrastructure (B9 road and civil status office), and cultural assets (local church) with flood damage (Duvat, Anisimov & Magnan, 2020b). In 2018, the government reacted by constructing a 10 m wide gravel beach and parapet wall along the 100 m length with 50 m groynes on each side effectively separating the two mangrove stands from one another (Duvat, Anisimov & Magnan, 2020a). This can be seen on the right of Figure 4.6. The decision seems to be strange since the ecologist's report by Diospyros (2017) describes the two mangrove stands as "healthy and dynamic, providing physical protection to the road behind them", and supporting the biodiversity of the surrounding lagoon.

Figure 4.6 Satellite Images of Case Noyale between August 2018 (left) and March 2022 (right)

(Google Earth, 2018a, 2022d)

A possibly more environmentally desirable and sensitive solution which still offers protection may have been to consider restoring the degraded site by planting mangroves saplings along the 100 m length to reconnect the separated mature stands. Once the new mangroves have matured the site would have been more ecologically sustainable and still provide sufficient coastal protection whilst enhancing the ecosystem services as discussed by Diospyros (2017) such as the provision of food and materials, and regulation by filtration and carbon sequestration.

Figure 4.7 Case Noyale groyne-protected gravel beach construction in late 2018

(Google Street View Photo Sphere, 2018)

5.2.4 Mon Choisy

Mon Choisy, about 16 km north of Port Louis, is one of the longest and most popular beaches on the northern end of Mauritius. The surrounding area is home to several hotels, resorts, and an international golf course making it a popular area for tourists visiting the island.

The shoreline of Mon Choisy is made up mostly of sandy beaches and dunes. The dunes are occupied by non-indigenous *Casuarina* trees which were planted as wind breaks around the island in the 20th century and have since self-seeded on the dunes along Mon Choisy. *Casuarina* trees have a shallow root system and at high tides, if the roots are exposed, they create turbulence causing erosion during uprush and rundown (Borrero et al., 2016). The trees form dense stands which displace deep rooting endemic coastal vegetation increasing the risk of erosion.

The sediment source of Mon Choisy comprises broken fragments from the fringing coral reefs (Borrero et al., 2016), however, due to worsening water quality and destructive anthropogenic activities (such as net fishing, and vessel anchoring) the coral reef condition is deteriorating (JICA, 2015). This is resulting in less coral sediment feeding the beaches. The deteriorating reef and declining seagrass beds are also losing their protective capacity to shelter the beach against offshore waves resulting in increased sediment turbidity and accelerating rates of erosion (Borrero et al., 2016). Therefore, to address the long-term problem of sediment supply one needs to address improving the condition of the fringing reefs and the seagrass beds.

Figure 4.8 adapted from Borrero et al. (2016) summarises the sediment movement within the lagoon around Mon Choisy. The green arrows show the sediment source from the corals which move into the lagoon and circulate shown by the orange arrows before being lost through one of the sand sinks indicated by the red arrows.

The natural sediment movement has been interrupted at the southern end of Mon Choisy due to a series of private groynes that have been built south of the beach, as shown in Figure 4.8. However, sediment continues to move from the southern end of Mon Choisy to the northern end creating an imbalance attributing to the southern beach erosion (Borrero et al., 2016). Overall, according to JICA (2016), the area of Mon Choisy also experiences an annual sediment loss of 500 m^3 from the sand sinks exacerbating the erosion.

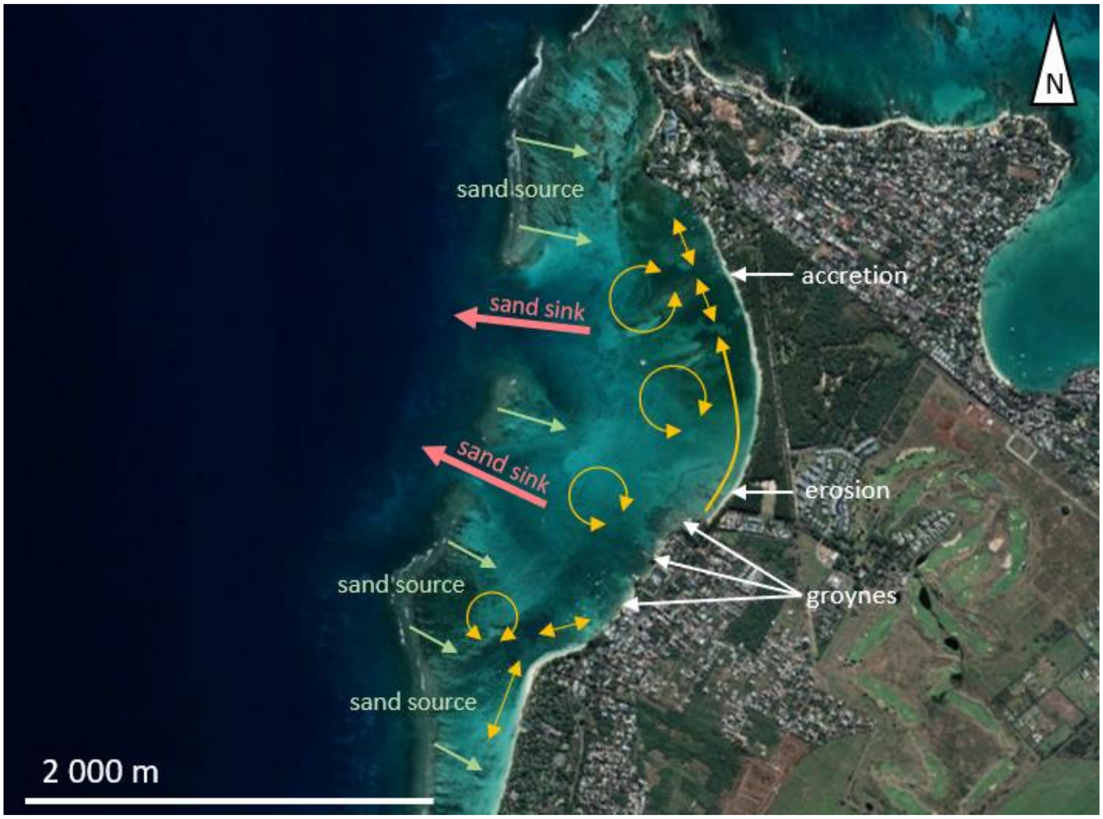

Figure 4.8 Graphical summary of sand movement around Mon Choisy

(adapted from Borrero et al., 2016; Google Earth, 2021)

Generally, the structures built around Mon Choisy beach are located behind the recommended 30 m high water mark setback. However, given the rate of erosion, JICA (2016) suggests that future developments should observe a minimum setback of 40 m to account for sea-level rise and future storm surges and inundation levels.

The Mauritian Government took steps in 2019 to protect the southern end of Mon Choisy by installing an artificial reef, seen in Figure 4.9, with 895 submerged reef balls with five designs (Subcon, 2019). This project is intended to dissipate wave energy and reduce beach erosion (Duvat, Anisimov & Magnan, 2020a). Concurrently beach and dune nourishment were done by distributing 7500 m^3 of sand in a gentler slope than the previous scarp in the area indicated in the lower left image of Figure 4.9. The 180 *Casuarina* trees located along the renourished dunes were replaced with 600 more appropriate trees behind the new dune (some of which are indigenous to Mauritius), and vegetation on the dune (Government of Mauritius, 2022). The cost of this project was estimated to be USD 2 000 000 and was paid for by the UNDP Climate Change Adaptation Fund (Duvat, Anisimov & Magnan, 2020a).

Figure 4.9 Mon Choisy coastal protection: artificial reef, beach nourishment, and dune revegetation
(adapted from Google Earth, 2018, 2019b, 2021; Subcon, 2019)

Figure 4.10 shows the before and the after images of the site from two Google Photo Spheres. In the left image, one can see the under-scouring of the *Casuarina* trees which needed to be cut down to prevent them from toppling. The right image of Figure 4.10 shows the restored and fenced-off dune and dedicated foot paths about two years after project completion.

Figure 4.10 Mon Choisy dune restoration before (left - Dec 2018) and after (right - Jul 2021)
(adapted from Google Earth Steet View Photo Sphere, 2018, 2021)

5.2.5 Coastal Vulnerability Index

This study considers all the standard vulnerabilities from the CVI discussed in Section 3.8.1 except for distance to the 20 m isobath and the number of cyclones. The 20 m isobath vulnerability was omitted because the information could not be sourced. Given their prevalence in Mauritius fringing coral reefs were included in the CVI, and the scoring ranges are adapted from the dissertation by Theron (2016) as explained at the end of Section 3.8.1. As for Mozambican sites, an argument could be made that cyclones should be included in CVI analysis, however, as the number of cyclones experienced by a site's segments is the same one does not gain an insight into the relative vulnerability to cyclones within the sites. For this reason, it is not considered in the CVI. In an island-wide CVI assessment of Mauritius, cyclones need to be considered as they approach from the east and thus the west coast is somewhat sheltered from their impact.

Albion Beach

Albion's CVI measurements can be found in Appendix B and are presented visually in *Figure 4.11*. As seen in the figure, the southern end of the lagoon (A, B, and C) is the least vulnerable section as most of the coast is made up of mostly rocky shore. The central length of the lagoon (D to G in Figure 4.11) scores a high vulnerability mostly due to it comprising sandy beaches, and relying on the fringing reef for protection. The northern extent of the lagoon (H, I, and J) becomes rockier, with some privately built hard defences, and scores a moderate vulnerability. The CVI highlights that the middle part of Albion requires the most attention followed by the northern section.

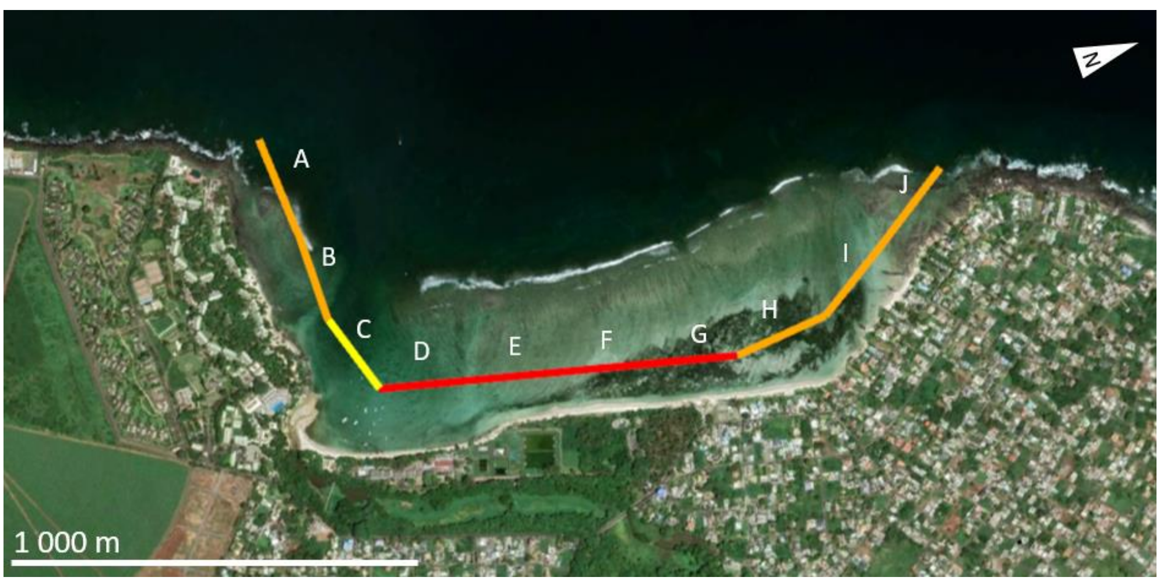

Figure 4.11 Palmer's CVI applied to Albion (Google Earth, 2022c)

Mon Choisy

Figure 4.12 captures the result of the CVI applied to Mon Choisy. Due to being a mostly homogeneous coastline, there was little variation in score values at Mon Choisy (ranging from 17 to 20) however, the CVI showed that there is a slightly higher risk at either end of the bay (K and L or Q and R in Figure 4.12). This may be attributed to reliance on the protection provided by the fringing coral reef. The central section (M to P in Figure 4.12) scored a moderate risk as the coast is more exposed due to the gap in the fringing reef. This is not to say that attention should only be given to the northern and southern ends of Mon Choisy, but attention should be prioritised to these areas before attending to the central stretch. Appendix B has the detailed measurements for the CVI and risk scoring for Mon Choisy.

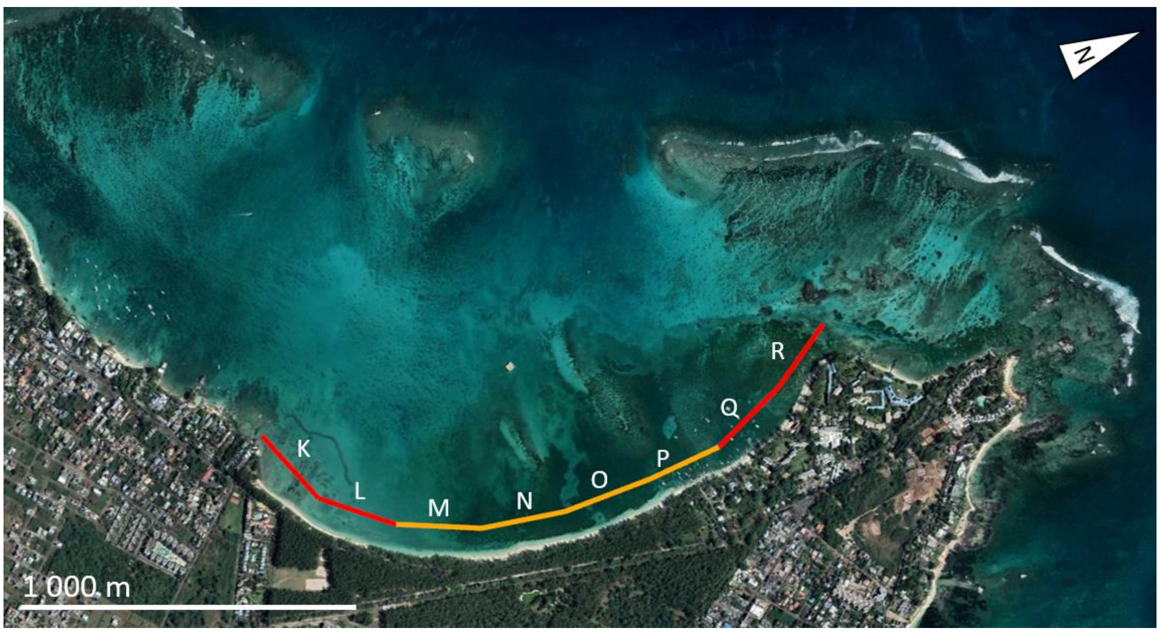

Figure 4.12 Palmer's CVI applied to Mon Choisy (Google Earth, 2021a)

Case Noyale

The CVI for case Noyale is not explored as the site has already had grey infrastructure intervention, thus making the CVI process difficult with the variables used and to some extent redundant as it is already a defended site. The case study was included as an illustration where a green infrastructure solution may have been more preferable and environmentally sensitive than the grey infrastructure solution that has been implemented.

5.2.6 Recommendations

Albion Beach

The lagoon would be suited to widespread coral restoration because of the earlier success that the Albion Fisheries Institute has had in growing mature corals from fragments in the lagoon.

Thus, it is proposed that an artificial submerged reef be constructed like the one at Mon Choisy using reef ball units. Once constructed coral fragments can be attached to the units with the intention that the corals will colonise the artificial reef.

The submerged breakwater will immediately protect the lagoon from waves. At first, the solution would be considered eco-friendly as the coral fragments will not provide protection: the primary protection is provided by the reef ball. However, once the corals mature into a reef, the project will constitute a hybrid defence because both the artificial reef units and the coral provide wave protection. As sea levels rise the corals can adapt by continuing to grow vertically thus continuing to provide protection, which is not possible when only implementing a grey infrastructure breakwater.

Another benefit of planting and restoring the coral cover is that the coral sediment feeding the beaches will increase, combating the effect of sediment lost from the reef. Thus, increasing the coral volume simultaneously slows the rate of erosion and increases sediment generation.

However, to restore the coral reef cover further intervention is needed to address the original cause of reef deterioration. As already discussed, some of the lagoon's degradation can be attributed to harmful net fishing practices and unregulated recreational activities that disturb the marine environment such as coral trampling. These practices can be prevented by licencing a limited number of responsible operators within the lagoon, and issuing fines for those not following regulations. Additionally creating public awareness is important to alert the public to the drive against destructive practices and efforts to restore the lagoon. This may include local newsletters, advertisements (radio and television), and signposting at the entry points of the beach.

The quality of fresh water entering the lagoon via the southern river was also attributed as a cause of deteriorating lagoon conditions according to JICA (2015). However, JICA (2015) did not expand on what this meant. An investigation could be done to assess the quality of the water runoff in the catchment of the river. Perhaps the farms adjacent to this river are using fertilizers or insecticides that are harmful to the lagoon environment. If this is the case the farmers should be encouraged to switch to non-harmful alternatives. Alternatively, pollutants may also enter the river from rain runoff from the town of Albion which is negatively affecting the lagoon. An option worth investigating would be the planting of mangrove stands along the river to filter and absorb these pollutants so that they do not enter the lagoon.

Other degradation causes previously discussed that are beyond direct control include cyclone-generated waves and warming sea temperatures. An artificial reef similar to the natural reef before its deterioration could be used as a 'barrier' protection against cyclone-generated waves. Rising sea temperatures cannot be managed locally. However, its impacts can be monitored and perhaps countered with defensive measures such as an artificial reef partially replacing the functions of a natural reef.

It is recommended that the lagoon restoration aims for a cross-section similar to that shown in Figure 4.13. Cross-section X-X of Figure 4.13 is based on the natural cross-section of the 1967 satellite image in Figure 4.5. Cross-section X-X was placed within the most vulnerable section of Albion Lagoon, D to G, as seen in Figure 4.14.

On the leftmost side, an artificial reef is placed with 'reef ball'-like units to cause waves to break before entering the lagoon. The width of the artificial reef is dependent on the water depth and wavelength and will likely be about 10 m. The placing of the artificial reef should be cognisant of the existing coral reef and avoid damaging any live coral. Attached to the reef ball units are coral fragments which will hopefully establish a hybrid reef system protecting the lagoon and increasing sediment feeding to the lagoon's beaches. Inside the artificial reef, further corals should be planted where previous coral had died so as to extend the reef area to about 160 m to its 1967 extent. Then a 50 m section is left as open seafloor. A 20 m strip in the centre of this 50 m open area can be made available for small vessels within the lagoon. This 'contained' space allows for recreational activities to continue without negatively affecting the sensitive restored areas.

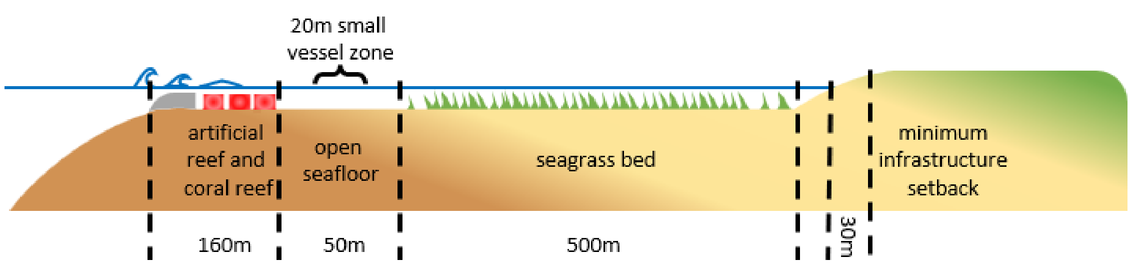

Figure 4.13 Proposed restoration cross-section X-X (see Figure 4.14) for Albion Lagoon

Then the 500 m extending from the open boating area to the shore should be planted and restored as a seagrass bed with native species illustrated in Figure 4.5. This provides a nursery and refuge habitat for marine life, as well as stabilising some of the sediment movement within the lagoon.

It was noted earlier that some infrastructure has been built within 30 m of the high-water level despite national guidelines. Although the coastline has already been mostly developed, future developments should be located at least 30 m away from the 30 m guideline, if not further inland. Existing infrastructure within the 30 m setback should not be upgraded or replaced. When the appropriate time for replacement comes, the new infrastructure should be implemented at a retreated location. i.e. more than 30 m from the shoreline. Figure 4.13 shows a plan view of the proposed restoration described in the previous two paragraphs extending from D to J. A small vessel entrance channel is proposed between G and H to allow vessels to travel from the public beach entrance at G to the small vessel zone between the sea grass beds and the restored coral reef.

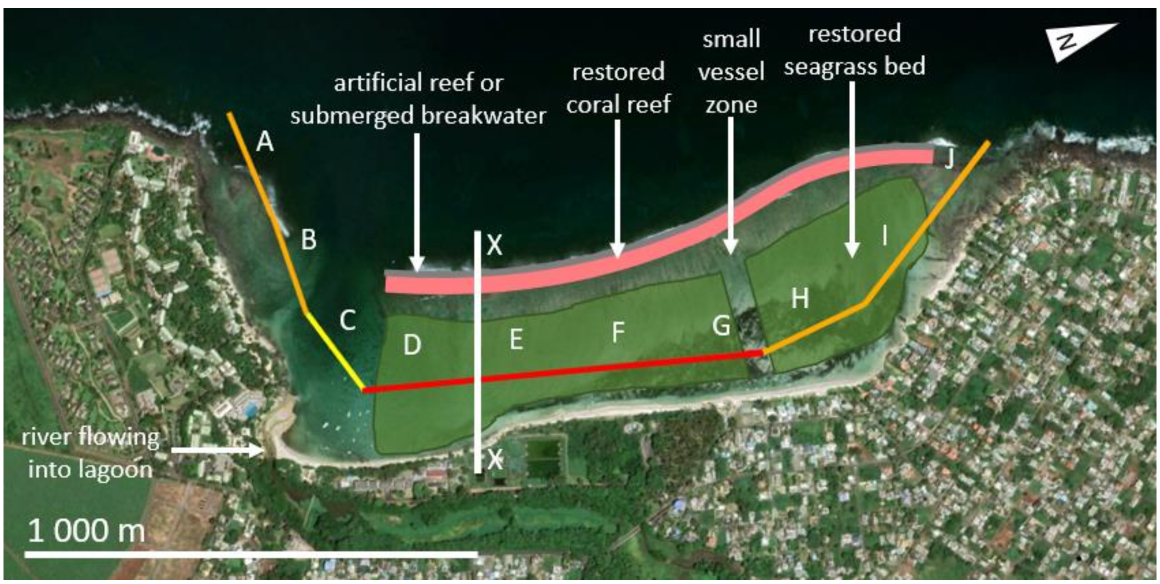

Figure 4.14 Plan view of Albion Lagoon restoration Section X-X is indicated with the white (Google Earth, 2022c)

Appendix E hereof details the artificial reef design and calculation process that was done by adapting the method from the Rock Manual (Section 5.2.1.2) for submerged rock structures in the marine environment. The primary assumption is that the reef stability number, N_s, must be equal to or less than 1 so that the reef ball units are static and can support coral growth. N_s the relative density of the unit, *Δ*, the nominal unit dimension, *D*, and significant wave height, H_s, at the -2 m bathymetric contour were determined as discussed in Appendix E.

By doing this calculation, it was found that the *super reef ball* size, as per the reef ball manufacturer's specifications, will meet the stability assumption above ($N_s \leq 1$). It is recommended that these 1.37 m high and 1.83 m wide *super reef ball* be units are placed in eight tightly packed off-set rows along the indicated grey line in Figure 4.14. This will create a 10 m wide artificial reef.

It is also recommended that the 1.37 m reef balls be placed on a 1 m berm to raise the crest of the artificial reef and reduce the wave transmission through the reef. As discussed in Appendix E and shown in Figure 4.15, with no berm, wave energy is unobstructed even at low sea levels. Raising the reef crest to just below the chart datum at 2 m (i.e., even at low tides the reef will not be visible) is better, reducing the wave energy transmission. However, at higher water levels such as the extreme still water level and accounting for SLR, this reef height may not offer enough wave protection. Raising the reef by 1 m so that the crest is just below the mean low water level (i.e., the top of the reef will be visible during below-average tide levels) reduces wave transmission by 40% at mean sea level and by nearly 20% at ESWL as seen in Figure 4.15. This does have a negative visual effect during low tides when the top of the reef ball reef is visible, but this compromise may be worth accepting to ensure adequate lagoon protection. It is worth noting that the raised berm also future proofs the structure for SLR when the lowest astronomical tide has risen by 0.5 m in 2100. Additionally, if the coral successfully colonises the artificial reef, as intended with this hybrid solution, it may grow with the rise in sea levels.

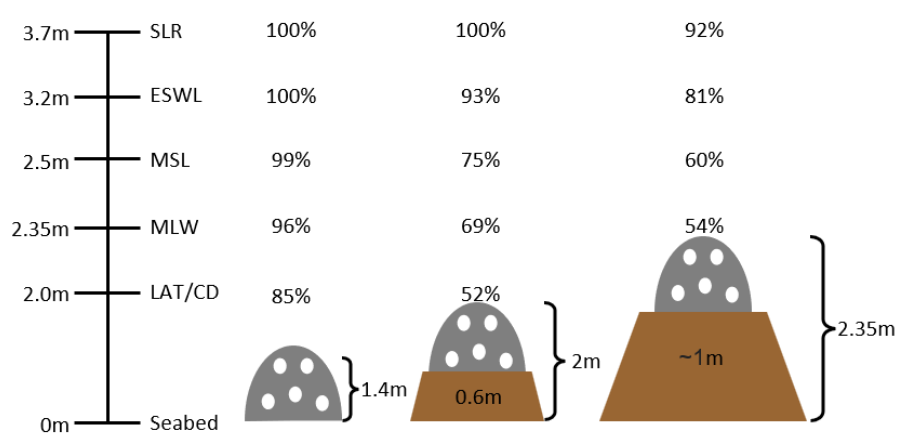

Figure 4.15 Wave transmission for different berm heights (heights are not to scale)

Mon Choisy

Before the restoration project of the southern portion of Mon Choisy beach in 2019, Borrero et al. (2016) and JICA (2016) recommended that a beach management program needed to be implemented with the following objectives:

- nourishing and reprofiling the beach and dune to correct the beach scarps
- removing the inappropriate and nonindigenous *Casuarina* trees
- planting indigenous trees behind dune, and dune vegetation upon the dune
- demarcating the restored area with fences and signs

In addition to the beach nourishment, Borrero et al. (2016) recommended that an offshore artificial reef be constructed along the 2 m isobath to shelter the southern end of Mon Choisy.

It appears that the dune restoration project and artificial reef, in the southern end of Mon Choisy Beach (K and L in Figure 4.12), have been implemented with these recommendations in mind, and the authorities should be applauded for their efforts. Hopefully, the project will become an example of how the rest of Mon Choisy and other vulnerable Mauritian beaches can be improved in both protective capacity against coastal hazards and tourist appeal. The artificial reef was constructed with generic reef balls, and it will be an interesting project to monitor because if it proves a success, the solution may be implemented further along Mon Choisy or elsewhere in Mauritius.

Finally, Borrero et al. (2016) and JICA (2016) also recommended regulating nautical activities in the lagoon, and exploring sea grass restoration. As the beach is a popular tourist location, a few businesses operate in the lagoon providing diving, jet skiing, and boating service. Regulating these businesses can ensure that damage to the marine environment is minimised, and licencing fees can contribute towards the restoration costs. As seagrass restoration is not fully understood, it is recommended that it be tested in the lagoon, experimenting with the methods of planting and differing areas of exposure to wave action. It was not clear from government publications studied whether these regulatory measures have been implemented.

Most of the landward side of Mon Choisy has not been developed apart from the southernmost and northernmost points which have hotel developments. As already discussed, JICA (2016) suggest that before developing the rest of this area, authorities could consider extending the coastal development setback to 40 m, as opposed to the national guideline of 30 m, given the current erosion rate.

Given the success of the southern dune restoration project, it is recommended that the authorities consider extending the project to the rest of the Mon Choisy beach with a similar profile to that in Figure 4.16.

This entails removing *Casuarina* trees within 20 m of the shoreline. This is followed by re-grading the beach slope and constructing a dune. Behind the dune, the *Casuarina* trees should be replaced with indigenous trees and shrubs such as *Tournefortia argentea* (octopus bush), *Scaevola taccada* (beach cabbage), *Pandanus* (screw palm), and *Dictyosperma album* (princess palm) (Borrero et al., 2016). Upon the dune, creepers such as *Ipomoea* (morning glory), coastal grasses like *Lepturus repens* (thin tail), and *Paspalum vaginatum* (silt grass) should be planted (Borrero et al., 2016). Bundy et al. (2021) recommend using a diverse plant palette with a variety of species. Additionally, new dunes should be planted with plants of varying maturity and with different methods such as sowing seeds, planting seedlings from trays, and rooting cuttings from mature plants from neighbouring sites. Introducing a variety of species and varying maturities to a new dune will enable the dune to establish itself faster.

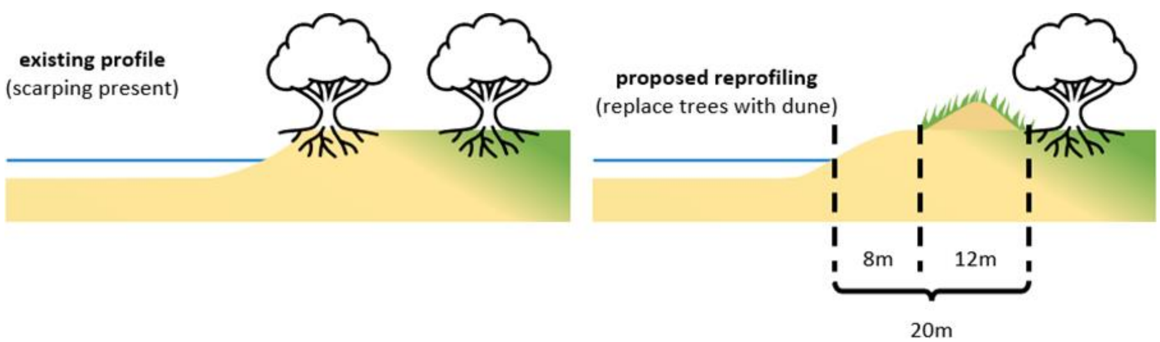

Figure 4.16 Proposed reprofiling of Mon Choisy beach

The dunes should be fenced off to prevent the public from trampling and damaging the vegetation. Additionally, access to the beach should be directed to a few raised boardwalk paths that limit the effect of people traversing the dune.

A possible way to combat the loss of 500 m^3 of sediment from the lagoon annually is to implement a regular sand nourishment program. Sediment lost from the lagoon can be trapped in a dredged trench at the mouth of the two sediment sinks. Over a period, sediment leaving the lagoon will accumulate in the trap. Once the trap is partially full, the sediment can be dredged and used to nourish the beach section which has eroded the most. The most cost-effective way of approaching this would be to use a manoeuvrable jet pump operated from a small pontoon with an attachment to a fixed discharge point. The jet pump would be attached to an adjustable buoyancy system that adjusts the pump depth and has a pipe extending to the shoreline. Next to the boat, clean seawater is sucked and pumped to the jet pump which 'loosens' and sucks up the sediment. The sediment slurry then moves into the pipe extending to the beach where it is discharged. In Figure 4.17, this jet pump dredging system is illustrated.

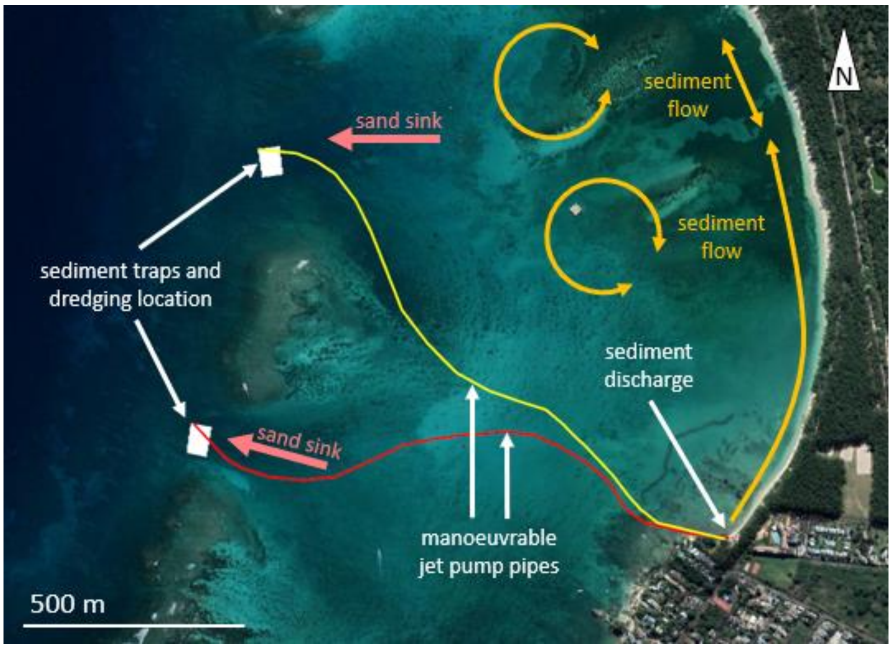

Figure 4.17 Proposed sediment traps and jet pump dredging in Man Choisy (Google Earth, 2021a)

The two 3 000 m^2 white rectangles are the proposed locations of the sediment traps in the deepest channel of the sand sinks. The red and yellow lines illustrate different positions of the same floating pipe that carries the sediment slurry from the pump to the fixed discharge point at the southern end of Mon Choisy beach. The discharged sediment will gradually move northwards due to natural longshore transport.

The pipes will need to be at least 1 500 m long to span the distance between the discharge point and the sediment traps. The pump also needs to be powerful enough to pump the slurry over this distance. However, it may be more cost-effective to have a second booster pump along the pipe length rather than one more powerful pump.

Whilst this proposal may prevent sediment from being lost from the lagoon, it is not without problems. One problem is that dredging and discharging slurry can be very disruptive to the marine environment. The benthic environment at the sediment trap will be destroyed and the water around the discharge point will contain suspended fine sediment affecting water clarity in the lagoon. Another challenge is that it is an ongoing solution that requires regular emptying of the sediment traps so that they continue to function. This may be costly. An environmental impact assessment and cost-benefit analysis would need to be undertaken to assess the environment (such as finding whether the deeper sand traps lead to detrimental changes in wave propagation or currents), as well as the financial viability of this proposal.

5.3 Mozambique

5.3.1 Overview

The World Bank (2021a) estimates that the Mozambican population was about 30.66 million people in 2019. The country is considered to be relatively poor with a GDP per capita of about USD 500 (The World Bank, 2021b). More than 40 percent of Mozambicans live within the coastal zone with especially high densities in port settlements like Maputo, Beira, and Nacala (UNDP, 2012). UNDP (2012) explains that this concentrated population is under-resourced, and thus heavily reliant on coastal goods and services for subsistence.

Coastal conditions and weather

Mozambique has a tropical climate with warm wet summers from November to April and cooler dry winters from May to October. Annually Mozambique experiences landfall of 1.5 cyclones in the central parts of the country between Ilha de Mozambique to Tofo (Theron et al., 2012; Leahy, 2019). The maximum registered wave height in the north is about 4.2 m and tends to increase further south to 6.2 m although, generally, most of the coast is subject to moderate waves partially due to the sheltering effect of Madagascar (Theron et al., 2012).

In Mozambique, Mucova et al. (2021) estimate sea-levels to rise between 0.5 m and 1.0 m by 2100 (from 2005 levels) depending on the RCP outcome (or emitted greenhouse gas concentration). A 0.5 m estimate corresponds with outcomes of RCP2.6, RCP4.5, and RCP6.0. A 0.7 m rise in sea level is expected for RCP8.5 and the most pessimistic outcome, a 1.0 m rise, is the upper limit of the likely range forecast for RCP8.5 (Mucova et al., 2021).

Coastal area

Mozambique has the longest WIO coastline of 2470 km. A variety of habitats are found along this coastline including mangrove deltas, coral reefs, and sandy beaches (Costa et al., 2005)

With about 3 000 km^2 of mangrove forests, Mozambique has the largest mangrove area in the WIO (Fatoyinbo et al., 2008). These forests are usually found in the central regions of Mozambique in the deltas of the Zambezi, Save, Pungwe, and Limpopo rivers. Mozambican mangrove forests have experienced high rates of deforestation with a reduction in cover of 27% between 1990 and 2002, especially in urban areas like Maputo and Beira (Barbosa, Cuambe & Bandeira, 2001; UNEP-Nairobi Convention & WIOMSA, 2015). Causes for this reduction are that the land is being cleared for salt pans, agriculture, firewood, dam construction, tourism and residential developments (Fatoyinbo et al., 2008).

The northern Mozambican coast has well-developed fringing coral reefs covering 1 860 km^2, however, 76% are at risk (Spalding, Ravilious & Green, 2001), and this percentage has likely increased since 2001. These reefs span 770 km from the Tanzania border to the town of Moma, and about 70% of fish caught in Mozambique can be attributed to the presence of these coral reefs (UNDP, 2012). The southern coastline from the South African border to the Bazaruto Archipelago consists of high sandy dunes spanning a distance of about 850 km (Spaldinget al., 2001; UNDP, 2012).

Mozambique boasts one of the highest diversities of seagrass species in the region with 10 species covering 4 390 km^2 along the southern sandy coastlines and the northern coral reefs (Short & Green, 2003). The country has a single salt marsh in Maputo Bay which is merged with the local mangrove forest (UNEP-Nairobi Convention & WIOMSA, 2015).

Importance of coastline

43% of Mozambicans live in dense populations in the coastal region, and are heavily reliant on coastal goods and services for subsistence (UNDP, 2012). Considering the impact of sea-level rise and a 10% increase in storm surge Wheeler, Dasgupta, Laplante, *et al.*, (2009) foresee that Mozambique will lose 3268 km^2 (40%) of its coastal land, impacting nearly 52% of the coastal population or 380 000 people. Furthermore, 78 km^2 (55%) of coastal urban areas and about 291 km^2 (24%) of the coastal agricultural area will be affected.

Current coastal status

Mozambique is the 5th most vulnerable country in the world to sea level rise by percentage area of dryland lost by 2100 (Tol, 2004). Already significantly impacted by flooding and tropical cyclones, Theron and Barwell (2012) state that Mozambique is one of Africa's most vulnerable countries to climate change. Theron and Barwell list the following as contributing to this vulnerability: large coastal plains like deltas, being prone to cyclones and high wave energy, having a soft sandy coastline, and ageing coastal defence infrastructure.

The potential increase in cyclone severity and wave energy will impact already compromised coastal defences like dunes, mangroves, and coral reefs (Theron et al., 2012). Several coastal lagoons are found in Mozambique which are only separated from the sea by sandy dunes. The rise in sea level and increase in storm surges may compromise the sheltered environments provided by these dunes and erode the inner shoreline with more direct wave attack (Theron et al., 2012). Furthermore, if sea-level rise exceeds the growth rate of coral reefs, the protection these reefs offer to sandy beaches against wave attack will be diminished, allowing coastal erosion along such shorelines (Theron & Rossouw, 2008).

As much of the central Mozambican coastal region consists of flat, low coastal plains and deltas, small increases in sea level will see a significant inland movement of the high-water mark (UNEP-Nairobi Convention & WIOMSA, 2015). This means that settlements in central Mozambique, like Beira, are at risk to inundation (Theron et al., 2012). For this reason, Beira was selected as the Mozambican case study.

5.3.2 Beira

Beira is an important port linking landlocked Zimbabwe, Zambia, and Malawi to the Indian Ocean allowing for imports and exports to international markets. According to the 2017 Mozambican census released in 2019, Beira has a population of over half a million people, making it the fourth most populous city in Mozambique.

Figure 4.18 Location of Beira (U.S. Central Intelligence Agency, 2013; Google Earth, 2020b)

The city occupies the peninsula northeast of the Pungwe and Buzi rivers which converge and flow into the Indian Ocean roughly in the middle of the Mozambican coastline (see Figure 4.18). The ocean side of the peninsula consists of a narrow stretch of low-lying dunes which are threatened by erosion from natural forces such as wind and waves, and anthropological forces such as sand mining, dune trampling, and building in sensitive areas (Macamo, 2021).

Large parts of the peninsula are low-lying wetlands making the city vulnerable to flooding during storms. This is worsened by Beira's rapid urban expansion which has not been managed in respect of ensuring proper drainage infrastructure in reclaimed land (Theron et al., 2012; Macamo, 2021). Theron et al. (2012) warned that the city was at risk of significant flooding should a cyclone pass nearby, and that this risk is projected to increase with climate change. In March 2019, Cyclone Idai made landfall slightly north of Beira, and had a devastating impact on the city and the central Mozambique region, displacing 400 000 people and killing over 600 people (Macamo, 2021). Figure 4.19 shows some of the damage and flooding in Praia Nova, Beira after Cyclone Idai.

Figure 4.19 Drone images of the destruction of Praia Nova, Beira after Cyclone Idai (Bergensia, 2019; Winsor, 2019)

In January 2021 Cyclone Eloise passed Beira. Fortunately, the city was better prepared due to the 2020-reformed National Institute for Management and Disaster Risk Reduction (INGD, acronym in Portuguese) working to proactively evacuate citizens in high-risk areas, and to provide some households with emergency kits (Macamo, 2021). The port and airport were also proactively closed until the cyclone storms had passed.

This study focuses on the south-eastern part of Beira. This area is divided into Praia Nova (shaded green in Figure 4.20), an 'informal settlement' that is located within a mangrove forest and wetland, and Ponta Gea (shaded red in Figure 4.20), a 'formal suburb' bordering a narrow stretch of sandy beach.

Figure 4.20 Praia Nova and Ponta Gea study site within Beira (Google Earth, 2022e)

5.3.3 Praia Nova

Theron et al. (2012) summarise Praia Nova as a low-lying and vulnerable area prone to inundation and erosion. This area was probably never intended to be developed, and was left as a buffer between the city and the sea. However, due to the proximity to Beira's city centre and the socio-economic challenges faced by Mozambicans, an informal settlement has been established here as shown in Figure 4.21. Praia Nova is likely populated by people looking to improve their economic opportunities by living near the centre of Beira. It appears that some of the residents sustain themselves by fishing given the number of small vessels on the Praia Nova beachfront (indicated in Figure 4.21). These people may have not realised how vulnerable Praia Nova is to coastal hazards, or perhaps they are willing to take the risk pending improvement of their economic circumstances.

Examination of the footprint of Praia Nova from the satellite images from 2004, 2013, and 2022, in Figure 4.23, highlights the vulnerable and unsustainable nature of Praia Nova. Using the Polygon Tool in Google Earth the settlement's building footprint was measured for each selected year and compared. The shoreline advancement was measured with the Ruler Tool by overlapping the polygons and measuring the perpendicular distance between two polygon edges. In Figure 4.23, the polygon footprint for each year overlays the satellite image for the two other years to highlight the change. For example, the 2004 satellite image with the 2022 footprint shows how the shoreline has advanced inland, forcing citizens into a smaller space.

Figure 4.21 Satellite view of Praia Nova informal settlement (Google Earth, 2022f)

In 2004 the structures in Praia Nova occupied a footprint of 190 000 m^2. By 2013, this area increased to 265 000 m^2 despite retreating about 50 m from the advancing shoreline. In 2022, after Cyclone Idai (2019) and Cyclone Eloise (2021), the settlement footprint had reduced to 195 000 m^2 and the shoreline had eroded a further 30 m. It is alarming to note that the coastline has advanced inland by about 80 m in 18 years.

The area occupied by a mangrove forest north of Praia Nova has reduced by nearly 35% from 76 500 m^2 in 2004 to 50 000 m^2 in 2022. In addition, the remaining density of the mangroves trees has reduced as can be seen in Figure 4.22.

Figure 4.22 Mangrove forest north of Praia Nova in 2004 (left with an overlay of 2022 coverage) vs 2022 (right with an overlay of 2004 coverage) (Google Earth, 2004a, 2022g)

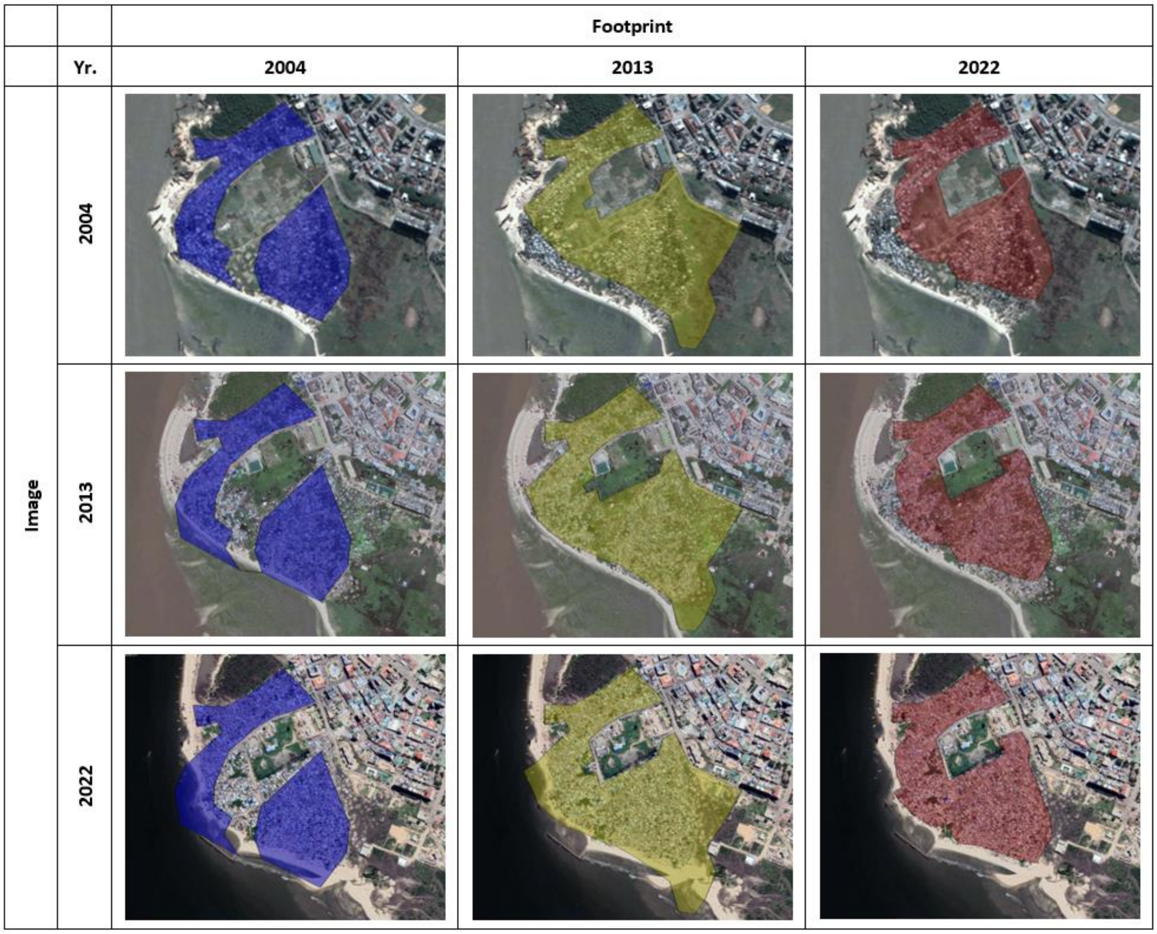

Figure 4.23 Satellite images showing the Praia Nova footprint change over time in 2004 (blue), 2013 (yellow), and 2022 (red) (Google Earth, 2004a, 2013, 2022g)

5.3.4 Ponta Gea

Macamo (2021) states that efforts had been made along the Ponta Gea coastline to control dune erosion such as the planting of casuarina trees, and the construction of groynes and seawalls. However, even before Cyclone Idai, the trees were old and dying and the hard infrastructure needed repair. During Cyclone Idai many trees were uprooted and significant damage was done to the protective hard infrastructure (Macamo, 2021). The loss of the green and grey infrastructure has made the landward civil infrastructure, such as roads and houses, more vulnerable. However, it appears from satellite images that the groynes have helped to keep the beach width constant.

Because sediment accretes on the east side and erodes on the west side of the groynes, as seen in Figure 4.24, sediment is transported from east to west. Westwards of the largest and furthest west 80-metre long groyne a sediment deficit is noticeable in Figure 4.24. Before this groyne was built, in early 2013, there were two small rock groynes around which the beach extended in a narrow 10 m wide stretch towards the Praia Nova wetland. Examining satellite images from 2012 and 2022 in Figure 4.25, one can see that since the groyne's construction in 2013, the beach on the western edge of Ponta Gea has eroded to the point that the sea threatens the properties on this side. Thus, rocky revetments have been constructed to protect these properties. Since 2012, the land has retreated over 50 m next to the leftmost triangular-shaped property in Figure 4.25.

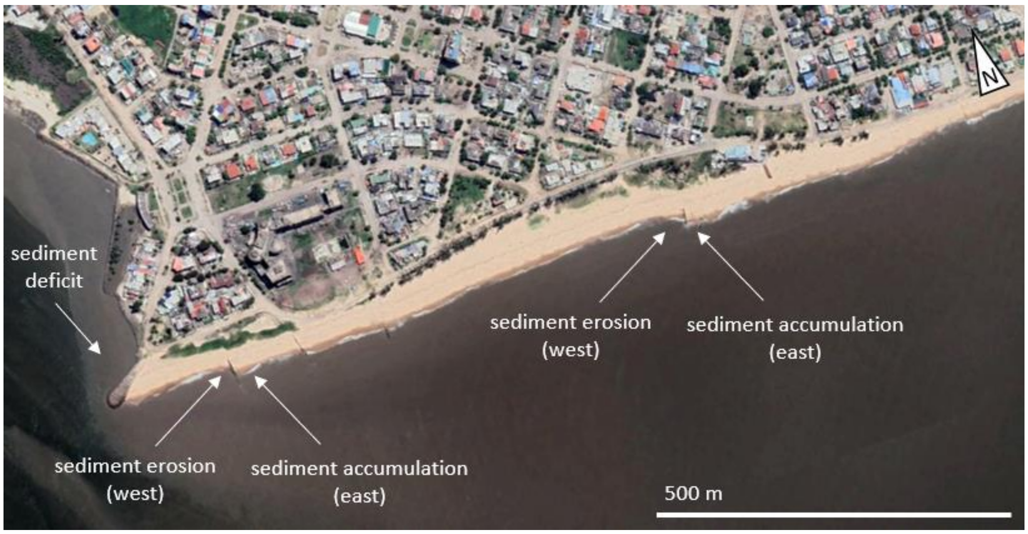

Figure 4.24 Sediment transport along Ponta Gea coastline (Google Earth, 2022e)

Figure 4.25 2012 and 2022 Satellite images of Ponta Gea beach comparing erosion west of groyne built in 2013 (Google Earth, 2012, 2022e)

Whilst the 2013 groyne cannot be the sole cause for the erosion of Praia Nova, discussed in Section 5.3.3 (as some erosion had occurred before 2013), the groyne has worsened the situation by disturbing the natural east to west sediment movement.

5.3.5 Coastal Vulnerability Index

For Beira, the adapted CVI (see **Error! Reference source not found.** in Section 3.8.1) was used, e xcluding the vulnerabilities for distance to the 20 m isobath, fringing reef percentage and number of cyclones. The 20 m isobath vulnerability was omitted because the isobath lies about 30km away from the Beira coastline (Chevane et al., 2016) and will not have a material effect between different segments (distances of 4 km or less are needed to change the 20 m isobath score). An argument could be made that cyclones should be included for Beira. However, like the 20 m isobath score it will not add meaningful information as all the segments at Beira will experience the same number of annual cyclones. For this reason, it is not considered in the CVI. Fringing reef percentage was also omitted as they are not present along this section of the Mozambican coastline.

It was decided that an additional vulnerability score should be given to the Praia Nova area facing into the estuary or river mouth which carries additional risk from river flooding. Ponta Gea did not have this additional vulnerability added as it faces the open sea.

Appendix C contains a table with all the CVI measurements and scoring for Praia Nova and Ponta Gea. Figure 4.26 captures the result from the table graphically along the coast of Beira.

Figure 4.26 Palmer's CVI applied to Beira (Google Earth, 2022e)

Beira, and particularly Ponta Gea (K to Q in Figure 4.26), has a relatively homogenous coastline and applying the CVI reveals minor variation in risk score (15 or 16 with an average of 15.6). This may be because the vulnerability score ranges originally set by Palmer et al., (2011) are not sensitive enough for Beira, especially considering the narrower ranges of the vulnerability measurements found in the Beira segments. For example, the ranges in the CVI allow for dune widths up to 150 m while in Beira the widest dune width was found to be 22 m. This limits insight into the relative vulnerability between segments as all the segments achieve the same vulnerability risk score of 4 with dune under 25 m.

Praia Nova has a more diverse coastline with a section of formal housing with hard defence (I and J), some more natural sections with a large setback (A, B, G and H), a section with an informal settlement and no setback (C, D, and F), and a section of informal settlement with partial hard defence (E). Including the estuary vulnerability factor for catchment flooding, Praia Nova is found to be more vulnerable than Ponta Gea with an average score of 18.7 (refer to Appendix C). The most vulnerable segments were A, C, and D, followed by F to H. This is a concern for the informal settlement that lies behind segments C, D, and F. Segment E is less vulnerable due to the parallel-to-shore rock breakwater which was accounted for as a rocky coastline in the CVI measurements. This is the same case for the 'formal' properties fronting the coastline with hard defences in segments I and J (assuming these defences were well designed and constructed and can withstand severe attack from the sea or the river).

Removing the estuary vulnerability applied to Praia Nova reveals Praia Nova to be less vulnerable than the Ponta Gea section with respective averages of 14.7 against 15.6. This can be attributed to some sections of Praia Nova having rocky hard defences, wider beaches, and greater setback distances at some points. However, the segments in Praia Nova with informal settlement remain as vulnerable at the Ponta Gea stretch even with the estuary vulnerability excluded.

The breakdown of the CVI measurements and scoring can be seen in Appendix C.

5.3.6 Recommendations

Praia Nova

Praia Nova was probably developed due to the socio-economic challenges that Beira, and the rest of Mozambique, face. Impoverished people are trying to move as close as possible to urban centres so that they can access economic opportunities, however, the urban centres cannot provide basic infrastructure and services for these new residents. The result is that informal settlements develop in inappropriate locations which, in this case, are vulnerable to flooding.

Addressing these socio-economic challenges of Praia Nova and Beira are beyond the scope of this study. However, these problems must be addressed to improve Beira's coastal vulnerability. The authorities could review their land ownership and urban planning policies to avoid informal settlements lacking basic infrastructure spawning and developing in vulnerable areas. Ideally, authorities will relocate these people, with their consent, to safer locations that have the basic infrastructure in place without compromising these people's economic opportunities. This may be a new location that provides an equal economic opportunity or a transport subsidy to provide the relocated people with the same or better economic access as before.

The relocation of the informal settlement to a safer location frees Beira to restore the area to its natural state, and provides a setback for the coastal edge of the city centre and a buffer from coastal hazards. The setback could also retain water during flooding. Furthermore, the buffer will help the city by providing ecosystem services like recreation, filtration, and nursery habitat.

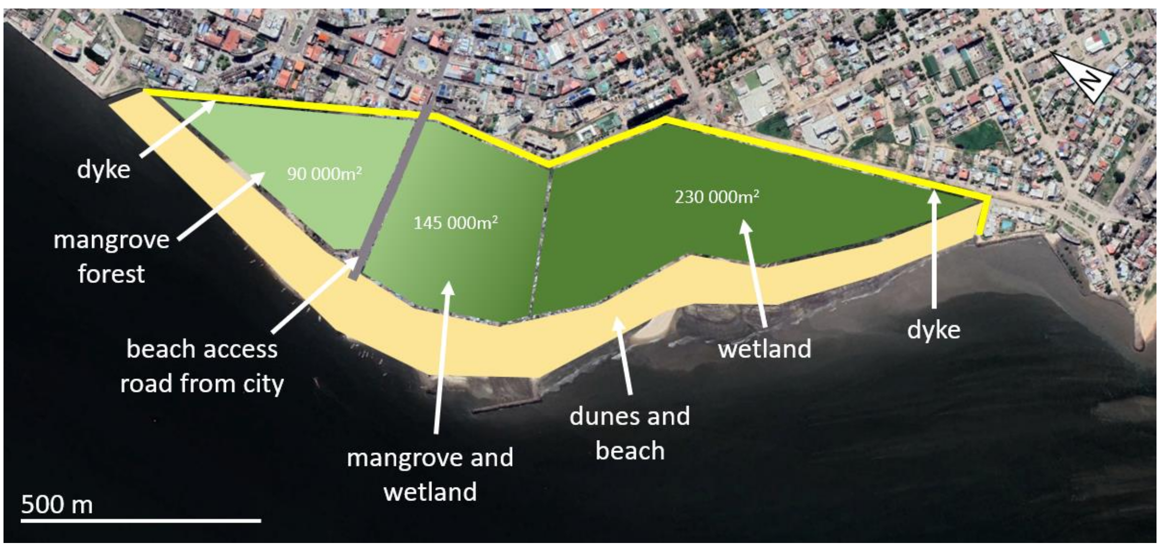

Figure 4.27 Restoring Praia Nova mangroves and wetlands (Google Earth, 2022e)

The hybrid restoration project may resemble Figure 4.27. Along the road bordering the area, a rocky dyke about 1 800 m long, indicated by the yellow line, should be constructed. The southernmost section of 230 000 m^2 should be restored to its original wetland state. The northernmost 90 000 m^2 section should remain as a mangrove forest. The 145 000 m^3 area between these two areas, in which most of the Praia Nova settlement is, could be restored to either a mangrove forest or a wetland (or a combination of both). The sandy beachfront could remain much as it is today. A road or pathway could remain to provide access to the beach from the city centre so that anglers can continue to access their vessels and the sea. The project, if implemented, will require significant effort and resources, and should be phased into three parts starting with the wetland, then the mangrove forest, and finishing with the middle 145 000 m^2 section and dyke.

Appendix F on page 144 details the step-by-step process of designing and dimensioning the rock dyke (see Figure 4.28) for the above-proposed hybrid coastal defence solution. Because the dyke is part of a hybrid coastal defence strategy it has been conservatively designed with a 2050 extreme still water level of 5.3 m (2 m storm surge + 2.9 m tide + 0.4 m SLR) as opposed to a 2100 extreme still water level of 5.9 m (2 m storm surge + 2.9 m tide + 1.0 m SLR). The reasoning is that the wetland vegetation will still be maturing by 2050 and thus not provide full protective capacity. By 2100 it is expected that the wetland will have matured sufficiently to attenuate waves and mitigate the effect of the predicted 0.6 m rise in sea level between 2050 and 2100. Furthermore, the matured wetland vegetation will reduce the scouring, and thus, the design wave height at the base of the dyke.

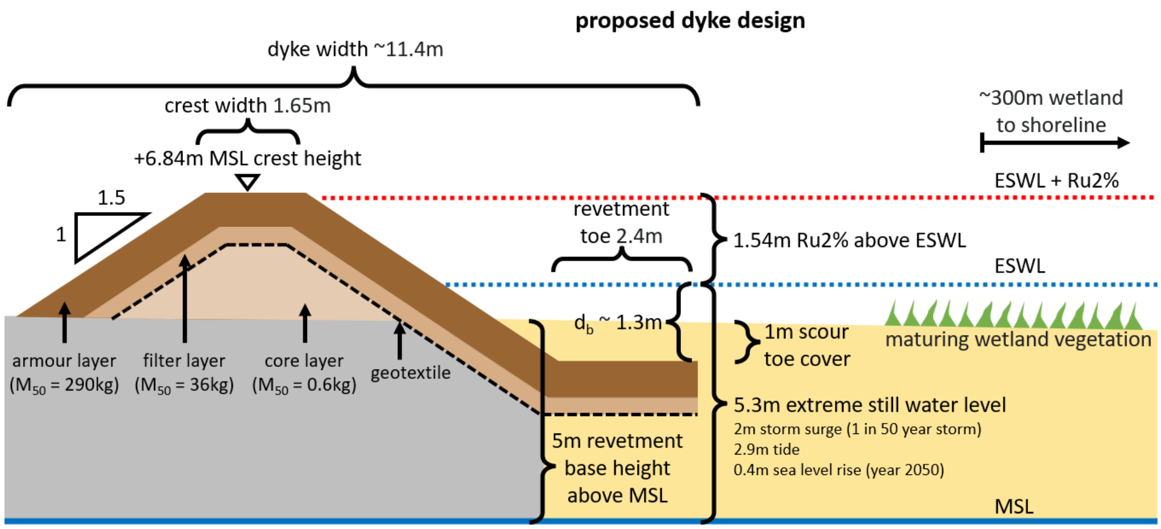

Figure 4.28 Proposed Praia Nova dyke profile

The method used in Appendix F to design the dyke follows that set out by van der Meer and Stam (1992). Firstly, the design wave-breaking depth, d_b, is estimated from the extreme still water level, ESWL, above. With this and the mean wave period, T_m, the surf similarity parameter, ξ_{0m}, was found and in turn determined the 2% exceedance wave runup level, $R_{u2\%}$. The $R_{u2\%}$ added to the ESWL determined the dyke crest height of 6.84 m, in this case. Van Gent's method was used to size the armour, filter, and core layer elements which are shown in Figure 4.28.

Should the community not be relocated, the city may need to investigate an alternative hard defence measure such as a dyke or breakwater on the existing shoreline similar to that shown in Figure 4.29. The revetment will be a much larger structure than the one above because it will experience a much larger run-up due to being five meters lower on the coastline than the proposed dyke above. Thus, the design wave breaking depth will be 6.9 m as opposed to 1.9 m. The length of this alternative structure will be approximately 2000 m.

Figure 4.29 Alternative revetment or dyke option for Praia Nova (Google Earth, 2022e)

The baseline of avoiding intervention at Praia Nova is not advised because the residents, the city and the environment will remain compromised and vulnerable in the current status.

Ponta Gea

Theron et al. (2012) propose that the preferred option for defending the southern sandy edge of Beira is to increase the beach width and volume with sand nourishment. This could be done by dredging sand from the river mouth and depositing it east near the first groynes as shown in **Error! Reference source not found.**. Due to the natural sediment transport, the sand will gradually move westwards nourishing the full sandy length of Beira. To assist the trapping of sand and widening of the beach, a 300 m to 600 m groyne can be built with rock or concrete extending from the westernmost edge of Ponta Gea (near the traffic circle seen in **Error! Reference source not found.**) (Theron et al., 2012). The eastmost groyne of Ponta Gea should also be extended to a similar length. Once the beach has been widened sufficiently, dunes can be constructed and vegetated to defend the coastline and coastal infrastructure from the impacts of climate change.

The proposal by Theron et al. (2012) acknowledges the vulnerability of the properties east of the last groyne, and it is suggested that a 400 m rock or concrete revetment be constructed to protect these properties which have also been indicated in **Error! Reference source not found.**.

Figure 4.30 Proposal to widen the Ponta Gea beaches (adapted from Theron et al., 2012; Google Earth, 2020b)

This approach, Theron et al. (2012), appears to be the most practical way to defend Ponta Gea given how narrow the coastal setback is with infrastructure bordering the narrow beachfront. To increase the coastal resilience with green coastal protection the beach width needs to be increased. The easiest way to implement this is with a sediment nourishment scheme as well as extending the groynes.

This study recommends a proposal similar to the one by Theron et al. (2012). As illustrated in **Error! Reference source not found.**, it is recommended that the beach be widened at least 75 m f rom the seaward-most infrastructure (mostly the road except for the restaurant close to the centre of the study area). This widening is done by replacing the existing groyne field with new 100 m to 150 m rock (or concrete if rock cannot be locally sourced) groynes, as well as a sediment nourishment program to feed the beach. Once the beachfront has widened to the desired width, a minimum of 25 m wide managed, vegetated dunes should be developed adjacent to the seaward-most infrastructure as shown in green in **Error! Reference source not found.**. This leaves a t least 50 m of beach width.

Figure 4.31 Proposed Ponta Gea beach widening project plan view (Google Earth, 2020b)

Below in **Error! Reference source not found.** are the existing and proposed Ponta Gea beach p rofiles at the Y-Y cross-section in **Error! Reference source not found.**. The replacement and lengthening of the old groynes and sand nourishment can widen the beach to a more appropriate width and allow for dunes to be established. The dune width of 25 m will allow a dune height of slightly more than 3 m given the dune design criteria discussed in Section 3.4.2. However, it must be ensured that the dune crest height is at least 6 m above mean sea level.

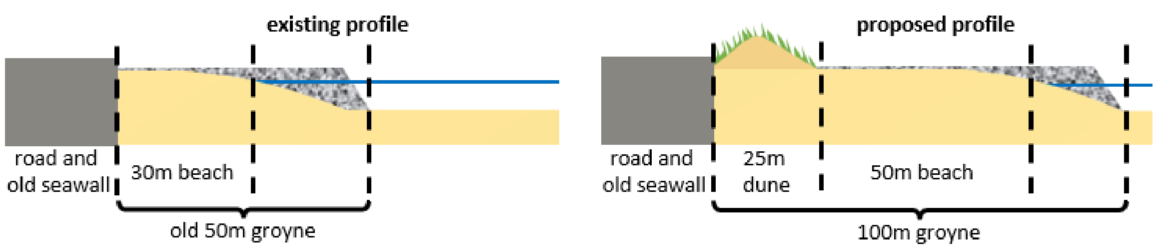

Figure 4.32 Reprofiling Ponta Gea beach at cross-section Y-Y (existing profile left and proposed profile right)

The managed dunes should be stabilised with indigenous coastal vegetation. Examples of the type of vegetation to plant may be found from nearby undisturbed coastal dunes to the north and south of Beira. The old Casuarina trees should be removed and replaced with appropriate coastal shrub vegetation. Beach access should be provided with raised boardwalks that cross the dunes diagonally to the shoreline. Perpendicular dune crossings should be avoided as these leave the dune more vulnerable to erosion during inundation than diagonal dune crossings. Signage and fencing are necessary to prevent beach users from traversing the restricted rehabilitation areas. Consideration should be given to selecting a fence that is not prone to theft or vandalism (Bundy et al., 2021). Bundy et al. (2021) also caution against using a fence that may restrict natural sediment movement.

The seafloor near Ponta Gea is shallow and of sandy composition, as can be seen with the sand banks in **Error! Reference source not found.** during what was likely a low tide and low river flow p eriod. Due to the proximity to the shoreline of these sand banks, the sediment is likely to have comparable properties to the beach sand found at Ponta Gea. Therefore, this sediment would be appropriate for a dredging and beach nourishment exercise as illustrated in **Error! Reference s ource not found.** with a cutter suction dredger. The proximity of the sediment source will also keep transport costs low. Given the shallow water depths, it is recommended that the dredger uses rainbowing to place sediment on the shore from a distance. Once sufficient sediment has been placed and accumulated along the groyne field, backhoe diggers or bulldozers can be used to construct the dunes.

Figure 4.33 Shallow sand sediment can be seen offshore of Beira in satellite images with low river flow and low tides

(Google Earth, 2015)

5.4 South Africa

5.4.1 Overview

The World Bank (2021a,b) estimated that in 2019 South Africa had a population of 58.55 million people and a GDP per capita of about USD 6 000.

The 2800km South African coastline stretches from the Namibia border where the Orange River flows into the Atlantic Ocean to Kosi Bay on the Indian Ocean near the Mozambique border. Most of the South African coast is exposed to high wave energy with few sheltered bays. Wigley (2011) points out that existing protective bays tend to have been settled and developed such as Saldanha Bay, Table Bay, False Bay, Mossel Bay, Algoa Bay, Durban Bay and Richards Bay. Around 40% of South Africans live within 100km of the coast and are reliant on this coast to some degree for transport, businesses, sustenance, and recreation (Wigley, 2011).

The South African coast can be divided into the west coast and the east coast due to the different meteorological and geological characteristics of each region and the different approaches each region requires (Bundy et al., 2021). The western and southern coasts have a wide continental shelf and are comprised of rugged rocky shores and repeating crenulate bays which are exposed to high wave energies. The fairly linear east coast has a narrower continental shelf and comprises mostly sandy beaches with intermittent small rocky headlands with coves (Palmer et al., 2011). The northern part of the east coast or KwaZulu Natal coast increases in coastal sandiness as one moves northwards with each successive river depositing sediment which accumulates in the northbound longshore sediment transport (Theron, 2016).

As the KwaZulu-Natal coast is the southern end of WIO, this study is limited to this coastline in South Africa and in particular, this study focuses on Richards Bay.

Coastal conditions and weather

The western and southern coast is affected by the cool Benguela (from the Antarctic) current and has warm dry summers and cool wet winters whilst the east coast is affected by the warm Agulhas current (from North to South) and has warm wet summers and dry winters (World Climate Guide, 2020).

The most significant and severe storm swells and wave heights in South Africa occur on the west and south-west coasts, and are generated by cold fronts during the winter months (Rossouw & Theron, 2009). These swells are experienced to lesser intensity as one moves up the east coast.

Some of the most severe waves and storm events along the east coast are generated by cut-off low cells and sometimes cyclones moving down the Mozambican channel (Guastella & Rossouw, 2012).

Coastal area

In South Africa salt marshes (as opposed to mangroves, sea grass meadows, and corals) are present due to the more temperate coastal conditions; however, they are almost exclusive to estuaries and lagoons. These marshes have a cover of 1 230 km^2, and include five marsh plant species that grow in different zones depending on the height above mean sea level (UNEP-Nairobi Convention & WIOMSA, 2015). Along northern parts of the east coast the salt marshes transition and merge with mangroves in the more subtropical conditions. With an estimated saltmarsh loss of 10% by 2100, South Africa ranks fifth most vulnerable worldwide in terms of such losses resulting from climate change (Tol, 2004).

South Africa has a limited mangrove forest cover of 300 km^2 occurring on the east coast between the border with Mozambique and Nahoon Estuary in East London (UNEP-Nairobi Convention & WIOMSA, 2015). Over 80% of this mangrove cover is in the Mhlathuze estuary near Richards Bay. Between 1980 and 2005 mangrove cover was reduced by 14% (UNEP-Nairobi Convention & WIOMSA, 2015).

South Africa has a limited coral reef cover of less than 50 km^2 within the iSimangaliso Wetland Park lying at depths of 8 m or more below the surface (Spalding, Ravilious & Green, 2001).

Importance of coastline

The South African Government Coastal Policy Green Paper published in 1998 valued the country's coastal goods and services at R179 billion (about R605 billion in today's terms taking into account an average annual inflation of 5.2%) or equivalent to 37% of the country's GDP. This accounts for, among other factors, at least 3.6 million citizens depending on the coast for subsistence, cargo transporting revenue, commercial and recreational fishing, and tourism.

Wigley (2011) reported that about 40% of South Africans live within 100 km of the coastline and rely on this coastal zone for their business, food, recreation, and transport. Wheeler *et al.* (2009) modelled the impact of sea-level rise and a 10% increase in storm surge, and estimated that South Africa is at risk of losing 607 km^2 of coastal land (of which 93 km^2 is urban land), affecting 48 000 people and compromising about 30% of GDP generated in the coastal zone.

Current coastal status

South Africa was the first WIO country to adopt a national Integrated Coastal Management Act (ICM policy) in 2000 (Francis & Torell, 2004). This act intended to ensure optimal and sustainable utilisation of South African coastal resources and to protect the coastal environment without jeopardising people or property.

Due to the relief of the South African coastline, few developed areas are at risk of inundation from sea level rise although the following areas are vulnerable; Saldanha Bay, Table Bay, northern False Bay, Mossel Bay to Nature's Valley (George, Wilderness, Sedgefield, Knysna and Plettenberg Bay), Port Elizabeth and urban areas on the KwaZulu Natal coast (Theron & Rossouw, 2008).

Tidal gauge data between 1993 and 2018 has shown that sea levels are rising around 3 mm per year which is in line with the global mean sea level rise. However, Allison, Palmer & Haigh (2022) project that by the end of this century South African sea levels will have risen by approximately 0.5 m (0.25–0.8 m) following RCP2.6, or around 0.85 m (0.5–1.4 m) following RCP8.5. This is about 7% to 14% higher than that which is projected for global mean sea level rise. The difference in the global mean sea level rise is attributed to how the oceans circulate around South Africa and local seawater density (Allison, Palmer & Haigh, 2022). The rotational and gravitational forces also contribute to the expected local sea-level rise being higher than the global average.

5.4.2 Richards Bay

Richards Bay is a regional economic hub and port town found on the Mhlathuze River estuary on the Kwa-Zulu Natal coast of South Africa. In the 1970s the Mhlathuze River was diverted, and the estuary was divided in half. The southern part continues to function as an estuary whilst the northern portion was developed into the largest coal export port facility in the world at the time. Currently, in addition to the coal terminal and general cargo facilities the port supports the nearby dune mining activities (extraction of iron ore, rutile, and zircon) and an aluminium smelter.

Before the 1970s long-term records indicated that the northern beaches were dynamically stable, not experiencing long-term net erosion or accretion (Theron, 2008). Estimations and models found the longshore transport rate along the beaches north of the port entrance to be about 900 000 m^3 per annum (800 000 m^3 per annum (Coppoolse & Schoonees, 1991; Laubscher et al., 1991); 850 000 to over 1 000 000 m^3 per annum (Schoonees, 2000); 900 000 to 1 000 000 m^3 per annum (Soltau & Theron, 2006; Theron, 2008)).

In 1977, breakwaters were constructed to create a formal entrance channel to the harbour. The entrance channel extends past the shoreline, interrupting the natural northbound longshore sediment transport (Coppoolse, Schoonees & Botes, 1994). This results in sediment accumulating at the southern breakwater and in the deepened entrance channel whilst the coastal processes continue to move sediment along the coastline north of the breakwater. Thus, without intervention, the northern shore will erode due to this imbalance. To address this, a sediment bypass scheme has been implemented with a dredging vessel that collects accumulated sediment from the southern breakwater and discharges it beyond the northern breakwater at Alkantstrand Beach. The dredging is also important to ensure that sediment does not enter the entrance channel and reduce channel depth, risking ship grounding (Rautenbach & Theron, 2015). Figure 4.34 is a satellite image showing schematically where the dredger feeds dredged sediment into the bypass scheme, and the discharge point on Alkantstrand Beach.

Figure 4.34 Satellite image capturing the dredging process at Alkantstrand, Richards Bay (Google Earth, 2022f)

Theron (2008) reports that between 1989 and 2005 an average sediment volume of 607 000 m^3 per annum was pumped to nourish the beach. This means that the flow of sediment along the beaches north of the breakwater is still being starved of about 300 000 m^3 of sediment per annum, given the natural sediment volumes of 900 000 to 1 000 000 m^3 per annum, and continues to be prone to erosion. Table 4.2 summarises the more recent underperformance of the planned dredging volumes.

Table 4.2 Budgeted and achieved dredging volumes of Richards Bay for financial years 2011 to 2014
(adapted from Rautenbach & Theron, 2015)

Financial year	Budgeted volumes	Achieved volumes
2011-2012	1 250 000	662 000
2012-2013	1 250 000	753 000
2013-2014	1 151 000	253 000
2014-2015	836 000	291 000

Theron (2008) attributes some of the dredging deficit to the fact that the beach south of the breakwater has accreted such that the beach angle has changed relative to the approaching waves. This change has resulted in less sediment being moved into an accessible location for dredging. Sediment is also lost into the entrance channel where it is difficult for the dredger to retrieve without interrupting port operations (Rautenbach & Theron, 2015).

Figure 4.35 shows the focus area of this section, the northern erosion-prone beaches, especially the first 6 km starting immediately north of the entrance channel of Richards Bay port from Alkantstrand Beach (28°48' 05" South, 32° 05' 45" East) to the northern edge of the uMhlathuze Municipality (28°45'50.00" South, 32° 8'25.00"East).

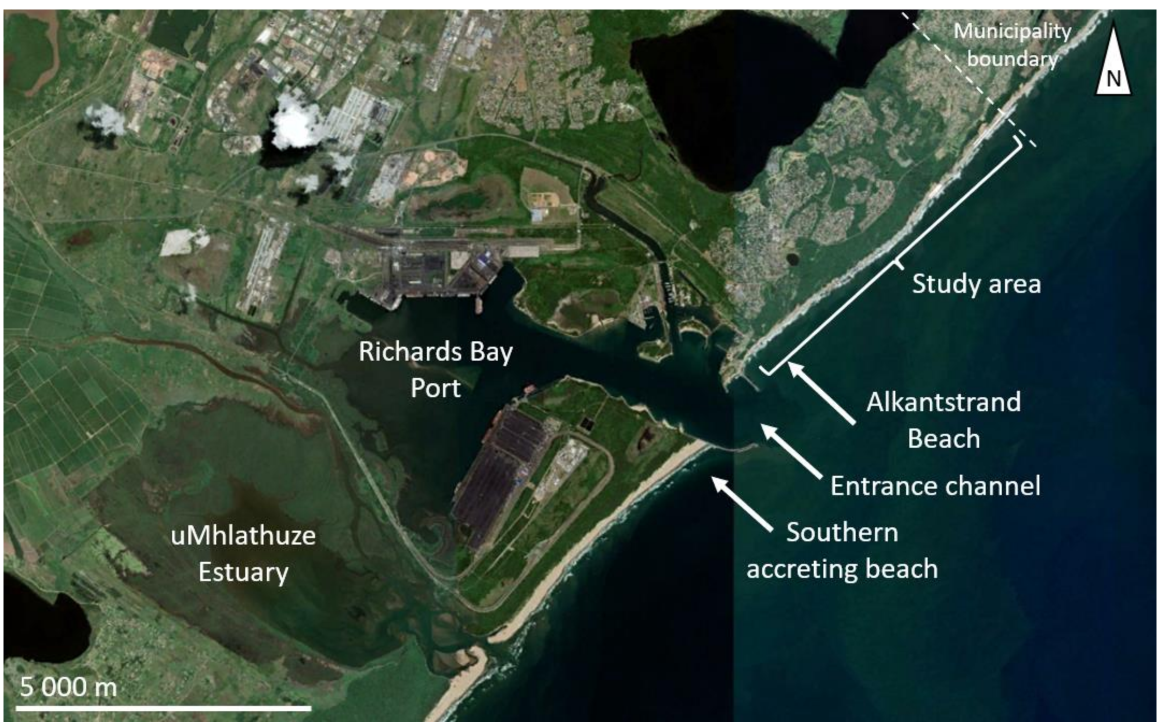

Figure 4.35 Satellite image of Richards Bay Port (Google Earth, 2021b)

The impact of sediment starvation and subsequent erosion of the Richards Bay northern beaches is clear from two cases that are featured regularly in various local media reports, namely Alkantstrand Lifeguard House and the Richards Bay Lighthouse. These two examples clearly illustrate the unstable nature of this stretch of coastline. Figure 4.36 shows the locations of these two cases which are discussed in more detail below.

Figure 4.36 Two examples of infrastructure threatened by erosion at Richards Bay (Google Earth, 2021b)

Alkantstrand Lifeguard House

Alkantstrand Beach has a lifeguard station off the northern breakwater (see Figure 4.36). As reported repeatedly by Zululand Observer, the erosion of Alkantstrand Beach was threatening the lifeguard facility and by 2014 and 2015 some of the paving surrounding the building had washed away. Figure 4.37 shows the extent of the beach recession that was encroaching on the lifeguard facility.

In 2015, the City of uMhlathuze responded to the emergency by placing eleven overlapping rows of 2.8-tonne geotextile bags in front of the lifeguard house, and another section 200 m northwards. The project cost R24 million and has an annual maintenance cost of R2 million (Ndonga, 2018). According to CoastKZN (2021), the intervention has been successful in protecting the coastline locally. However, after six years some bags have begun slipping (see Figure 4.38) and, if not replaced, there are concerns that the intervention will lose its protective capacity at an accelerated rate.

Figure 4.37 Erosion of the Alkantstrand Beach threatening the lifeguard house (Zululand Observer, 2014)

Figure 4.38 Geotextile bags slipping compromising the defence (Zululand Observer, 2021)

Richards Bay Lighthouse

When built in 1979, the Richards Bay Lighthouse was located 200 m from the dune cliff edge (SAHRIS, 2019). Gradual erosion and sudden dune slips have resulted in the cliff edge retreating.

In April 2018, the lighthouse was demolished due to concerns that it was in eminent danger of collapsing. Within two months after the demolition, the old lighthouse location had eroded. Transnet replaced the lighthouse with a temporary LED long-range beacon mounted on a steel structure. Transnet has also proposed and received approval to move the lighthouse to a permanent location 500 m west-northwest of the current location to an undeveloped piece of municipal land. The new location is about 200 m inland from the existing cliff edge.

Figure 4.39 compares the approximate location of the 1979 cliff edge with the 2004 lighthouse location and 2021 cliff edge. The 1979 cliff edge was approximated from the 200 m setback description by SAHRIS (2019) and the location of the lighthouse before demolition. The cliff edge had eroded by approximately 145 m between 1979 and 2004 and 55 m between 2004 and 2021.

Figure 4.39 Satellite images comparing the erosion near the Richards Bay Lighthouse from 1979 (orange line), 2004 (left), and 2021 (right) (Google Earth, 2004b, 2021b; Sailing, 2018)

5.4.3 Coastal Vulnerability Index

Palmer et al.'s 2011 CVI study divided the length of the KZN coast into 50 m by 50 m squares which were assigned scores for each vulnerability parameter as discussed in Section 3.8.1 and **Error! Reference source not found.** (beach width, dune width, distance to 20 m isobath, vegetation distance behind beach, and percentage outcrop). High vulnerability scored a maximum of 4 points whilst low vulnerability scored a minimum of 1 point. The cumulative vulnerability score indicates the risk. Scores of less than 14 are low risk, scores of 15 to 18 are moderate risk, and scores of 19 and more are high risk. The results of the study are visually presented online at https://maps.coastkzn.co.za/CoastKZN/, and the section of the Richards Bay northern beaches has been extracted and is shown in Figure 4.40.

As seen in Figure 4.40, Palmer et al. (2011) found that between Alkantstrand and the uMhlathuze boundary most of the coast (74%) consists of moderate coastal risk (amber) segments whilst there are also some (15%) high coastal risk (red) segments. Compared to the rest of the KZN coast (which has a length of 68% with moderate vulnerability and a 12% length with high vulnerability) this section is more vulnerable.

Figure 4.40 Palmer et al.'s CVI of Richards Bay (CoastKZN, 2022)

In applying the adapted CVI developed in this study, and using the coarse 250 m segments, (see Figure 4.41), slightly different results were obtained than those above. However, the results were not dissimilar. Some sections of the coast showed lower risk (especially in the middle section, J to T) and the high-risk area moved to Alkantstrand (A to C). The difference in results could be attributed to different survey dates, interval sizes, and different data extraction techniques. Palmer et al. (2011) used orthographs captured in 2007 whilst this study used 2022 satellite images from Google Earth, and there have been some physical changes in the interim such as the lighthouse erosion. Palmer et al. (2011) used a finer interval of 50 m while this study uses a courser interval of 250 m. Finally, Palmer et al. (2011) used computer software to extract the necessary data whilst in this study data was manually measured on Google Earth and captured in MS Excel. The data captured in this study can be found in Appendix D.

Figure 4.41 Adapted CVI applied Richards Bay Beaches (Google Earth, 2022f)

It was found that the first 2 km from the break water were the most vulnerable, particularly the first 750 m (A, B, and C) (Alkantstrand Beach) which scored over 19 points. Section D to H cover the camp site that has been developed near the cliff edge which resulted in a narrow vegetated buffer from the beach and thus a higher score. J to T has a deep vegetated setback before any infrastructure resulting in a lower risk score. Interestingly, sections that have eroded recently (since Palmer et al.'s study) appear to have reduced in risk such as sections O to T covering the former lighthouse location. This may be due to the mudstone having been exposed recently and becoming clearer in the satellite image (contributing to a lower score for a rocky shore). Another contributing factor to this section's lower score is due to the wider dune section which resulted from the cliffs eroding. This, however, will be a temporary reprieve, as the present sediment deficit and resulting erosion will recede the shoreline to the dune toe. Currently, U to X is at moderate risk due to the encroachment of the settlement and subsequent narrowing of the vegetated buffer.

5.4.4 Recommendations

The coastal protection strategy of the northern beaches of Richards Bay should address the primary cause of erosion which is insufficient sediment bypassing the harbour entrance. Whilst an active bypass scheme is currently in place, unfortunately it is not maintaining the historic longshore sediment transport volumes. This imbalance is resulting in the coastline eroding continuously. Therefore, every effort must be made to increase the annual sediment bypassing to 950 000 m^3. If these volumes are not achieved other coastal protection measures are likely to be required.

A capital sediment nourishment project is an option to quickly increase the beach sediment volume to the desired beach width that provides the necessary protection for the lifeguard house and surrounding infrastructure. This mitigates the immediate risks to this infrastructure, and quickly improves the beach's appeal to beach users. Thereafter the 950 000 m^3 sediment by-pass volume can maintain the beach width achieved in the capital project. The sediment for a capital nourishment project can be sourced from the accreting beach adjacent to the south breakwater. Theron (2008) points out that the realignment of this beach may also increase the rate of sediment accumulation in the sand trap, and will provide more sediment for the northern beach nourishment.

However, any beach widening program should be cognisant that beach volumes above a certain amount will also pose problems, especially near the breakwater. This is due to strong rip currents forming parallel to the breakwater during storms. These may 'suck' sediment from the area where the breakwater meets the beach, and deposit it at the end of the breakwater where it spills into the entrance channel causing vessel navigation issues.

The geotextile sandbags have temporarily halted the rate of shoreline retreat with some success, but they are not expected to continuously reflect wave energy. Furthermore, geotextile revetments are not intended to disperse wave energy which means that when they deflect waves, they can increase the rate of sediment erosion in front of them. This can cause revetment instability where bags begin to slip. This is probably what happened in 2021.

The 2021 damage to the revetment needs to be repaired urgently, as the surrounding bags are compromised when one bag slips out of place. This may result in the rest of the revetment failing relatively quickly, and the shoreline eroding rapidly as if the revetment had never been there. Even if the revetment is repaired it should be expected that the failure will continue to occur as the beach width narrows due to the continuous wave reflection and subsequent erosion. Bags may even slip under normal conditions and not just during storms.

Geotextile sandbags work best as a last defence (such as a sleeping defence within a dune that has eroded during a storm), or temporary emergency measure (such as temporarily protecting vulnerable infrastructure immediately after a storm), and not as a permanent solution which seems to have been intended at Alkantstrand. For the sandbag revetment at Alkantstrand to be the 'last defence,' the beach needs to be widened so that the waves do not reach the revetment under normal conditions. Covering the sandbags with sediment to create a dune also improves the longevity of the sandbags from UV damage and vandalism.

Vegetating the dune and thereby trapping windblown sediment, will further increase the beach's resilience. In the 2016 dissertation by Theron, it is recommended that vegetation buffers for trapping wind-blown sand at Richards Bay should be 15 m wide. The vegetation will be able to naturally regrow after experiencing limited seasonal erosion. However, intervention will be required to rehabilitate the vegetated area after severe storm erosion.

For illustration purposes, a capital nourishment project is estimated for cross-section Z-Z in front of the lifeguard house as shown in Figure 4.42. It was decided arbitrarily that the Alkantstrand beach should be restored to a profile such as that in the early 2000s. At that time, the beach was about 70 m wider than at present at cross-section Z-Z in Figure 4.42.

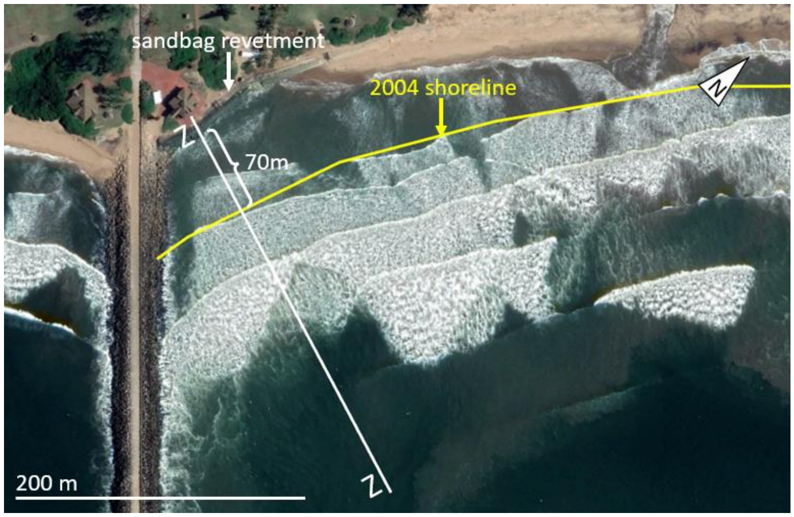

Figure 4.42 Cross-section Z-Z used to estimate a capital nourishment project with the 2004 shoreline 70 m seawards from the present (Google Earth, 2004b, 2022f)

Without site surveys, it is challenging to determine the capital volume needed to restore the beach to this profile. However, in Appendix G on page 147, using Dean's Beach Equilibrium equation, the depth 70 m from the current shoreline is estimated to be -2.00 m. Therefore, the seafloor needs to be raised by 2 m for the first 70 m. The distance to the depth of closure was not found in the literature, but was assumed to be about 225 m, approximately half the length of the 450 m breakwater. From this, the recommended beach profile was drawn, as seen in Figure *4.43*.

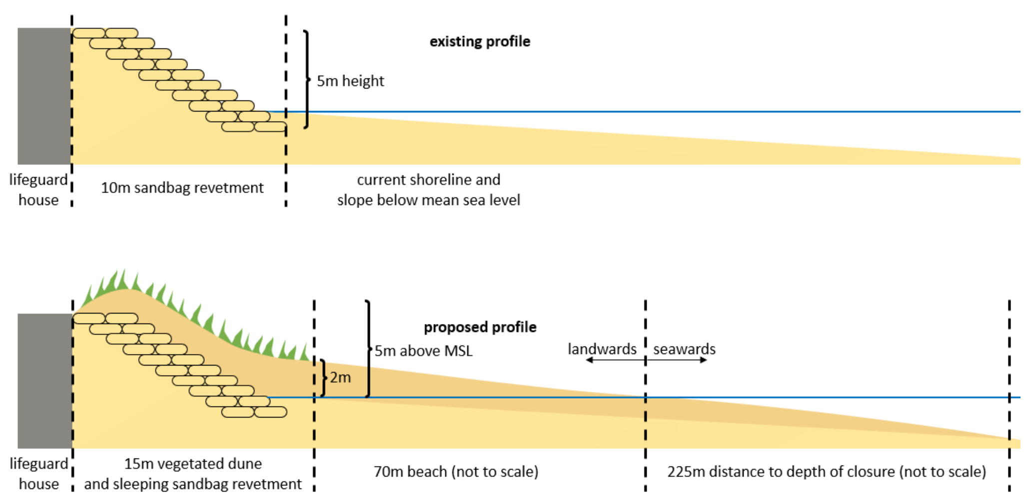

Figure 4.43 Existing and proposed Alkantstrand profile on cross-section Z-Z with the new sediment shown darker

Figure 4.43 is used to estimate the capital nourishment volume. Landwards one needs 2 m over 85 m (70 m beach width and 15 m vegetated dune sleeping revetment) and seawards one needs a triangular area from the 2 m height at the shoreline to the depth of closure 225 m away shown in Figure 4.43. This works out to a volume of 170 m^3 per m and 225 m^3 per m, respectively which gives a total of 395 m^3 per m. If this is applied to the first kilometre north of the breakwater for the most vulnerable 250 m-sections at Richards Bay (A, B, C, and D) a capital sediment volume of about 395 000 m^3 will be needed. Another factor to be cognisant of is the annual sediment deficit may increase with the effects of climate change and possible future increase in wave energy storminess. Thus, the sediment nourishment volumes may need to be increased with time to compensate for possible increases in the sediment deficit.

For the coastline beyond the first 750 m (Alkantstrand), it is recommended that an adequate development setback line is followed to avoid developing infrastructure that may become vulnerable within its design life. Existing infrastructure, such as the campsite facilities (along sections D, E, and F) or the residential area (along V, W, and X) should not be upgraded at the end of its design life, but retreated inland. This approach can be reviewed if it is found that increased sediment bypass volumes prevent further erosion, and the shoreline position stabilises or accretes seawards.

6 RECOMMENDATIONS AND DISCUSSION

6.1 Summary of case study recommendations

In Mauritius, proposals were made for the Albion Lagoon and Mon Choisy Beach, and an alternative coastal defence strategy was suggested for Case Noyale. Albion is an enclosed lagoon in the centre of the western Mauritian coast and is an unusual site because it has not had any coastal defences implemented. However, the lagoon is vulnerable to erosion due to anthropological actions (such as unregulated fishing and tourism) damaging the coral reef that shelters the bay and the seagrass beds that stabilise sediment. Other threats include warming sea temperatures and sea level rise. Successful small-scale coral propagation trials have been done within the lagoon. With a sufficient budget, this could be scaled into a larger lagoon-wide restoration project. It is recommended that an artificial reef be constructed on the seaward side of the lagoon to reduce the wave energy entering the lagoon, using reef balls which can be seeded with coral fragments and support marine life. Once completed, the seagrass bed and coral reef should be restored by the propagation of seeds and coral fragments. The activities in the lagoon should be monitored so that destructive activities are limited. An example may be to licence motorboats in the lagoon and create a dedicated boating area.

Mon Choisy is a popular tourist beach on the northern coast of Mauritius with a few hotels nearby. The surrounding lagoon experiences direct and indirect anthropogenic threats similar to Albion which is reducing the cover of protective coral reef. This exposes the lagoon to higher wave energy and reduces the volume of coral sediment feeding the beaches. These two factors, as well as inappropriately located private groynes, are causing the southern end of Mon Choisy to erode. The beach is backed by invasive casuarina trees that are not effective in retaining beach sediment and causing unattractive beach scarping. In 2018, the Mauritian authorities acted on recommendations to build an artificial reef with reef ball units, and to regrade the southern beach slope to reduce erosion in this section. The project included removing casuarina trees and constructing a vegetated dune behind the beach. This study recommended that the dune restoration and beach regrading project be extended along the rest of Mon Choisy. Depending on the success of the artificial reef, it could be extended to other vulnerable sections of the lagoon. To combat the negative sediment budget in the lagoon a sediment trap and nourishment scheme is recommended. Sediment trapped in the lagoon's sand sinks could nourish the southern beaches with a manoeuvrable jet pump dredger system.

Case Noyale is a small collection of houses and municipal offices in southwest Mauritius. The site was investigated as an example of where a green coastal infrastructure project could have been implemented instead of the newly constructed hard infrastructure with the same level of protection and with the additional benefit of ecosystem services. Here, the vulnerable road and surrounding infrastructure are defended with two rock groynes and a gravel beach. This was a strange choice as the site has two mangrove stands on either side of the new gravel beach, and it may have been suitable to adopt a mangrove restoration solution.

The Mozambican case studies described two adjacent areas in Beira, namely Ponta Gea and Praia Nova. Ponta Gea is a suburb that fronts a narrow groyne-stabilised sandy beach. The existing infrastructure has protected Ponta Gea well. However, it is old and in need of repair, especially after recent cyclones. This study recommends that the beach be widened by at least 75 m with a hybrid sand nourishment-groyne approach. The existing groynes should be replaced with groynes between 100 m and 150 m long, and with a 250 m terminal groyne. Sediment for beach nourishment can be sourced near the river mouth and placed on the east of the groyne field to 'naturally' nourish the beach via sediment transport. Once the beach has widened, the landward-most 25 m should be developed into a vegetated dune that replaces the casuarina trees presently in site.

Praia Nova is an informal settlement that has developed near the city centre over a wetland and mangrove forest area. The residents, likely seeking better economic opportunities by living here, are very vulnerable to flooding and erosion, especially during cyclones. This study recommends that the residents be moved to a safer location, and that the area be restored to its original state creating a coastal buffer for the city. The proposed restoration project also includes constructing a dyke along the city edge to create a hybrid coastal solution in conjunction with the wetland and mangrove forest.

In South Africa, the beach north of the Richards Bay harbour entrance was chosen for investigation. The site is an interesting one because of the sediment by-pass scheme in use at the Richards Bay Harbour mouth. The CVI revealed that the southernmost 750 m of shoreline comprising Alkantstrand Beach is most vulnerable due to many years of erosion caused by insufficient sediment by-pass volumes. This threatened the lifeguard house at Alkantstrand, and the town responded by building a geotextile sandbag revetment in 2015. However, this structure is beginning to fail. This study recommends increasing the sediment by-pass volumes, and that authorities adopt a capital nourishment project to replace the lost sediment, and hence to widen Alkantstrand beach. The sediment can be sourced from the beaches south of the harbour entrance which have accreted. This presents an opportunity to realign the beach such that more sediment moves into the sediment trap. This may increase the volumes captured within the existing sediment nourishment program and assist to achieve the historical volumes, which will reduce the rate of erosion.

Table 4.3 summarises the recommendations discussed above and in Chapter 5. A colour key has been used in the last row of the table, categorising the range of infrastructure from grey to green.

Table 4.3 Summary of proposed coastal protection interventions at case study locations

Country	Case Study Location	Current vulnerabilities or threats	Existing interventions	Proposed Interventions
Mauritius	Albion	Eroding coastline	None	1. Construct an artificial reef breakwater
		Reducing coral cover (reducing sediment source)		2. Restore coral reef
				3. Restore seagrass bed
		Reducing seagrass cover		Regulate nautical activities
		Destructive fishing and tourism practices		Regulate building setback lines
	Case Noyale	Degraded site threatening infrastructure and road	Gravel beach between 2 breakwaters	Alternative: mangrove forest restoration
	Mon Choisy	Eroding southern beach (interrupted longshore sediment flow)	Dune restoration	Extend dune restoration
				Replant with native vegetation
		Loss of sediment in lagoon	Replaced Casuarina trees	Sediment trap and sediment nourishment
		Destructive tourism practices	Artificial reef on 2 m bathy	Regulate nautical activities
				Possible: Extend artificial reef on 2 m bathy

Mozambique	Ponta Gea	Narrow coastal buffer Deteriorating vegetation cover and loss of trees Inappropriate casuarina trees planted	Historically casuarina trees planted Historic seawall Historic groyne field	1. Construct new 100 m groyne field and 250 m terminal groyne 2. Implement sediment bypass scheme to widen beaches 3. Construct 25 m wide vegetated dunes and remove old trees
	Praia Nova	Extremely vulnerable informal settlement Inundation Reducing mangrove and wetland cover Eroding coastline	150 m breakwater Revetment along formal properties	Relocate community 1. Construct 2 km dyke along city edge 2. Restore 230 000 m^2 wetland 3. Restore 90 000 m^3 mangrove forest 4. Restore remaining 145 000 m^3 Alternative: Construct 2 km 224 000 m^3 dyke
South Africa	Richards Bay	Insufficient sediment by-passing Eroding coastline threatening infrastructure	Geotextile sandbags revetment which has begun slipping	Capital nourishment of Alkantstrand Increase sediment by-pass volumes to 950 000 m^3 per year Maintain appropriate development setback
Colour key:	Green or soft defence	Hybrid infrastructure	Grey infrastructure	Policy interventions

6.2 General recommendations for WIO

The case studies have illustrated some ways in which the green and hybrid coastal defence approaches, discussed in Sections 3.4, 3.6, and 3.7, can be used by WIO countries in responding to coastal hazards. However, before investigating coastal defence approaches, designers should be cognisant that 'defence' is one of four options in responding to coastal hazards. Sometimes choosing one of the other three options, to retreat inland, accommodate the changes, or to 'do nothing' may result in a more favourable outcome than defending the coastline.

If it is decided that coastal defence is the best approach, it is important to fully understand the coastal geomorphology, ecological processes, and socio-economic environment at the site. It is recommended that WIO countries consider monitoring the annual changes along their coastlines, and regularly check the condition of infrastructure after extreme events. This, with bathymetric surveys every ten years at important or vulnerable sites, will contribute to understanding the coastal geomorphology and ecological processes active along the coastline of WIO countries.

The chosen coastal defence measure should be selected for its effectiveness in responding to the coastal hazards in the context of coastal geomorphology, ecological processes, and socio-economic factors. In their design phase, coastal defence strategies should take cognisance of the maintenance, and long-term financial requirements, environmental impacts, and social effects. This is especially important in the WIO region given the limited resources at the disposal of WIO countries.

Whilst WIO countries are generally under-resourced, there are charitable international organisations that appear to be keen to assist developing countries in combating the effects of climate change. At the most recent United Nations Climate Change Conference in 2021 (COP26), developed countries pledged a USD100 billion annual climate finance fund for developing countries. A portion of this finance is intended for climate adaptation. WIO countries should welcome these opportunities as collaborative exercises, sharing knowledge and expertise whilst developing innovative greener coastal protection strategies.

Stakeholder engagement is particularly important in the WIO region because of the diverse socio-economic relationships that the WIO population has with its coast, ranging from subsistence anglers to large hotel chain owners. It is important to engage with and involve all affected stakeholders in the decision-making process in an equitable way so as to ensure that no one is left compromised because of a decision taken without their involvement.

7 CONCLUSION

7.1 Study objectives

This study focused on green coastal protection strategies that can be adopted by countries in the Western Indian Ocean to respond to coastal hazards. The region has a large under-resourced coastal population of sixty million people who are vulnerable to the effects of climate change in the coastal environment. The region needs sustainable and affordable solutions to protect its coastlines and coastal populations.

Firstly, a literature review was conducted on the range of coastal protection infrastructure un use. Traditionally engineers have turned to hard or grey infrastructure, such as breakwaters and seawalls, to defend vulnerable coastlines. However, the literature indicates that the sustainability of hard-engineered solutions is beginning to be questioned, and awareness is being raised on soft or green alternatives. Natural ecosystems can adapt to changes such as coral reefs that can grow vertically, or mangroves and wetlands having the ability to retreat inland with rising sea levels. This is an advantage over traditional hard engineering solutions which are static. Another benefit is that natural ecosystems can regenerate after storms, while hard engineered solutions need to be maintained or repaired before the next storm should they be damaged. Finally, natural ecosystems offer benefits to people living near the coastline such as recreational opportunities or sustenance provision from fish nurseries.

Hybrid approaches that combine both grey infrastructure and green infrastructure solutions are discussed as an option to gain the benefits of both approaches, such as revetments fronted by wetlands, or sleeping defences within dunes. Eco-friendly hard infrastructure is also discussed as “green” hard infrastructure so that the environment gains some ecosystem services.

Literature was gathered on the development of the coastal vulnerability index (CVI) to quantify the relative vulnerabilities of coastlines. This study explored how the method has changed over time and has been adapted to suit different regions around the world. The CVI by Palmer et al. (2011) was appealing in the context of this study due to the choice of measurement of variables. In this CVI the variables are easily obtainable and measurable from satellite images and are not reliant on detailed coastal surveys or historical records of coastal data which may be limiting for under-resourced developing countries. This CVI was adapted for the current study by including vulnerabilities relevant to the Western Indian Ocean such as the presence of coral protection from the CVIs by Theron et al. (2010) and Theron (2016). These variables include the beach width, dune width, rocky outcrop percentage, distance to the 20m isobath, vegetation distance behind the beach, fringing coral percentage, cyclones per annum and estuarine mouth environments.

Traditional approaches to evaluating project proposals in the context of coastal engineering overlook the ecosystem services provided by soft infrastructure, as they were not relevant for conventional hard engineering projects. This study investigated some of the new ways that the literature proposes to account for the ecosystem services of soft infrastructure in developing a more robust evaluation matrix for both hard and soft engineering project proposals.

In line with the last objective of this study, proposals were made on how green infrastructure could be incorporated into the coastal protection strategies using case studies for three countries in the WIO: Mauritius, Mozambique, and South Africa.

7.2 Further study

7.2.1 Coastal Vulnerability Index

The CVI developed by Palmer et al. (2011) which was adapted for this study did not account for the coastal dune crest elevation landward of the shoreline. This variable is worth including in future CVI studies because the height of a dune indirectly influences the sand reservoir volume that can nourish a beach during extreme events (and thus the protective capacity provided by the dune). At the time that this study was done, the satellite image programme used, Google Earth Pro, did not provide the height estimates. However, the online version of Google Earth did include an estimated height to the nearest meter above sea level, for the cursor location on the satellite image. These values were not found to be very consistent for the case study locations investigated in this document. However, they will likely be refined and improved to the point that the coastal elevation variable could be included in future CVI studies.

Another CVI variable that could be added to the adapted Palmer CVI is the degree of protection from prevailing wave exposure. This variable requires a wave rose to find the prevailing wave direction, and a relatively basic analysis of the satellite image to determine which areas are sheltered and which are exposed. The case studies used in this document did not cover a large area and thus this variable would not have made much difference. However, studies considering larger coastal areas such as whole bays or peninsulas could consider including such a variable.

7.2.2 Cost evaluation and cost-benefit analysis

Costing of each of the recommendations was beyond the scope of this study, but it would be a worthwhile exercise to pursue in future studies. For any of the proposals made in this study to be implemented, their cost needs to be feasible and justifiable compared with grey infrastructure alternatives, especially considering the limited financial resources of WIO countries. However, fortunately, there appears to be an appetite for international funding organisations to make resources available for developing countries to evaluate climate change adaptation strategies such as the Mon Choisy beach restoration project, and the aid provided to Beira after Cyclone Idai.

Furthermore, such costing studies will be able to reach conclusions by evaluating and comparing green coastal defence options against grey coastal defence alternatives using the CBA information covered in Section 3.8.2. These studies can also assess the different cost evaluation techniques that were covered in Section 3.8.2. For example, studies addressing Praia Nova's coastal defence strategies within the social context could consider using the participatory or stated preference valuation process that engages residents, city planners, and other affected stakeholders in an equitable way.

Once the costing exercise and CBA have been completed, the *Design and Planning* process can be iterated until the most advantageous design is identified which falls within the budget limitations as well as meeting the original design objectives.

7.2.3 Modelling

Future studies could assess whether the proposed recommendations in this document achieve their objectives using models or simulations. Examples of models or simulations may include evaluating the artificial reef proposal for the Albion lagoon, the sand trapping proposal for Mon Choisy, the groyne field and capital nourishment for Ponta Gea, the restoration area of Praia Nova, or the increased sediment bypass volume effect for Richards Bay. The process of modelling may iteratively improve the proposal until the best solution is found.

7.2.4 Develop guidelines for green coastal defence and hybrid defence

One of the reasons that green and hybrid coastal defences do not enjoy widespread implementation may that there are no established guidelines or manuals to assist with their implementation. Research that focuses on developing such guidelines is crucial for the general acceptance and adoption of green and hybrid coastal defences.

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APPENDIX A: Development of the Coastal Vulnerability Index

Table A.1 CVI by Thieler & Hammar-Klose (1999)

Variable	Ranking of Coastal Vulnerability Index				
	Very low	Low	Moderate	High	Very high
	1	2	3	4	5
Geomorphology	Rocky, cliffs, fiords	Medium cliffs, indented coasts	Low cliffs, glacial drift, alluvial plains	Cobble beaches, estuary, lagoon	Barrier beaches, sand beaches, salt marches, mud flats, deltas, mangroves, coral reefs
Coastal slope (%)	> 0.2	0.2 – 0.07	0.07 – 0.04	0.04 – 0.025	< 0.025
Relative SLR (mm/yr)	< 1.8	1.8 – 2.5	2.5 – 2.95	2.95 – 3.16	> 3.16
Shoreline Erosion (m/yr)	> 2.0 (accretion)	1.8 – 2.0	- 1.0 – 1.0 (stable)	-1.1 – -2.0	< -2.0 (erosion)
Mean tide range	> 6.0 m	4.1 m – 6.0 m	2.0 m – 4.0 m	1.0 m – 1.9 m	> 1.0 m
Mean wave height	< 0.55 m	0.55 m – 0.85 m	0.85 m – 1.05 m	1.05 m – 1.25 m	> 1.25 m

Table A.2 CVI by Coelho et al. (2006)

Vulnerability	Ranking of Vulnerability				
	Very low	Low	Moderate	High	Very high
	1	2	3	4	5
Elevation	> 30 m	20 m – 30 m	10 m – 20 m	5 m – 10 m	< 5 m
Distance to shore	> 1000 m	200 m – 1000 m	50 m – 200 m	20 m – 50 m	< 20 m
Tidal range	< 1 m	1 m – 2 m	2 m – 4 m	4 m – 6 m	> 6 m
Max wave height	< 3 m	3 m – 5 m	5 m – 6 m	6 m – 6.9 m	> 6.9 m
Erosion and accretion	> 0 m/yr (accretion)	1 m/yr (erosion)	1 – 3 m/yr (erosion)	3 – 5 m/yr (erosion)	> 5 m/yr (erosion)
Geology	Magmatic	Metamorphic	Sedimentary	Corse sediment	Fine sediment
Geomorphology	Mountain	Rocky cliff	Erosive cliff, sheltered beach	Exposed beach, flats	Dune, river mouth, estuary
Ground cover	Forest	Ground vegetation, agriculture	Uncovered	Rural urbanised	Urbanised, industrial
Anthropogenic actions	Shoreline stabilisation intervention	Intervention without limiting sediment supply	Intervention limiting sediment supply	No intervention and no sediment supply limit	Intervention and sediment supply limit

Table A.3 CVI variables for Southern African coast by Theron et al. (2010) and Theron (2016)

Vulnerability	**Ranking of Vulnerability**				
	Very low	**Low**	**Moderate**	**High**	**Very high**
	1	**2**	**3**	**4**	**5**
Degree of protection from prevailing wave energy	Leeside of island or spit	Leeside of rocky headland	Partial shelter from deep-sea wave energy	Direct exposure to slightly refracted deep-sea waves	Direct exposure to storm waves with narrow surf zones
SLR Bruun erosion inshore slope	< 0.1	0.1 – 0.029	0.03 – 0.014	0.015 – 0.005	> 0.005
Relative height of foredune	> 20 m	10 – 20 m	5 – 10 m	0.5 – 5 m	< 0.5 m
Cyclones per year	0	0 – 1	1 – 2	2 – 3	> 3
Fringing Coral % length of coastline	< 10%	10 – 30%	30 – 50%	50 – 80%	> 80%

Table A.4 CVI of South African coast by Musekiwa et al. (2015)

Vulnerability	**Ranking of Vulnerability**				
	Very low	**Low**	**Moderate**	**High**	**Very high**
Elevation	> 30 m	20 m – 30 m	10 m – 20 m	5 m – 10 m	< 5 m
Beach width	> 150 m	100 m – 150 m	50 m – 100 m	20 m – 50 m	< 20 m
Tidal range	< 1 m	1 m – 2 m	2 m – 4 m	4 m – 6 m	> 6 m
Max wave height	< 3 m	3 m – 5 m	5 m – 6 m	6 m – 6.9 m	> 6.9 m
Geology	Magmatic	Metamorphic	Sedimentary	Corse sediment	Fine sediment
Anthropogenic activity	Shoreline stabilisation intervention	Intervention without sediment source reduction	Intervention with sediment source reduction, breakwater	Without intervention or sediment source reduction, dams	Without intervention but with sediment source reductions
Distance to 20 m isobath	> 4 km	2 km – 4 km	1 km – 2 km	500 m – 1 km	< 500 m
Relative SLR (mm/yr)	< 1.8	1.8 – 2.5	2.5 – 2.95	2.95 – 3.16	> 3.16
Mean wave height	< 0.55 m	0.55 m – 0.85 m	0.85 m – 1.05 m	1.05 m – 1.25 m	> 1.25 m
Beach geomorphology	Boulder beach	Dissipative beach	Dissipative intermediate beach	Intermediate beach	Reflective beach

Table A.5 CVI of Xiamen coastline by Zhu et al. (2019)

Vulnerability	**Ranking of Vulnerability**				
	Very low	**Low**	**Moderate**	**High**	**Very high**
	1	**2**	**3**	**4**	**5**
Geomorphology	Rock, sea dyke	Port	Seawall	Gravel beach	Beach
Elevation	22 m – 24 m	20 m – 22 m	18 m – 20 m	16 m – 18 m	14 m – 16 m
Slope (degrees)	5.1 – 10.7	3.3 – 5.1	1.9 – 3.3	0.9 – 1.9	0 – 0.9
Natural habitat	Mangroves		Coastal dunes		No natural habitat
Buffer ability	2 m – 4 m	0 m – 2 m	-3 m – 0 m	-6.5 m – -3 m	< -6.5 m
Significant wave height	0.1 m – 0.2 m	0.2 m – 0.3 m	0.3 m – 0.4 m	0.4 m – 0.5 m	< 0.5 m
Storms (relative value per m)	0 – 300	300 – 1100	1100 – 2500	2500 – 5600	> 5600
Roads (relative value per m)	0 – 1280	1280 – 3531	3531 – 7045	7045 – 9790	> 9790
Building value (relative value per m^2)	0 – 2534	2534 – 9184	9184 – 23,651	23,651 – 54,665	> 54,665
Population density	No population	Low	Medium	High	Very high
Fiscal revenue (Billion yuan)	4.5 – 5.5	3.5 – 4.5	2.5 – 3.5	1.5 – 2.5	< 1.5
GDP per capita (Ten thousand yuan)	14 – 17	11 – 14	8 – 11	5 – 8	< 5

Table A.6 CVI of KZN coastline by Palmer et al. (2011)

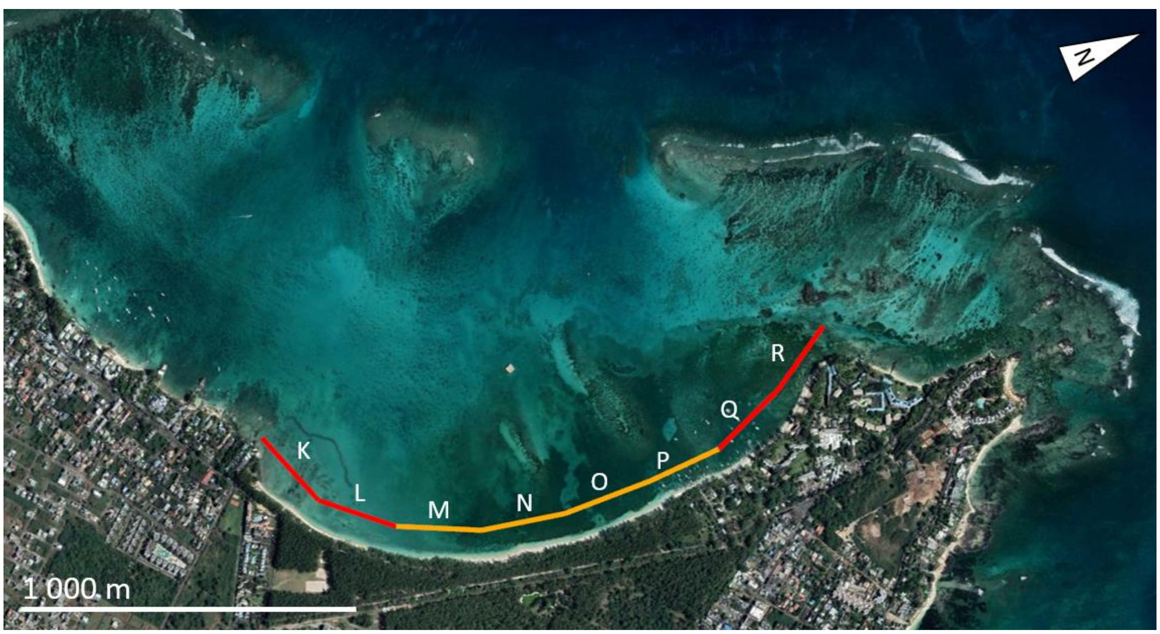
Variable	**Ranking of Variable Vulnerability**			
	Extremely low	**Low**	**Moderate**	**High**
	1	2	3	4
Beach width	> 150 m	100 – 150 m	50 – 100 m	< 50 m
Dune width	> 150 m	50 – 100 m	25 – 50 m	< 25 m
Rocky outcrop percentage	> 50%	20 – 50%	10 – 20%	< 10%
Distance to 20 m isobath	< 4 km	2 – 4 km	1 – 2 km	< 1 km
Vegetation distance behind beach	> 600 m	200 – 600 m	100 – 200 m	< 100 m
Estuarine mouth	No	No	No	Yes
High vulnerability	No	No	No	Yes

APPENDIX B: CVI for Albion and Mon Choisy in Mauritius

Mauritius											
Transect (250 m)	**Beach Width (m)**	**Score**	**Dune width (m)**	**Score**	**Rocky shore (%)**	**Score**	**Vegetation distance behind beach (m)**	**Score**	**Fringing coral (% length)**	**Score**	**Totals**
Albion											
A	0	**4**	0	**4**	100	**1**	32	**4**	10	**2**	**15**
B	6	**4**	0	**4**	50	**1**	8	**4**	10	**2**	**15**
C	16	**4**	0	**4**	50	**1**	8	**4**	0	**1**	**14**
D	8	**4**	0	**4**	0	**4**	13	**4**	50	**4**	**20**
E	9	**4**	0	**4**	0	**4**	7	**4**	75	**4**	**20**
F	12	**4**	17	**4**	0	**4**	12	**4**	100	**4**	**20**
G	8	**4**	9	**4**	0	**4**	0	**4**	100	**4**	**20**
H	5	**4**	12	**4**	20	**2**	0	**4**	100	**4**	**18**
I	18	**4**	0	**4**	30	**2**	0	**4**	100	**4**	**18**
J	0	**4**	0	**4**	90	**1**	0	**4**	100	**4**	**17**
Mon Choisy											
K	5	**4**	0	**4**	10	**3**	32	**4**	50	**4**	**19**
L	0	**4**	0	**4**	10	**3**	43	**4**	50	**4**	**19**
M	5	**4**	0	**4**	0	**4**	66	**4**	25	**2**	**18**
N	10	**4**	0	**4**	0	**4**	49	**4**	10	**2**	**18**
O	7	**4**	0	**4**	0	**4**	64	**4**	0	**1**	**17**
P	8	**4**	0	**4**	0	**4**	28	**4**	10	**2**	**18**
Q	5	**4**	0	**4**	0	**4**	0	**4**	50	**4**	**20**
R	6	**4**	0	**4**	0	**4**	0	**4**	100	**4**	**20**

Albion:

Mon Choisy:



APPENDIX C: CVI for Praia Nova and Ponta Gea in Beira

Beira										
Transect	Beach Width (m)	Score	Dune width (m)	Score	Rocky shore (% length)	Score	Vegetation distance behind beach (m)	Score	Estuary vulnerability	Totals
Praia Nova										
A	0	**4**	0	**4**	0	**4**	65	**4**	4	**20**
B	105	**2**	0	**4**	0	**4**	95	**4**	4	**18**
C	32	**4**	0	**4**	0	**4**	0	**4**	4	**20**
D	9	**4**	0	**4**	0	**4**	0	**4**	4	**20**
E	42	**4**	0	**4**	40	**2**	0	**4**	4	**18**
F	51	**3**	5	**4**	0	**4**	0	**4**	4	**19**
G	95	**3**	20	**4**	0	**4**	65	**4**	4	**19**
H	64	**3**	10	**4**	0	**4**	60	**4**	4	**19**
I	31	**4**	22	**4**	50	**1**	62	**4**	4	**17**
J	0	**4**	0	**4**	100	**1**	0	**4**	4	**17**
Ponta Gea										
K	44	**4**	0	**4**	0	**4**	22	**4**	0	**16**
L	27	**4**	0	**4**	0	**4**	2	**4**	0	**16**
M	52	**3**	0	**4**	0	**4**	22	**4**	0	**15**
N	51	**3**	0	**4**	0	**4**	50	**4**	0	**15**
O	46	**4**	0	**4**	0	**4**	6	**4**	0	**16**
P	36	**4**	0	**4**	0	**4**	0	**4**	0	**16**
Q	58	**3**	0	**4**	0	**4**	0	**4**	0	**15**

Praia Nova (A to J) and Ponta Gea (K to Q):

APPENDIX D: CVI for Richards Bay in South Africa

Richards Bay												
Transect	Beach Width (m) = A	Score	Dune width (m) = B	Score	Distance to 20 m isobath (km) = C	Score	Rocky shore (%)	Score	Vegetation distance behind beach	Score	Additional vulnerability (A,B, and C high)	Totals
Alkantstrand (south end)												
A	25	**4**	10	**4**	0.95	**4**	0	**4**	0	**4**	4	**24**
B	25	**4**	12	**4**	1.4	**3**	0	**4**	70	**4**	0	**19**
C	35	**4**	10	**4**	1.3	**3**	0	**4**	64	**4**	0	**19**
D	23	**4**	25	**3**	1.3	**3**	0	**4**	84	**4**	0	**18**
E	20	**4**	12	**4**	1.35	**3**	0	**4**	45	**4**	0	**19**
F	20	**4**	15	**4**	1.4	**3**	0	**4**	30	**4**	0	**19**
Middle Section												
G	20	**4**	22	**4**	2.8	**2**	0	**4**	30	**4**	0	**18**
H	28	**4**	32	**3**	3.2	**2**	0	**4**	75	**4**	0	**17**
I	15	**4**	22	**4**	2.9	**2**	10	**3**	140	**3**	0	**16**
J	5	**4**	17	**4**	2.8	**2**	20	**2**	310	**2**	0	**14**
K	5	**4**	13	**4**	2.8	**2**	20	**2**	450	**2**	0	**14**
L	5	**4**	16	**4**	2.6	**2**	10	**3**	405	**2**	0	**15**
M	11	**4**	19	**4**	2.5	**2**	0	**4**	55	**4**	0	**18**
N	16	**4**	15	**4**	2.4	**2**	20	**2**	165	**3**	0	**15**
O	14	**4**	18	**4**	2.3	**2**	50	**1**	410	**2**	0	**13**
P	12	**4**	22	**4**	2.3	**2**	20	**2**	370	**2**	0	**14**
Q	13	**4**	35	**3**	2.3	**2**	20	**2**	440	**2**	0	**13**
Municipality boundary (north end)												
R	15	**4**	70	**2**	1.77	**3**	20	**2**	450	**2**	0	**13**
S	15	**4**	35	**3**	1.76	**3**	50	**1**	400	**2**	0	**13**
T	25	**4**	25	**3**	1.73	**3**	20	**2**	230	**2**	0	**14**
U	20	**4**	33	**3**	1.75	**3**	0	**4**	40	**4**	0	**18**
V	20	**4**	54	**2**	1.83	**3**	10	**3**	90	**4**	0	**16**
W	30	**4**	60	**2**	1.85	**3**	10	**3**	150	**3**	0	**15**
X	25	**4**	56	**2**	1.8	**3**	10	**3**	60	**4**	0	**16**

Richards Bay:

APPENDIX E: Reef ball design calculations for Albion lagoon

This appendix details the reef ball design process for the Albion lagoon. As no guidelines exist for designing and sizing an artificial reef with reef balls, the stability guidelines for coastal rock structures in The Rock Manual (Section 5.2.1.2) were used. The properties used in the following calculations are for the super reef ball as per the manufacturer's specifications as shown in Table E.1 Properties of Super Reef Balls.

Table E.1 Properties of Super Reef Balls (www.reefball.org/technicalspecs.htm)

Type of reef ball	Width	Height	Concrete Volume
Super ball	1.83 m	1.37 m	1.19 m^3

It was assumed that for reef ball sizing the stability number, N_s, must be one or less so that the units are static and can support coral growth. N_s is calculated with Equation E.1.

Equation E.1 Stability number for definition (The Rock Manual, 2007)

$$N_s = \frac{H_s}{\Delta \cdot D}$$

Where Hs is the significant wave height, Δ is the relative density of the unit, and D is the nominal unit dimension

The first variable needed is the significant wave height, H_s, which can be estimated as the highest expected depth-limited wave at the -2 m bathymetric contour, where the recommended reef ball structure could be placed in the Albion lagoon. As the literature did not have sea level information, it was assumed to be the same as nearby Port Louis. The absolute highest sea level recorded at Port Louis is about 1.2 m above the chart datum or the lowest astronomical tide (University of Hawaii Sea Level Centre, 2022). It is assumed that this value accounts for both the extreme surge and high tide levels but does not include sea level rise. The artificial reef was designed to be placed on a 1 m berm to reduce wave transmission. Adding these heights together the design breaker depth, d_b, is found to be about 2.7 m (2 m bathymetric contour + 1.2 m ESWL + 0.49 m SLR - 1 m berm). Given the steep slope seaward of the lagoon, the wave breaker index can be taken as 0.78. Multiplying the breaker index with d_b finds H_s which is about 2.1 m in this case.

The second variable needed is the relative density of the reef ball unit, Δ, which is calculated by dividing the semi-ellipsoid reef ball density by the density of seawater as in Equation E.2. It is assumed that the density of seawater, ρ_w, is 1.025 kg/m^3.

Equation E.2 Relative density of reef ball

$$\Delta = \frac{Density\ of\ semi\ elipsoid}{Density\ of\ seawater} = \frac{\rho_{se}}{\rho_w}$$

The semi-ellipsoid reef ball density, ρ_{se}, is calculated by subtracting the water mass from the concrete mass and dividing the result by the reef ball semi-ellipsoid volume as in Equation E.3. The density of concrete, ρ_c, is 2.4 kg/m^3 and the volume of concrete, V_c, is obtained from the reef ball manufacturer or Table E.1 for the super reef ball size as 1.19 m^3.

Equation E.3 Density of semi-ellipsoid reef ball shape

$$\rho_{se} = \frac{\rho_c \cdot V_c - \rho_w \cdot V_w}{V_{se}}$$

The semi-ellipsoid volume is calculated in Equation E. 4 with the reef ball width and the height obtained from the manufacturer for the super reef ball size as 1.83 m and 1.37 m, respectively. The volume of seawater is simply found by subtracting the concrete volume from the semi-ellipsoid volume as seen in Equation E.5.

Equation E. 4 Volume of a semi-ellipsoid

$$V_{se} = \frac{1}{2}\left(\frac{4}{3} \cdot w^2 \cdot h\right)$$

Equation E.5 Volume of water in a reef ball

$$V_w = V_{se} - V_c$$

Thus, the relative density, Δ, for the super reef ball is found to be 1.66.

The final variable needed for Equation E.1 is the nominal dimension, *D*. For irregularly shaped rock armour, D_{n50}, the median equivalent cubic dimension is used. Following this convention, an average unit diameter for reef balls is found using Equation E.6. For the super reef ball D_{n50} or *D* is 1.34 m.

Equation E.6 Average unit diameter for irregular rocks

$$D_{n50} = \sqrt[3]{V_{se}}$$

Now solving Equation E.1 the stability number for the super reef ball on the 2 m bathy in Albion lagoon is 0.945 which is less than 1 and will be stable. The height of the super reef ball unit is 1.37 m, so the artificial reef is submerged by about 0.6 m at the lowest astronomical tide without a berm raising the crest height (on the 2 m bathy). The following paragraph and Figure E.2 make the case for placing the reef balls on berms to reduce the wave energy transmitting through the reef. Placing the 1.37 m wide units in eight offset rows as close together as possible to one another will create a 10 m wide artificial reef. Using Equation E.7 the percentage wave transmission, K_t, can be found for varying depths, *d*, and reef heights, *h*. Figure 3.1 defines the dimensions used in Equation E.7. The period, *T*, is taken as 12s, the width, *B*, is 10 m, and the incident wave height, H_i, varies depending on the depth.

Equation E.7 Wave transmission percentage through a reef ball reef

$$K_t = 1.616 - 31.322 \cdot \frac{H_i}{g \cdot T^2} - 1.099 \cdot \frac{h}{d} + 0.265 \cdot \frac{h}{B}$$

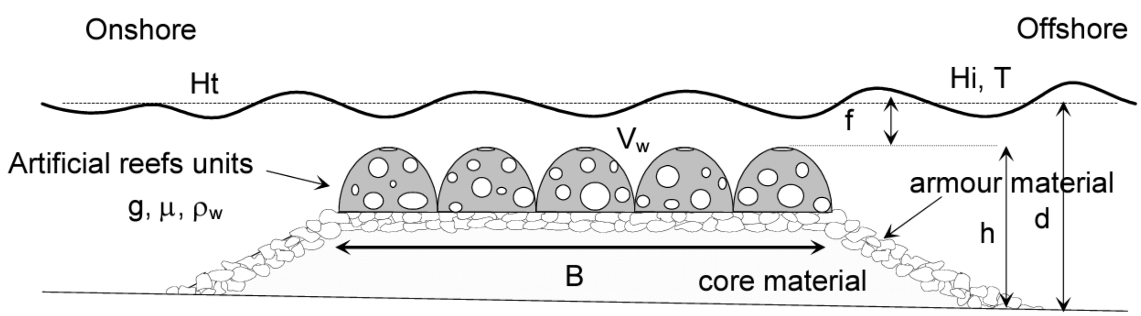


Figure E.1 Dimensions of reef ball reef to determine transmission percentage (Armono & Hall, 2003)

Figure E.2 shows the resulting transmission percentage calculated with Equation E.7 for different artificial reef ball reef heights. The left reef is placed on the seafloor and the reef crest is about 0.6 m below the lowest astronomical tide (or chart datum). At this height, the artificial reef has very little impact on wave transmission even at mean low sea level.

The middle design has a berm of 0.6 m which raises the reef crest to the lowest astronomical tide. At this height, the reef has some impact on wave transmission with a 25% reduction at mean sea level. However, at the extreme still water level, the reef's impact is small with a 7% wave height reduction.

Finally, the highest design, on the right of Figure E.2, with the 1 m berm height raises the reef crest to a mean low sea level of 2.35 m. This reef design will be partially visible at tides between the mean low tide and the lowest astronomical tide. This is not very desirable; however, the protection that it offers is greater than the two lower designs. At the extreme still water level nearly 20% of the wave is obstructed whilst at lower tides this approaches to nearly half the wave being obstructed. Although there is some compromise in the reef being partially visible at times this design provides good protection. The sea level rise case has been included for the three designs. However, they are not discussed as it is envisaged that the artificial reef, once seeded with live coral, will grow with the rising sea levels.

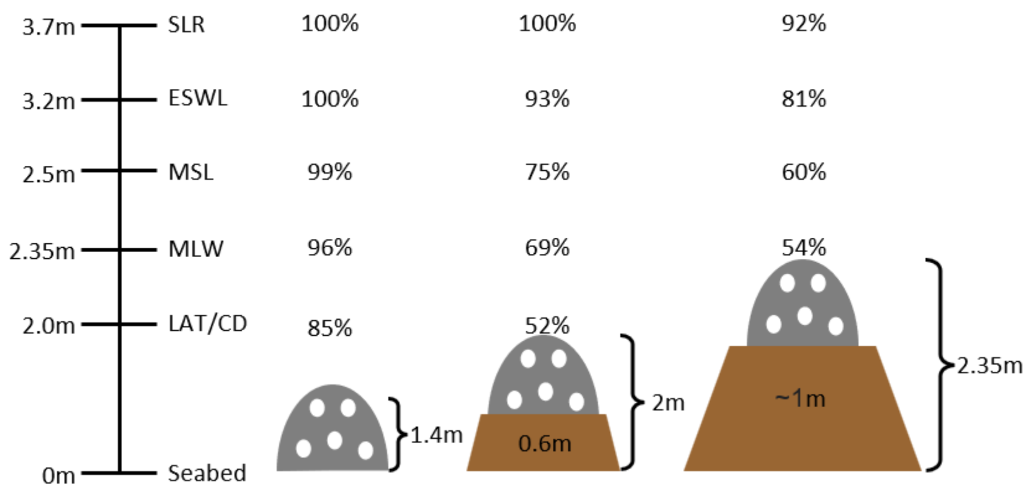


Figure E.2 Percentage wave transmission for differing heights of reef ball reef (heights are not to scale)

APPENDIX F: Dyke design calculations for Praia Nova

The primary parameter needed for designing a rocky dyke is the design extreme still water level, ESWL. For Beira, Theron et al. (2012) found ESWL to be 5.9 m above MSL (2 m for a 1 in 50 year storm surge, 2.9 m high tide, and 1 m 2100 sea level rise). However, it was decided that the dyke should rather be designed for 2050 as the most vulnerable period for the hybrid system, as the wetland seawards of the dyke will not have matured yet and thus provides little protection. It is envisaged that by 2100 the wetland vegetation will have matured, and will work as a hybrid system with the dyke, providing wave attenuation and mitigating the effect of the 2100 sea level rise on the ESWL. So instead, the design ESWL is estimated to be 5.3 m (2 m for a 1 in 50 year storm surge, 2.9 m high tide, and 0.4 m 2050 sea level rise).

From this, the desired ground level of the dyke, or level of the road behind the dyke, is subtracted which, in this case, is assumed to be 5 m above MSL, and an assumed 1 m of under scour is added. This results in a design wave-breaking depth, d_b, of 1.3 m (5.3 - 5 + 1). Multiplying d_b with the breaker index for the 1 in 50 slope of the wetland, 0.6 in this case, determines the incident significant wave height, H_{is}, as 0.78 m. The mean wave period, T_m, is calculated by multiplying the peak wave period, T_p, (11s from (Theron et al., 2012)) by 0.83 for a JONSWAP spectrum. Thus, T_m is 9.96s. The surf similarity parameter, ξ_{0m}, is calculated using H_{is} and T_m, with Equation F.1. $\tan\alpha$ is the revetment slope which is typically 1 over 1.5 or about 0.67.

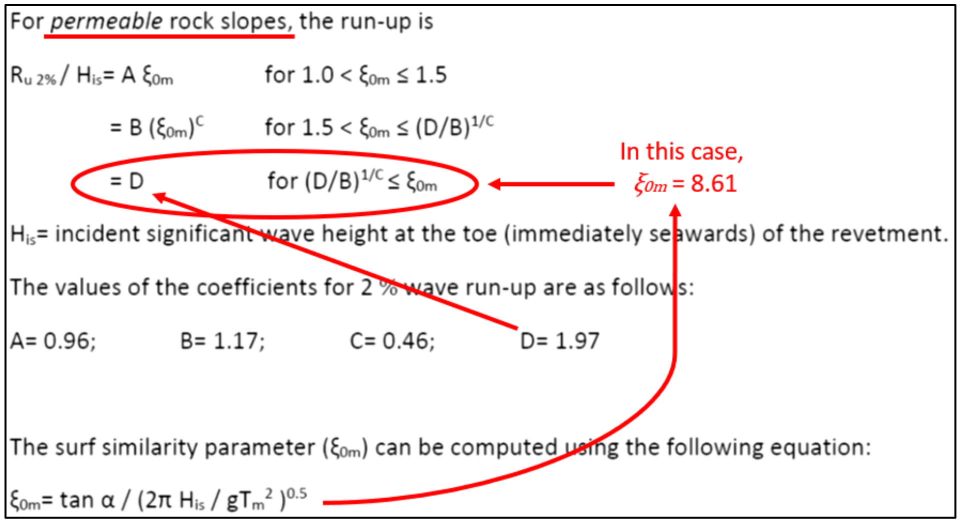
Equation F.1 Surf similarity parameter

$$\xi_{0m} = \frac{\tan\alpha}{\left(\frac{2\pi \cdot H_{is}}{9 \cdot {T_m}^2}\right)^{0.5}}$$

The surf similarity parameter determines the equation to be used for calculating the 2% wave run-up height, $R_{u2\%}$, for permeable slopes as set out by the coastal engineering manual. These equations and their associated surf similarity parameter ranges are included in Figure F.1. In this case, the surf similarity parameter is 8.61 and thus Equation F.2 is applicable for the $R_{u2\%}$. The $R_{u2\%}$ is calculated to be 1.54 m.

Equation F.2 2% exceedance wave runup level

$$R_{u2\%} = 1.97 \cdot H_{is}$$



For *permeable* rock slopes, the run-up is

$R_{u\,2\%} / H_{is} = A\ \xi_{0m}$ for $1.0 < \xi_{0m} \leq 1.5$

$= B\ (\xi_{0m})^C$ for $1.5 < \xi_{0m} \leq (D/B)^{1/C}$

$= D$ for $(D/B)^{1/C} \leq \xi_{0m}$

H_{is}= incident significant wave height at the toe (immediately seawards) of the revetment.

The values of the coefficients for 2 % wave run-up are as follows:

A= 0.96; B= 1.17; C= 0.46; D= 1.97

The surf similarity parameter (ξ_{0m}) can be computed using the following equation:

$\xi_{0m} = \tan\alpha / (2\pi\ H_{is} / gT_m^2)^{0.5}$

Figure F.1 Formulae for 2% exceedance run-up on rocky slopes using the surf similarity parameter

(adapted from van der Meer & Stam, 1992)

Thus, the minimum crest height above sea level and the dyke height can be found as 6.84 m (ESWL 5.3 + $R_{u2\%}$ 1.54 m) and 1.84 m (ESWL 5.3 + $R_{u2\%}$ 1.54 m - toe height 5 m), respectively. These dimensions are illustrated in Figure 4.28.

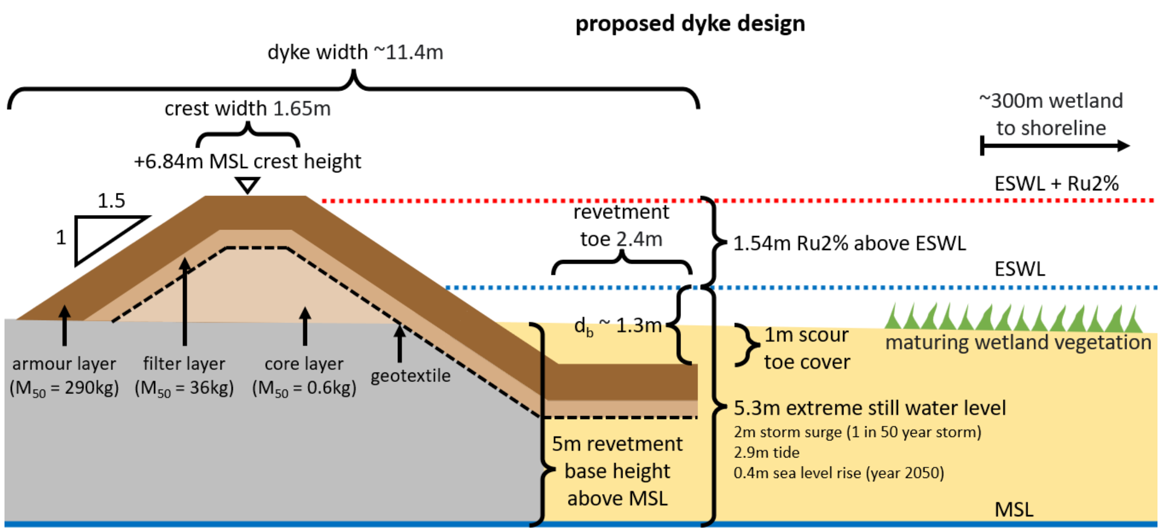


Figure F.2 Proposed Praia Nova dyke profile

The median size of the rock armour units, D_{n50}, are calculated using the Van Gent method (Equation F.3). Δ or the relative density of the rock to seawater is 1.63 if the rock density, ρ_r, is 2.7. The stability number, N_s, and number of waves, N, are 2.7 and 7500, respectively. A geotextile is used in the revetment design so the $D_{n50core}/D_{n50}$ ratio is 0.

Equation F.3 Van Gent's Method to determine the rock size

$$\frac{H_{is}}{\Delta \cdot D_{n50}} = 1.75 \cdot \cot \alpha^{0.5} \cdot \left(1 + \frac{D_{n50core}}{D_{n50}}\right)^{0.667} \cdot \left(\frac{N_s}{N^{0.5}}\right)^{0.2}$$

Thus, the D_{n50} of the armour layer is found to be 0.47 m. The filter layer rock should be half this, i.e., $D_{n50filter}$ = 0.24 m. And the rock core elements should be an eighth of the armour layer D_{n50}, i.e., $D_{n50core}$ = 6 cm. The median rock mass of each layer is found with Equation F.4.

Equation F.4 Median rock mass

$$M_{50} = (\rho_r \cdot D_{n50})^3$$

Thus, the rock masses are about 286kg, 35.8kg, and 0.6kg respectively for the armour, filter, and core rock elements. The armour and filter layers are usually two rock units thick, hence about 0.9 m and 0.7 m thick, respectively. The final required dimensions of the revetment are the crest width which is between three and four times the D_{n50}. So, 1.65 m is acceptable, in this case, and the revetment toe length is three times the H_{is} or 2.4 m, in this case.

APPENDIX G: Sand nourishment calculation for Alkantstrand

To calculate the sand volume needed to nourish Alkantstrand Beach to its 2004 profile with the 70 m wide beach the existing bathymetry needs to be known. Unfortunately, bathymetric information detailing the nearshore of Alkantstrand Beach was not available. However, using Dean's Beach Equilibrium equation the depth 70 m from the current shoreline can be estimated.

Equation G.1 Dean's Beach Equilibrium

$$h = A \cdot x^{\frac{2}{3}}$$

Where h is the water depth, x is the horizontal distance from the shore, and A is a constant determined by Equation G.2

Equation G.2 Constant A for Dean's Beach Equilibrium equation

$$A = 0.21 \times {D_{50}}^{0.48}$$

Where D_{50} is the average beach grain size.

Alkantstrand beach has an average grain size of 0.299 mm; thus *A*, from Equation G.2, is 0.118. The depth at 70 m, *h*, from Equation G.1, is thus found to be -2.00 m. Therefore, the beach profile height should be raised by 2 m to move the shoreline back 70 m. Everything landward of the proposed shoreline, including over the sandbags, should be raised by 2 m. This creates a dune height of 5 m at the crest of the sandbag revetment above mean sea level as seen in Figure G.1.

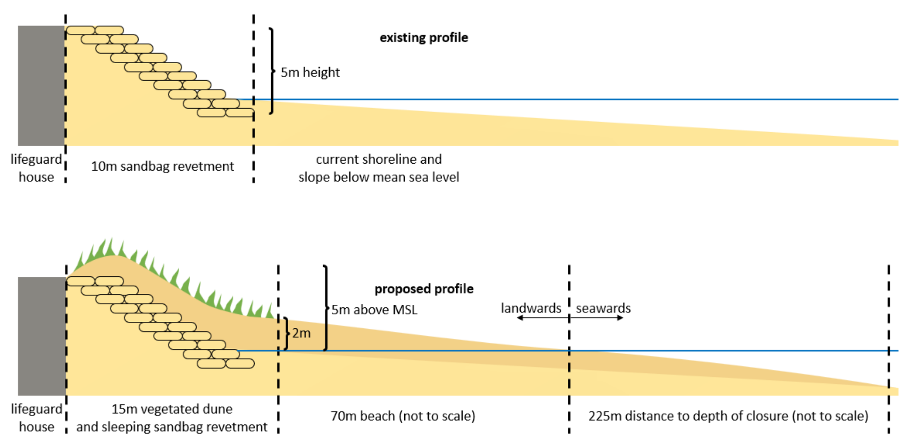


Figure G.1 Existing and proposed Alkantstrand profile with the new sediment shown darker

The distance to the depth of closure, the point where waves do not make measurable changes to the sea floor, was not found in the literature for Richards Bay. So, this was assumed to be about 225 m, approximately half the length of the 450 m breakwater.