RESPONDING TO CLIMATE CHANGE IN MOZAMBIQUE

Instituto Nacional de
Gestão de Calamidades

National Institute for Disaster Management (INGC)
PHASE II

THEME 2
COASTAL PLANNING AND ADAPTATION TO MITIGATE CLIMATE CHANGE IMPACTS

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REVISED VERSION

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EXECUTIVE SUMMARY

S.1 BACKGROUND

Mozambique is recognized as one of the countries in Africa that is most vulnerable to climate change. Hazards such as droughts and floods, variable rainfall and tropical cyclones already significantly affect the country.

The country's coastal zone is particularly vulnerable to the expected impacts of climate change. Contributing factors include:

- Vast low-lying coastal plains such as delta coasts;
- High population concentrations in close proximity to the sea;
- Poverty;
- Low capacity to defend infrastructure;
- Susceptibility to cyclone activity;
- Soft erodible coasts; and
- Inadequate and ageing coastal defences.

This situation is aggravated by direct exposure to high wave energy regimes in some parts, a potential increase in cyclone impacts, and impacted natural coastal defences such as dunes, mangroves and coral reefs. Large numbers of the local population also rely heavily on goods and services and economic benefits provided by the coastal zone.

In this regard, the National Institute for Disaster Management (INGC) initiated two studies to define and locally contextualise important drivers and impacts of climate change in the country. Phase I, completed in 2009, focused on determining the impacts of climate change on Mozambique at the macro level. The current project, Phase II, focuses on both the macro and the micro levels, with an emphasis on the implementation of adaptation measures and providing strategic and scientific evidence-based guidance for decision-making.

Led by the Mozambican government, the overall goal of the Phase II project is to help protect the country against the potential impacts of climate change, and to plan for and kick start prevention through the implementation of adaptation measures at national scale, on the basis of science and in support of sustainable development.

As such, a multi-disciplinary group of scientists from Mozambique and other institutions formulated 9 themes to encapsulate the research challenges faced, namely:

- *Theme 1*: Early Warning at a Different Scale
- *Theme 2*: Coastal planning and adaptation to mitigate climate change impacts
- *Theme 3*: Cities prepared for climate change
- *Theme 4*: Building resilience in partnership with the private sector
- *Theme 5*: Water – doing More with less
- *Theme 6*: Food – Meeting demands.
- *Theme 7*: Preparing People
- *Theme 8*: Extremes
- *Theme 9*: National Strategy: 'Climate Change and Disaster Risk Reduction"

While this study is primarily concerned with Theme 2, it is closely aligned with Themes 3 and 4, and addresses the following key questions:

- Where are the most vulnerable areas along the coast, at the local/micro level?
- What will these areas look like, with climate change, in future?
- Which key infrastructure and future investment plans are at risk in these areas?
- What recommendations are in order for planned investments along the coast, with emphasis on Beira and Maputo?
- What structural coastal protection measures are needed to compensate for the potential effects of climate change?
- What shoreline management plans are most appropriate for these areas?
- What should be the strategic framework on which all coastal structures and sea defences can be evaluated?
- What should go into a coastal zone information system?
- What input can be provided for in a coastal management policy?

The INGC also emphasised the need for a pro-active approach to protect lives and infrastructure, while at the same time finding sustainable solutions that are durable and low cost.

The Scope of Work is detailed in Appendix 3 with the response to the key questions and each expected deliverable from the study listed, together with the place in the document where the detailed results can be found.

Following the introduction and background information in *Chapters 1* and *2*, *Chapter 3* provides a brief overview of the study area and the study sites which form the focus of Theme 2. The research approach and methodologies are discussed in *Chapter 4*.

The physical factors that influence the risk to coastal infrastructure and development in current and future climate scenarios are discussed in *Chapter 5* under the heading of Drivers of Risk. An assessment of the coastal hazards associated with these drivers of risk is provided in Chapter 6.

The results of research on adaptation strategies and measures along with associated coastal protection options are presented in *Chapter 7* followed by a discussion and site specific recommendations in *Chapter 8*. The results of interaction with municipal and institutional leaders and technical officials at some of the study sites are provided in *Chapter 9*. The key conclusions with recommendations are summarised in *Chapter 10.* An extended list of references is provided as *Chapter 11* followed by a comprehensive *Glossary of Terms* in *Chapter 12*.

The underlying detail of selected sections is included in the Appendices.

Note that Chapter 10 can be extracted as a stand alone document.

S.2 KEY CONSIDERATIONS AND FINDINGS

S.2.1 Drivers of change

In Theme 2 the physical factors that influence the risk to coastal infrastructure in current and future climate scenarios were identified. This included consideration of the current situation along with future sea-level rise scenarios of 0.5m, 1.0m or 2m by 2100. These are further considered both with and without taking cyclones into account and the consideration of possible increases in "storminess" being another component of climate change.

The primary hazards to physical (abiotic) coastal infrastructure related to sea storms and climate change are:

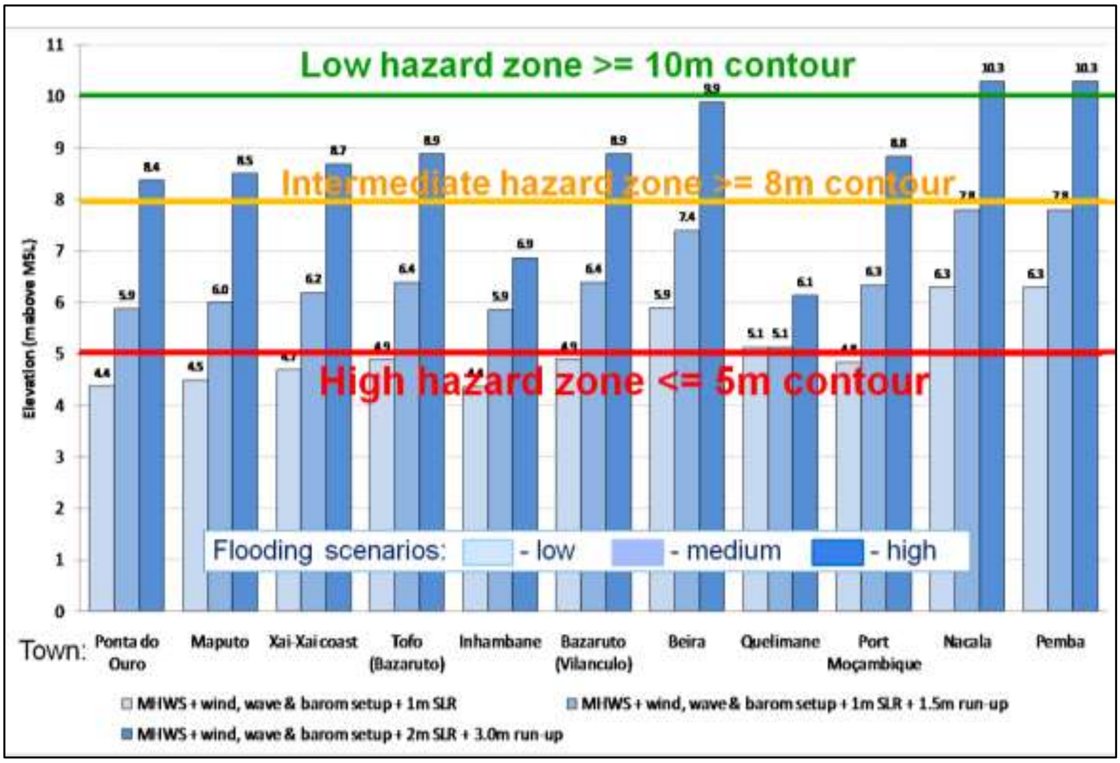
- Extreme inshore sea water levels resulting in flooding and inundation of low lying areas.
- Changes in cyclone characteristics, winds and local wave regime resulting in direct wave impacts.
- Coastal erosion and under-scouring of, for example, foundations and structures.
- System complexities, thresholds and non-linearities, for example related to sand transport.
- A combination of extreme events, such as sea storms during high tides plus sea level rise, will have the greatest impacts and will increasingly overwhelm existing infrastructure as climate change related factors set in time.

The main drivers of change related to the above are thus waves and sea water levels (and to a lesser extent winds and currents). A detailed discussion can be seen in Chapters 5 and 6.

The shoreline response and flooding impact is influenced by coastal parameters/processes such as: topography, geology, inshore wave action, sea level (including the tidal state and future rise), bathymetry and foredune volume.

To be of more use in hazard quantification and ultimately in finding ways of reducing risks and deriving practical adaptation measures, it is necessary to be able to predict or forecast the coastal response and severity of impacts. To this end, given the lack of historic data and information along the Mozambican coastline, three flooding scenarios are defined to establish the hazard levels at the specific sites in terms of possible flooding due to the various factors associated with 'normal' meteorological factors as well as the effects of climate change.

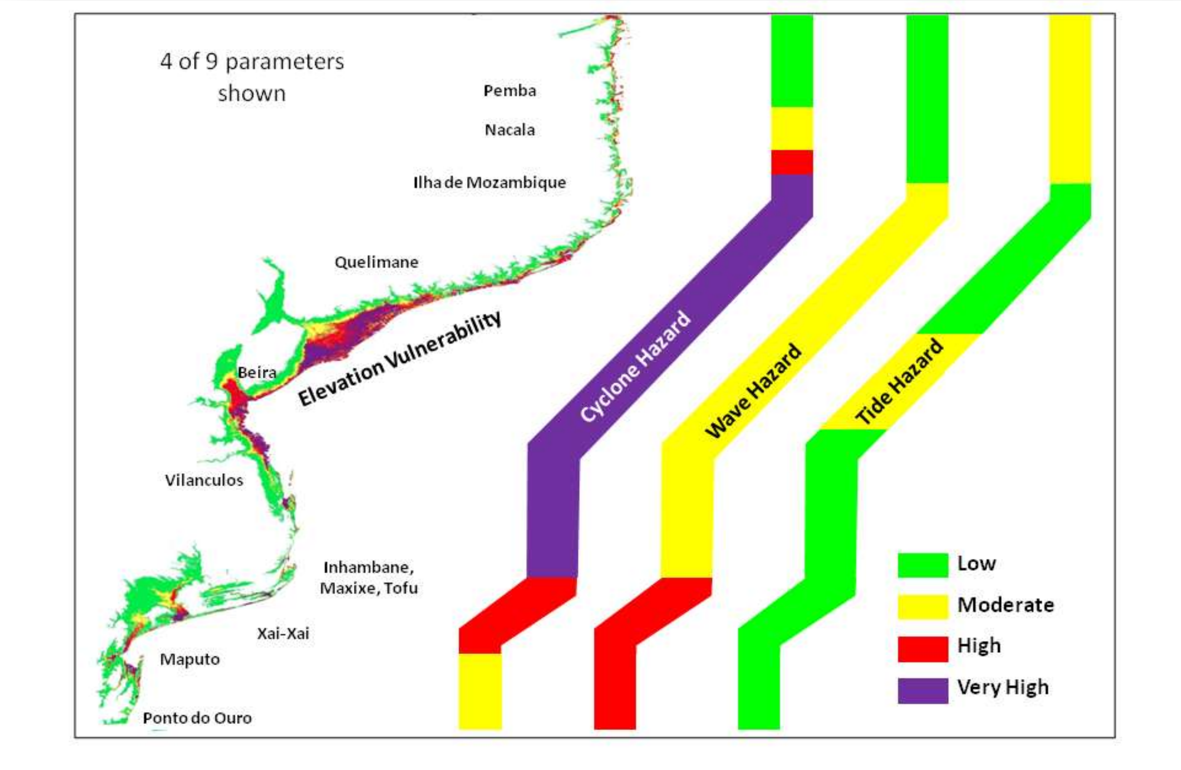
These three flooding level scenarios were calculated for each of the study towns and cities as depicted in the figure below (*the 3 bars for each town)*.



Coastal flooding levels for 11 towns/cities (see Figure 6.3 in Chapter 6)

S.2.2 Coarse scale coastal vulnerability assessment

Broadly speaking, the low lying central delta coast areas (e.g. Beira) are very vulnerable in terms of elevation (see Figure below). The highest occurrence of cyclones (very high hazard) is found along the central parts of Mozambique, tapering off to the south (from roughly Tofo) and also sharply to the north (from about Ilha de Mocambique).



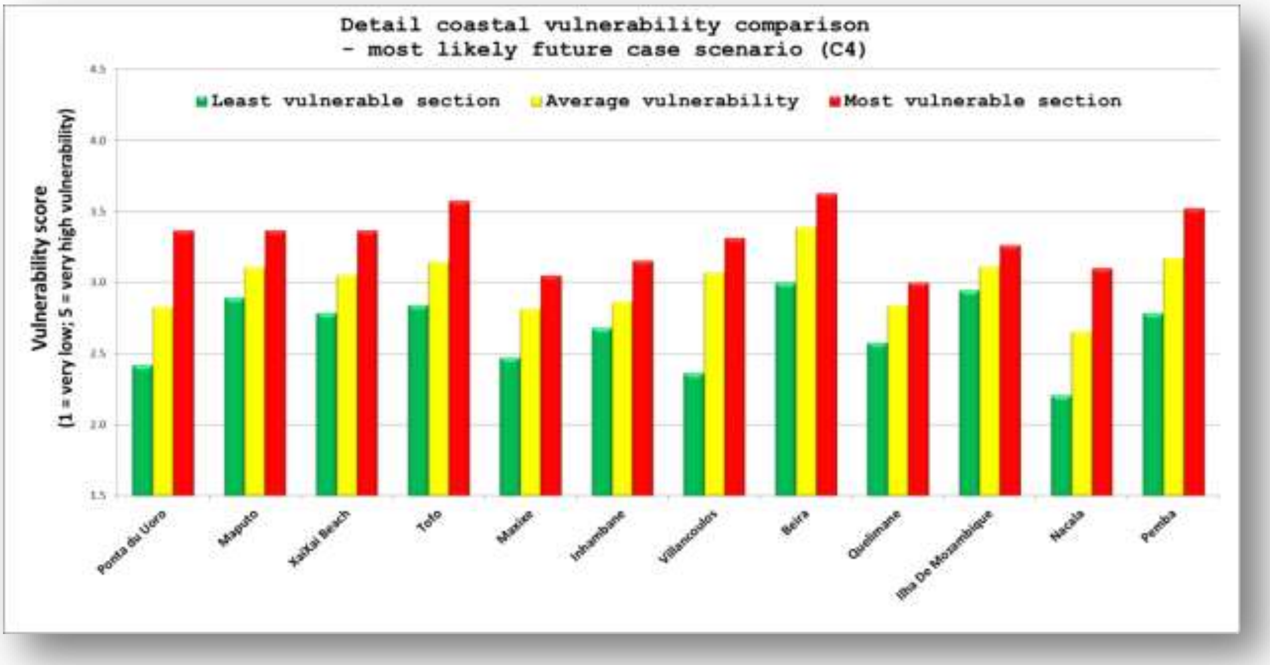
Coarse overview of hazards and vulnerability of Mozambican coast (See Figure 6.21 in Chapter 6)

S.2.3 Local / micro scale coastal vulnerability assessment

Analyses were carried out to determine the vulnerability of key coastal cities and towns (identified by the INGC) to the impact of a range of biophysical change scenarios.

The vulnerability to the forces from the sea of approximately 10 km of shoreline at each site was assessed by evaluating 14 abiotic parameters against an agreed to set of criteria (see Table 6.1 in Chapter 6). The vulnerability assessment was done with and without climate change factors, and also with and without the effect of cyclones. Total vulnerability maps are available for each of the study sites, for the 8 scenarios that include cyclones (i.e. C1 to D4).

The figure below shows the detailed coastal vulnerability comparison of the 12 coastal study sites when the most likely future climate change scenario, C4, is used. (Scenario C4 considers a 1m sea-level rise by 2100 and includes both the effects of cyclones and an increase in storminess due to climate change.



A comparison of the vulnerabilities of the 12 study sites under the most likely future case scenario (C4) (See Figure 6.36 in Chapter 6)

Results show that the most vulnerable towns are Ponta do Ouro, Maputo, XaiXai Beach, Tofo, Villanculos, Beira and Pemba. Beira is identified as the most vulnerable city.

S.2.4 Appropriate adaptation measures

A comprehensive literature review led to the identification of a number of management options and "soft" and "hard" coastal engineering methods available to protect the shoreline (see Chapter 7). By considering the coastal processes and characteristics of the study area, and factors governing suitability for coastal development, various potential response options were identified.

Based on the foregoing evaluation considerations and criteria, and including all appropriate options, the priority adaptation/"no-regret" measures were grouped according to type and impact, covering the most relevant climate change issues for Mozambique coastal towns and cities (Chapter 7).

The results together with site investigations allowed coastal engineers to determine the most appropriate adaptation options to introduce for a particular area within the study areas. Following a conservative and precautionary approach, a list of prioritised adaptation response actions for each town and city was recommended (Chapter 8).

S.3 KEY CONSIDERATIONS AND FINDINGS

S.3.1 Integrated coastal planning and management

The adoption and implementation of the strategic principles and guidelines on planning for and responding to coastal impacts and including specifically climate change impacts, as discussed in Chapter 7 is seen as the first and most important action point.

Most of the response options are purposefully what can be termed "soft" options or "working with nature". Following an integrated coastal planning approach is in line with strategic principles and best practise guidelines in terms of coastal management and responding to climate change. This simple management level decision will go a long way in reducing the need for constructing expensive coastal defences in many instances, especially in the long-term. Activities are, amongst others:

- Plan any coastal construction so that it is a safe distance away from the high-water mark and reinstate natural defence mechanisms with the necessary environmental authorisations.

- Undertake holistic planning and implementation through the development and implementation of Coastal Management Programmes that incorporate Shoreline Management Plans.

- Establish a coastal development setback line which is designed to protect both the natural environment from encroachment from buildings as well as protecting beachfront developments from the effects of storms and accelerated coastal erosion.

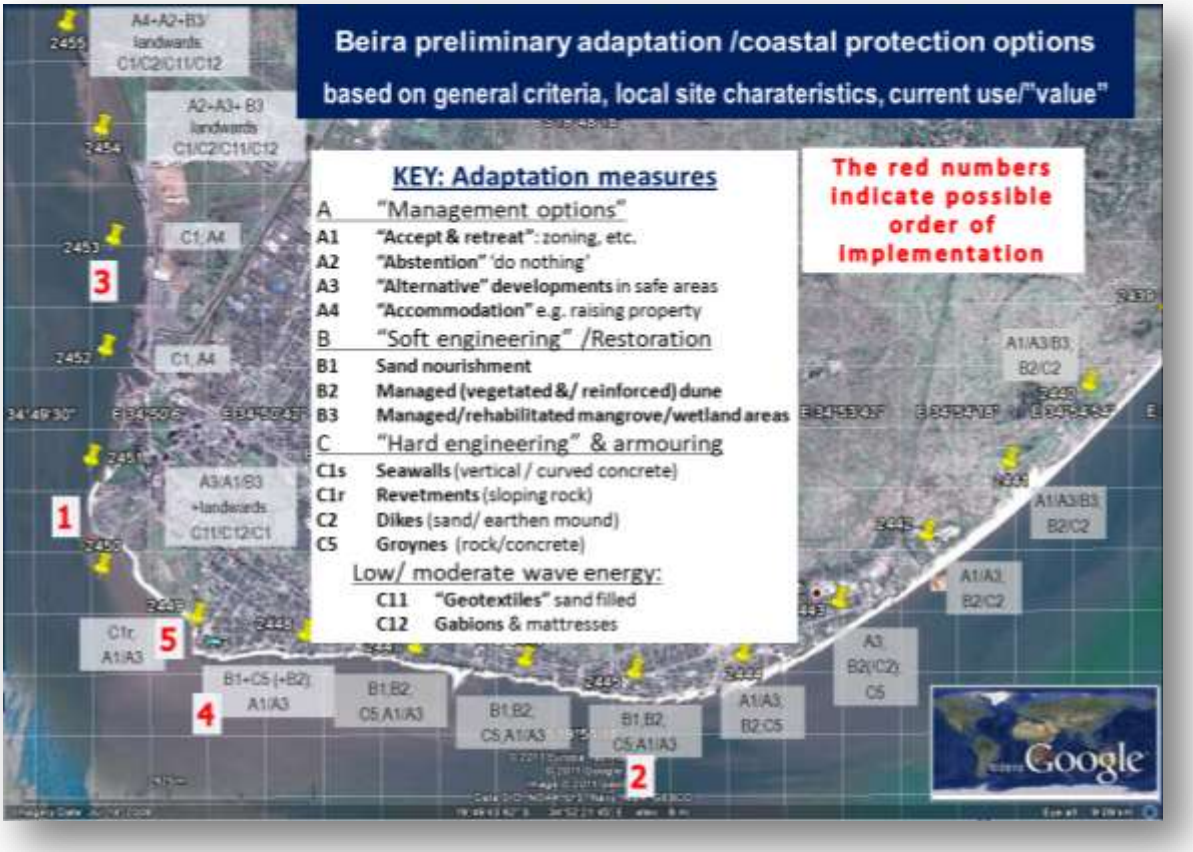
- Work with nature by protecting the integrity of buffer dune systems, which should be vegetated with appropriate dune species as per the original natural zones and maintained.

- Maintain, or even better, increase the sand reservoir (volume) stored in the dune system.

- Protection, restoration and maintenance of natural systems like mangroves and coral reefs.

S.3.2 Site specific adaptation options

To illustrate the assessment approach and the way the results are presented for each study site, the city of Beira is used as the example below. The results for the other study sites are presented in a similar manner in Chapter 8.



Beira preliminary adaptation /coastal protection options

based on general criteria, local site charateristics, current use/"value"

KEY: Adaptation measures

A	"Management options"
A1	**"Accept & retreat"**: zoning, etc.
A2	**"Abstention"** 'do nothing'
A3	**"Alternative" developments** in safe areas
A4	**"Accommodation"** e.g. raising property
B	"Soft engineering" /Restoration
B1	**Sand nourishment**
B2	**Managed (vegetated &/ reinforced) dune**
B3	**Managed/rehabilitated mangrove/wetland areas**
C	"Hard engineering" & armouring
C1s	**Seawalls** (vertical / curved concrete)
C1r	**Revetments** (sloping rock)
C2	**Dikes** (sand/ earthen mound)
C5	**Groynes** (rock/concrete)
	Low/ moderate wave energy:
C11	**"Geotextiles"** sand filled
C12	**Gabions** & mattresses

The red numbers indicate possible order of implementation

Adaptation / coastal protection options based on general criteria, local site characteristics and current use/"value" for Beira. (See figure 8.1 in Chapter 8)

The key adaptation measures found to be appropriate for Beira is summarised in the large white block in the figure, which include four "Management options" (labelled A1 to A4), three "Soft engineering"/Restoration measures (B1, B2 & B3), four "Hard engineering" & armouring options (C1s, C1r, C2, C5), and two options more suitable for low/moderate wave energy sites (C11 & C12).

The three or four options or combination of options considered most suitable for each 0.5 km alongshore section of the coast at Beira are indicated in the small white block adjacent to each marker on the map. The labels within each small block (e.g. A1 or C5, etc.) refer to the labelled options described in the large white block.

The large red numbers (1 to 4) on the figures indicate the recommended order of implementation of the identified coastal adaptation measures for Beira. In other words, Figure 8.1 represents a "plan" or "map" summarising the preferred adaptation options along each 0.5 km section of the western, southern and south-eastern Beira coast.

It should be noted that specific engineering design details and accurate costing of each option can only be done once site specific engineering and environmental investigations have been carried out. It is absolutely critical to involve experienced coastal engineering and coastal environmental professionals in the detailed planning, design and implementation of the chosen options.

S.3.3 Seek opportunities for public-private-partnerships (PPP)

In many cases sound planning and future development beyond the reach of the sea forces can be implemented successfully. Many opportunities for entering into 'design-&-build' type PPP exist which have the potential to co-fund the implementation of the more costly "hard"-engineering adaptation options.

S.3.4. Continue active engagement and communication with stakeholders to disseminate the outputs and facilitate uptake

Observations by the study team during interaction with stakeholder groups at various levels of authority leads to the following recommendations presented for consideration:

The recommendations fall into three categories, namely (a) those that relate to the various decision-makers, (b) those at a more technical/scientific level, and (c) those that relate to knowledge dissemination and decision-making.

S.4 MONITORING AND EVALUATION REQUIREMENTS

S.4.1 Establish a baseline

Following on the present Phase II work, it is expected that there will be an implementation phase. In any follow up phase of work, it is essential to include as priority additional data collection and monitoring to address the critical gap in regional, national and local level data and information required to enable detailed site planning and design and to increase the level of confidence in the key sets of information on which the adaptation measures identified in this study are based.

The parameters and issues which should be monitored include the following:

- ✓ Cyclone characteristics – done when appropriate.

- ✓ Winds and local wave regime (and sea storms) – ongoing.
- ✓ Inshore sea water levels (tides and sea level trends) - ongoing
- ▪ Shoreline stability and trends (erosion / accretion) - a baseline survey as soon as possible followed by repeat surveys every three to five years, and after each major cyclone.
- ▪ Integrity of built coastal defences/structures - a baseline survey followed by repeat surveys every three to five years. This should be a critical input into an effective infrastructure maintenance plan.
- ▪ Integrity of natural coastal defences (dunes, mangroves, coral reefs, wetlands) – a baseline followed by regular repeats as appropriate. This should also be a critical input into an effective maintenance and wider integrated coastal zone management plan.
- ▪ It is of utmost importance to collect sufficiently detailed topographic and bathymetric data at identified priority areas. This can mostly be a "once off" baseline data collection task, but should be repeated at longer intervals, perhaps every 10 years for the topographic data, or immediately after any major change caused by, for example, a cyclone that will then form the new baseline.

As far as can be determined, the first three items (indicated by a tick) are being monitored to some degree or can be derived indirectly from existing monitoring actions. However, the last four items (indicated by a square dot) are not being monitored (as far as it is known). These items are also critical for any proper integrated coastal zone management and sustainable coastal developments assessments and plans. Thus, it is strongly recommended that actions be taken to ensure that effective monitoring of all the above mentioned parameters is undertaken.

As indicated, while some of the parameters need to be collected at very short time intervals (e.g. sub-hourly wind data), others need only be collected every few years (e.g. topographic data).

S.4.2 Ongoing monitoring, evaluation, dissemination and response

Building onto the recommendation on decision-support that arose through the interaction with stakeholder groups, it is considered of strategic and tactical importance to implement a national programme of ongoing monitoring and reporting of key environmental indicators that are relevant to the climate change parameters identified during this study.

The INGC has a well established and proven network for near real-time information gathering, evaluation and response during the lead up and in emergency events, such as cyclones, floods, fires etc. It is therefore recommended that a complementary network for data gathering, evaluation and information dissemination regarding climate change effects, possible trends in the identified hazard drivers, and resulting impacts to build up the scientific database and knowledge on which informed decisions can be made be set up as soon as possible.

CONTENTS

USAID photo

Figures & Tables

CHAPTER 1: INTRODUCTION

Mozambique is recognized as one of the countries in Africa that is most vulnerable to climate change. Hazards such as droughts and floods, variable rainfall and tropical cyclones already significantly affect Mozambique. Following a first phase investigation (INGC Phase I) aimed at defining and locally contextualizing important drivers and impacts of climate change in Mozambique, the National Institute for Disaster Management (INGC) in Mozambique commissioned a second phase of investigation. While INGC Phase I focused on determining the impacts of climate change on Mozambique at the macro level, INGC Phase II focuses on both the macro and the micro level, with emphasis on implementation of adaptation, and providing strategic guidance.

The overall goal of the Phase II projects, led by the Mozambican government, is to help protect Mozambique against the potential impacts of climate change, and to plan for and kick start prevention through the implementation of adaptation measures at national scale, on the basis of science and in support of sustainable development. Phase II projects focus on a number of thematic research challenges that have been formulated and required a multi-disciplinary effort. To this end, Theme 2: ‘Coastal planning and adaptation to mitigate climate change impacts’ contributes to the ‘Coastal City Protection’ objective. This theme is considered to be aligned with the approach followed under Theme 3: ‘Cities prepared for Climate Change’ and Theme 4: ‘Building Resilience in participation with the private sector’. As such, the research included a number of coastal pilot sites in high impact locations that were selected under the other themes.

The focus on pilot sites introduced a scale dimension that made it possible to approach a deeper understanding of the environmental systems represented within the pilot sites. In addition, research undertaken at this scale made it possible to conceive interventions for climate change adaptation that are of sufficient substance to aid in their likely implementation. This contrasts the generalized adaptation interventions that would be conceived through research undertaken at more expansive scales.

The following key questions were addressed in Theme 2:

- Where are the most vulnerable areas along the coast, at the local/micro level?
- What will these areas look like, with climate change, in future?
- Which key infrastructure and future investment plans are at risk in these areas?
- What recommendations are in order for planned investments along the coast, with emphasis on Beira and Maputo
- What structural coastal protection measures are needed to compensate for the potential effects of climate change?
- What shoreline management plans are most appropriate for these areas?
- What should be the strategic framework on which all coastal structures and sea defences can be evaluated? What should go into a coastal zone information system? What input can be provided for an integrated coastal management policy?

In short, it can be said that the INGC wants to follow a pro-active approach to protect lives and infrastructure (Prevention is better than Cure). In addressing this task, the conservative/ precautionary principle should be applied, to find sustainable solutions that are durable and low cost to the Municipality and/or the State.

Key points from the INGC Phase I study relating to the coastal environment are highlighted in Chapter 2 whilst Chapter 3 provides a brief overview of the study area and the study sites which form the focus of Theme 2. The research approach and methodologies are discussed in Chapter 4.

The physical factors that influence the risk to coastal infrastructure and the lives and livelihoods of coastal communities in current and future climate scenarios are discussed in Chapter 5 under the heading of Drivers of Risk. An assessment of the coastal hazards associated with these drivers of risk is provided in Chapter 6.

The results of research on adaptation strategies and measures along with associated coastal protection options are presented in Chapter 7 followed by a discussion and site specific recommendations in Chapter 8. The results of interaction with municipal and institutional leaders and technical officials at some of the study sites are provided in Chapter 9. The key conclusions with recommendations are summarised in Chapter 10.

The underlying detail of selected sections is included in the Appendices.

CHAPTER 2: BACKGROUND

2.1 INTRODUCTION

The continuously rising concentrations of ”greenhouse” gases in the atmosphere lead to global warming and climate change. The effects of these rising concentrations are already detectable, mainly in terms of thermal variables and, in particular, global mean air temperature. The increase in surface temperatures leads to an increase in sea levels through the interaction of various processes such as thermal expansion of the oceans and melting of glaciers. It is predicted that climate change will also bring greater storm intensities. This makes coastal settlements vulnerable, especially considering that large portions of the coastal zone are densely populated and growing rapidly. Coastal resources are expected to be affected by a number of consequences of climate change, namely higher sea levels, higher sea temperatures, changes in precipitation patterns and sediment fluxes from rivers, altered oceanic conditions as well as changes in storm tracks, frequencies and intensities.

In a report published in 2001, the International Panel on Climate Change (IPCC) assessed the adaptive capacity of regions in the world, including Africa and adjacent small island states (IPCC 2001b). This assessment included Mozambique and extracts from the report are depicted in Table 2.1 below.

Table 2.1: Regional adaptive capacity, vulnerability, and key concerns

(Extracted from **Technical Summary** of **IPCC, 2001b**. With relevant sections of **IPCC 2001b** for each example given in square brackets).**(source: IPCC 2001b, extracted from Table SPM-2).**

Region	Adaptive Capacity, Vulnerability, and Key Concerns
Africa (including Mozambique)	• Adaptive capacity of human systems in Africa is low due to a lack of economic resources and technology, and vulnerability high as a result of heavy reliance on rain-fed agriculture, frequent droughts and floods, and poverty. [5.1.7] • Increases in droughts, floods, and other extreme events would add to stresses on water resources, food security, human health, and infrastructures, and would constrain development in Africa *(high confidence)*. [5.1] • Coastal settlements in, for example, the Gulf of Guinea, Senegal, Gambia, Egypt, and along the East–Southern African coast would be adversely impacted by sea-level rise through inundation and coastal **erosion *(high confidence)*. [5.1.5]**
Small Island States (also Mozambique)	• The projected sea-level rise of 5 mm per year for the next 100 years would cause enhanced coastal erosion, loss of land and property, dislocation of people, increased risk from storm surges, reduced resilience of coastal ecosystems, saltwater intrusion into freshwater resources, and high resource costs to respond to and adapt to these changes *(high confidence)*. [5.8.2 and 5.8.5] • Coral reefs would be negatively affected by bleaching and by reduced calcification rates due to higher CO_2 levels *(medium confidence)*; mangrove, sea grass beds, and other coastal ecosystems and the associated biodiversity would be adversely affected by rising temperatures and accelerated sea-level rise *(medium confidence)*. [4.4 and 5.8.3] • Tourism, an important source of income and foreign exchange for many islands, would face severe disruption from climate change and sea-level rise *(high confidence)*. [5.8.5]

Mozambique is therefore recognized as one of the countries in Africa that is most vulnerable to climate change (Tol, 2004). Hazards such as droughts and floods, variable rainfall and tropical cyclones already significantly affect Mozambique (e.g. Figure 2.1). The coastal zone of Mozambique is particularly vulnerable to the expected impacts of climate change (e.g. Table 2.1 above extracted from IPCC 2001). Existing problems exacerbate the situation, for example, in 2008, the Mozambican government announced that it needed US$18 million to resolve the problem of erosion in the coastal area of Maputo, according to newspaper reports (Notícias, 2008).

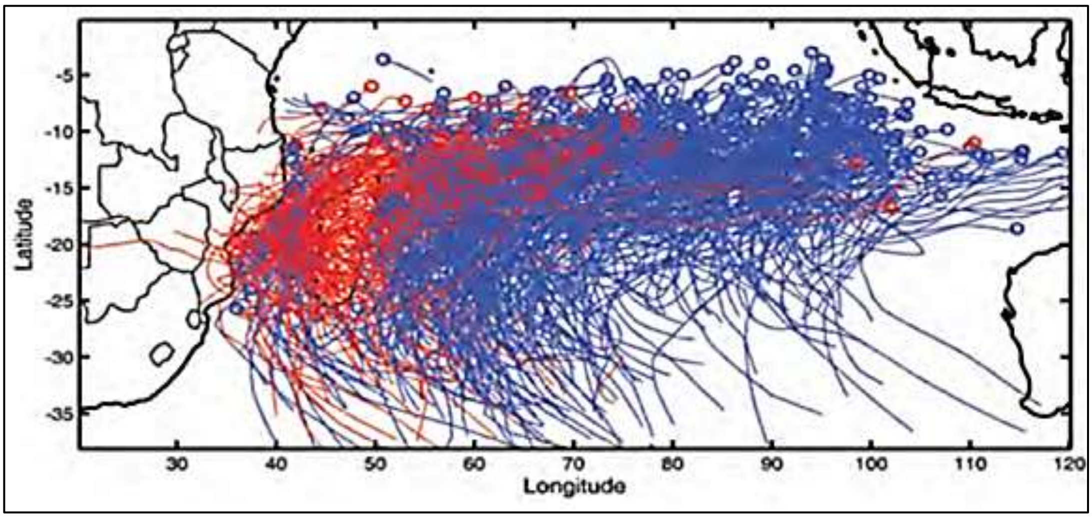


Figure 2.1: Cyclone tracks during November to April in the south-western Indian Ocean from 1952 to 2007 (Mavume et al., 2009)

Contributing factors include vast low-lying coastal plains such as delta coasts; high population concentrations in close proximity to the sea; poverty; low capacity to defend infrastructure; susceptibility to cyclone activity; soft erodible coasts; and inadequate and ageing existing coastal defences (Theron *et al.* 2011). This situation is aggravated by direct exposure to high wave energy regimes in some parts, a potential increase in cyclone impacts, and impacted natural coastal defences (e.g. dunes, mangroves and coral reefs). Large numbers of the local populations also rely heavily on goods and services and economic benefits provided by the coastal zone (Theron *et al.* 2011). Many Mozambicans therefore live close to the sea (and coastal lagoons and lakes) to gain easy access to fishing, being the main sustenance sources for many poor people living along the coast.

Mozambique also has numerous coastal lagoons/lakes separated from the sea only by a frontal dune. The joint effects of sea-level rise (SLR) and increased sea storminess could breach some of these dune barriers. Besides the resulting loss of some of these ecologically (and socially) important lagoon/lake systems, the presently sheltered inner shores would then be directly exposed to much more severe conditions (waves, winds & currents) leading to severe impacts such as shoreline erosion, etc. (Theron & Rossouw, 2008).

Mozambican examples of existing vulnerable coastal areas, likely to become more vulnerable due to climate change effects.

The most vulnerable areas along the coast will almost invariably be located where problems are already being experienced at present. In most cases these are the areas where development has encroached too close to the high-water line, or at a too low elevation above mean sea level (Theron, 2007).

Some examples of current problems in Mozambique are depicted in Figure 2.2. In some instances (especially in the more developed coastal towns/cities) some of the formal built infrastructure is at risk, while in most urban and rural coastal settlements there are informal settlements very close to the sea.

Mozambican examples of existing vulnerable coastal areas, likely to become more vulnerable due to climate change effects.

Figure 2.2: Mozambican examples of existing vulnerable coastal areas, likely to become more vulnerable due to climate change effects.

2.2 SOME RESULTS FROM THE INGC PHASE I STUDY

The following points are extracts from the results of the INGC Phase I report (INGC, 2009) and are included as background to the current study:

- As a result of climate change, the exposure to natural disaster risk in Mozambique will increase significantly over the coming 20 years and beyond. Temperatures in Mozambique may rise by as much as 2 to 2.5˚C by 2050 and 5 to 6˚C by 2090 (depending on the region).
- Rainfall variability will increase; there will be likely shifts in the start of rainy seasons with wetter rainy seasons and drier dry seasons. Flood risk will increase notably in the South. The central regions will be most heavily impacted by more intense cyclones and sea level rise, as well as drought risk around the Cahora Bassa area.
- Up to approximately 2030, more severe cyclones will pose the biggest threat to the coast; beyond 2030, the accelerating sea level rise will present the greatest danger, especially when combined with high tides and storm surges. The city of Beira is already in a very vulnerable situation, with inadequate coastal protection for annual return events. Parts of Maputo, as well as other coastal areas such as Pemba and Vilankulos and nearby islands, are also already at risk.
- Coastal City “Vulnerability” League Table:
    - Beira: Cyclone threat, exposed coast, low lying land, defences in poor repair
    - Inhambane: Cyclone threat, river flood, low land
    - Quelimane: Cyclone threat, river flood
    - Maputo: High land, beachfront at risk

  - Vilanculos: Protected by islands
  - Nacala : Protected from sea, high land

2.3 CONCLUSION FROM THE INGC PHASE I STUDY

Investments are being made in areas where the threats are increasing and the cost of insurance, even when borne by the government, is becoming very unattractive.

Vulnerability is expected to increase over the next two decades, as climate impacts reduce peoples' livelihood assets (health, water, infrastructure) and impinge on food production, thus undermining Mozambique's overarching goal of reducing extreme poverty. However, the extent to which the vulnerability of Mozambique will increase with increased exposure depends on its adaptive capacity. This in turn depends in large part on the socio-economic and technological development trajectory Mozambique will take, and on the adaptation measures, i.e. protection and planning it will put in place in the coming 5 to 10 years.

CHAPTER 3:STUDY AREA

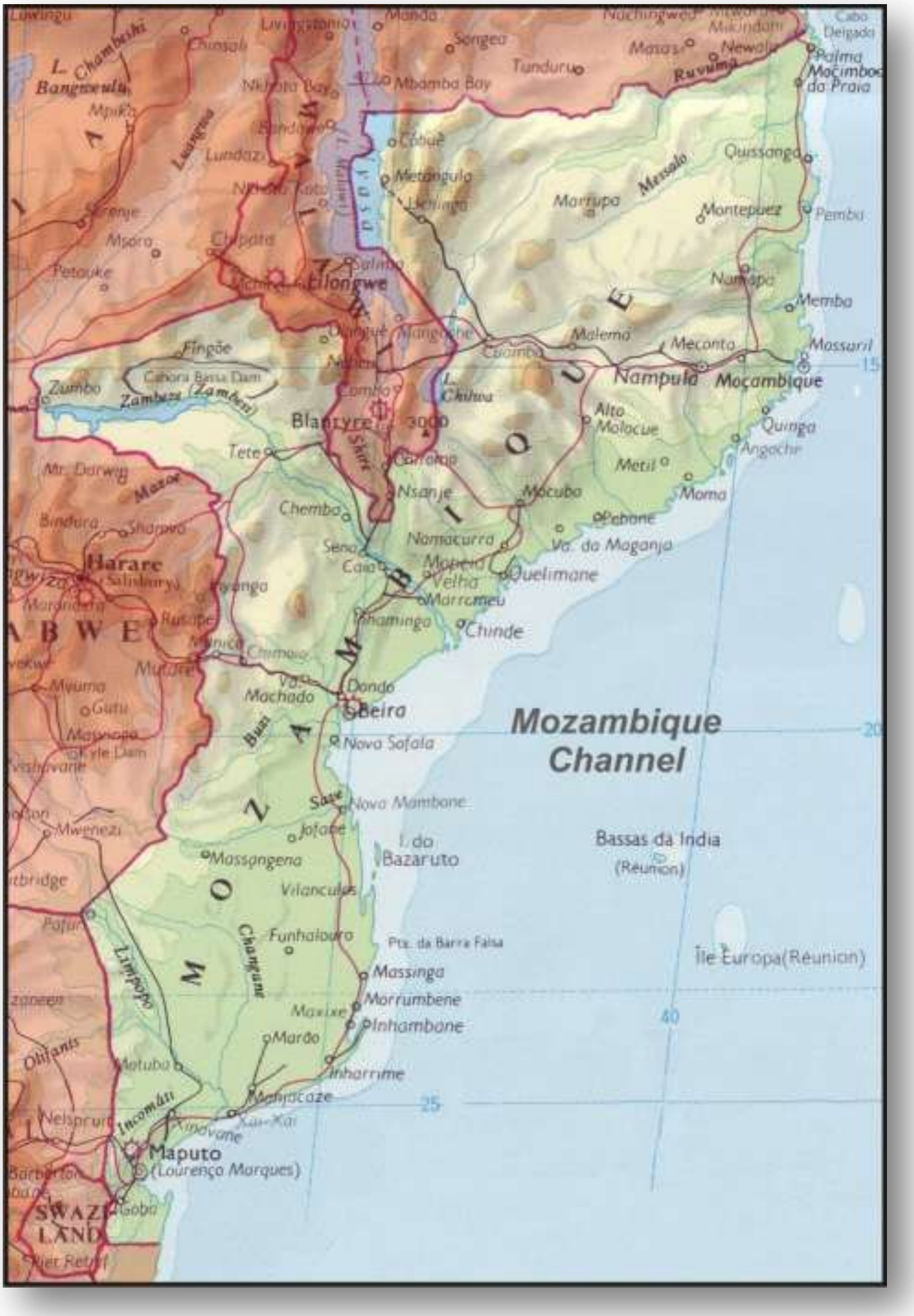


Figure 3.1: The coastal zone of Mozambique (INGC, 2009)

As discussed in the previous chapter, the coastal zone of Mozambique (Figure 3.1) is particularly vulnerable to the expected impacts of climate change and the adaptive capacity is poor. Contributing factors include vast low-lying coastal plains such as delta coasts; high population concentrations in close proximity to the sea; poverty; and low capacity to defend infrastructure. This situation is aggravated by direct exposure to high wave energy regimes in some parts and a potential increase in cyclone impacts. Large numbers of the local populations also rely heavily on goods and services and economic benefits provided by the coastal zone and are therefore located close to the sea in vulnerable areas.

As specified in the terms of reference and selected in conjunction with the INGC, research was focused on the following coastal towns and city areas shown in Figure 3.2:

Maputo / Matola; Xai-Xai Beach; Maxixe; Inhambane / Tofo; Vilanculos; Beira; Quelimane; Ilha De Mozambique; Nacala; and Pemba.

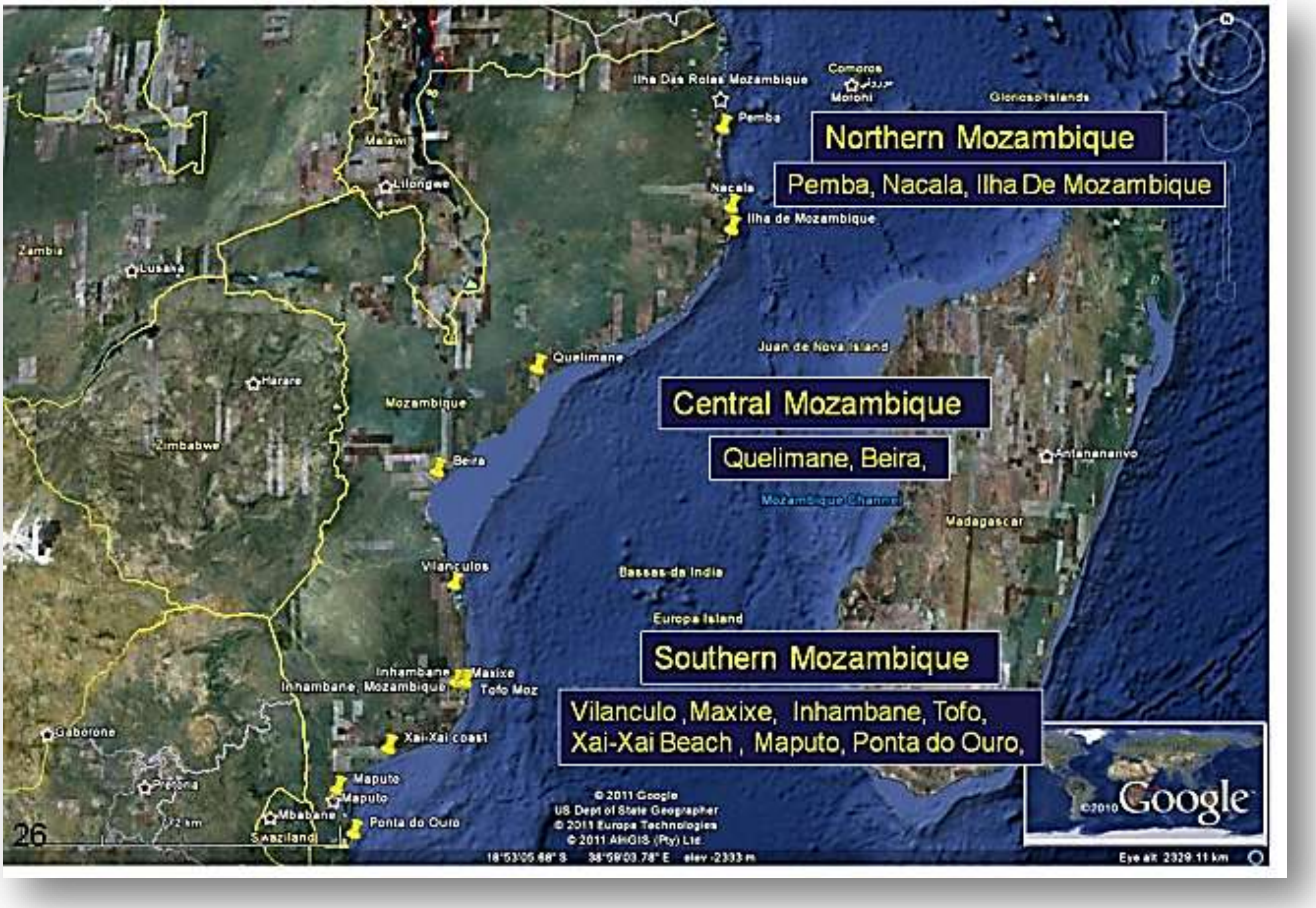


Figure 3.2: Coastal study areas (Google Earth $_{TM}$)

CHAPTER 4: APPROACH / METHODOLOGY

4.1 OVERVIEW OF THE APPROACH

Building onto the Phase I findings and using appropriate assessment techniques such as the use of remote sensing, aerial and field observations, high risk areas were identified (including hazardous areas of change), based on agreed criteria described in Chapter 6,

A coastal vulnerability index was adapted from available techniques described in literature (Chapter 6) and the study sites assessed using maps, satellite data and in-situ observations. The results were incorporated into a Geographical Information System (GIS) which made it possible to produce vulnerability maps that include realistic scenarios of future coastal conditions (Chapter 6).

By applying realistic scenarios of future coastal conditions (e.g. waves, extreme events and sea level rise -SLR) under climate change, and investigating the potential effects, specific adaptation measures and coastal protection options were developed for ten Mozambican towns to adapt to the physical impacts of climate change (Chapters 7 and 8). While some of these measures involve straightforward management options, others focus on soft engineering or restoration, and hard engineering or armouring as coastal defences.

4.2 METHODOLOGY

A list of the main tasks and studies that were conducted (in sequence) is presented below:

1. Review literature & Phase 1 outputs and collation of available data relevant to Theme 2. (Chapters 2 & 3)
2. Identify primary and secondary coastal hazard drivers and vulnerability parameters (Chapter 5).
3. Generate realistic scenarios of future coastal conditions (Chapter 5).
4. Analyse the offshore wave climate and undertake cyclone wave modelling (Chapter 5).
5. Determine and calculate: local tides, wind/wave and hydrostatic set-up, future sea-level and wave run-up levels (Chapter 5).
6. Develop and adapt suitable coastal vulnerability indexing methodology (Chapter 6).
7. Conduct coarse coastal vulnerability assessment for the whole Mozambique coastline (Chapter 6).
8. Undertake an aerial reconnaissance of the coast and in-situ investigation of specific sites; Inspect and assess local coastal processes, site characteristics, vulnerability, and current protection/adaptation options (Chapter 6).
9. Undertake a detail coastal vulnerability analyses of 10 sites based on the methodology developed in (6) above. (This resulted in the assessment of 14 physical parameters and 5

classes for each site for 16 scenario combinations of climate change and cyclones) (Chapter 6).

10. Map areas vulnerable to sea-level rise erosion (Chapter 6).
11. Map vulnerable areas: flooding and wave run-up levels (Chapter 6).
12. Identify a suite of suitable planning and adaptation options: considering relative costs, life expectancy, associated environmental impacts, and comparative functionality (Chapter 7).
13. Apply general coastal engineering principles and identify adaptation options relevant to local Mozambican conditions (Chapter 7).
14. Determine preliminary adaptation option costs including coastal construction capital cost estimates (Chapter 7).
15. Define appropriate and site specific adaptation/coastal protection options based on general criteria, local site characteristics and current coastal use/"value" (Chapter 8).
16. Recommend order of implementation of identified adaptation options at each study site (Chapter 8).
17. Interact with officials of coastal municipalities to understand degree of local understanding of climate change factors and if and how these are considered in current and future planning (Chapter 9).
18. Prepare recommendations for action in the short, medium and long term (Chapters 8 and 10).
19. Identify monitoring requirements to improve evidence-based decision-making (Chapter 10).

CHAPTER 5: DRIVERS OF RISK

5.1 INTRODUCTION

Understanding the potential risk to both human and natural elements of the coastal zone facilitates the mapping of vulnerable areas. The need therefore exists to determine areas of low risk (or vulnerability) which, in turn, require prediction of future vulnerability under future climate change scenarios. Studying the hazards associated with coastal processes and dynamics, in particular related to climate change in this case, will aid the planning and low risk location of new development areas and infrastructure. Such knowledge will also assist in the identification of appropriate adaptation options for existing developments that are assessed to be at risk.

In this chapter an overview of the wave climate around the Mozambican coast, as well as possible trends reflected in the regional data is provided. The focus is on the abiotic physical coastal aspects which include factors linked to climate change.

5.2 IDENTIFICATION OF KEY ULTIMATE DRIVERS OF RISK

Van Ballegooyen *et al*. (2003) identified all significant marine hazards relevant to parts of the Southern African (SA) coast. A hazard is defined here as an event or process (natural or anthropogenic) that results in a potentially deleterious impact on a desirable *status quo*. Marine hazards may be due to natural events or anthropogenic activities but are typically a combination of these two causes. Van Ballengooyen *et al*. (2003) point out that the full extent of risk (e.g. loss of life and financial loss) is not always fully appreciated, and cite as an example the long-term financial losses due to coastal erosion which are often poorly understood, particularly by local authorities. It can be said that all of the items in the hazard inventory of Van Ballegooyen *et al*. (2003) result from either erosion and/or under-scouring of foundations and structures; flooding and inundation; direct wind and wave impacts (occasionally currents); and, broadly speaking, algal blooms and pollution.

Focusing on the abiotic hazards to infrastructure and developments in the coastal zone, the main metocean drivers are thus waves and sea water levels (and to a lesser extent winds and currents in some instances). This is generally confirmed by the literature review of coastal vulnerability assessment methods (discussed in detail in Chapter 6) where the identified indicators almost all relate to parameters that affect vulnerability/resilience to erosion/under-scouring, and flooding/inundation (Theron *et al.* 2010). Regarding wind hazards and Mozambique, it is acknowledged that primary hazards to coastal

<u>NOTE – definitions and terminology:</u>

NOAA: *Storm surge: "A rise or piling-up of water against shore*, produced by strong *winds* blowing onshore. A storm surge is most severe when it occurs in conjunction with a high tide."

Expansion by the authors:
In southern Africa, *sea storms (i.e. high waves with run-up, impacts and scouring)* are also a big risk; *these can be exacerbated by strong winds and high tides.*

infrastructure should include likely high wind damage during cyclones. However, this report focuses on climate change and water (coastal/marine) related hazards. The damage that may be done to infrastructure and housing by cyclone winds should not be overlooked, but is understood to be within the scope of some of the other Themes ("preparing cities"). As such, cyclone wind impacts may be felt far inland with no influence from the sea, and therefore should rightfully be dealt with as a hazard to be included in risk assessment and response for virtually all areas/cities (not specifically the coast).

Similarly, tsunami hazard and vulnerability is noted as not being considered in this report. Tsunami risk is not associated with climate change (which *is* at the core of Theme 2), and is also considered to be a relatively low risk hazard for the Mozambique coast. (Although this is beyond the present scope of Theme 2, a focussed tsunami risk assessment for the Mozambican coast should probably be conducted in the near future, to properly assess vulnerability and quantify impacts/risks, so that the need for tsunami specific planning and adaptation can be ascertained.)

Finally, in also considering other abiotic "non-coastal/marine" hazards and impacts in the wider coastal zone, there is value in noting the combined hazard of high seawater levels with flooding from rivers. It is well known that the heavy rains accompanying cyclones also bring river floods that can be "backed up" by high seawater levels along the coast. If such joint extreme events occur, they add to the destruction experienced to infrastructure and services. *River flooding studies* need to take into account the possible effects of high seawater flooding levels. This detail of *exacerbated river flooding levels* is beyond the scope of this study, but should be considered (possibly within Theme 3: Cities prepared for Climate Change and/or Theme 4: Building Resilience). Attention must certainly be drawn to the potential combined flooding impact in the cities/towns where major rivers join the sea. However, it should be noted that since Theme 2 did not deal with the hazards driven by terrestrial processes, the riverine flooding of all areas (including coastal) should be treated in a different theme.

Shoreline 'stability', or the probability of erosion (and/or under-scouring of structures) is affected by many drivers, processes and activities, some of which are natural and others due to anthropogenic actions. Most of these variables are listed and "typed/classified" in the following diagram (Figure 5.1).

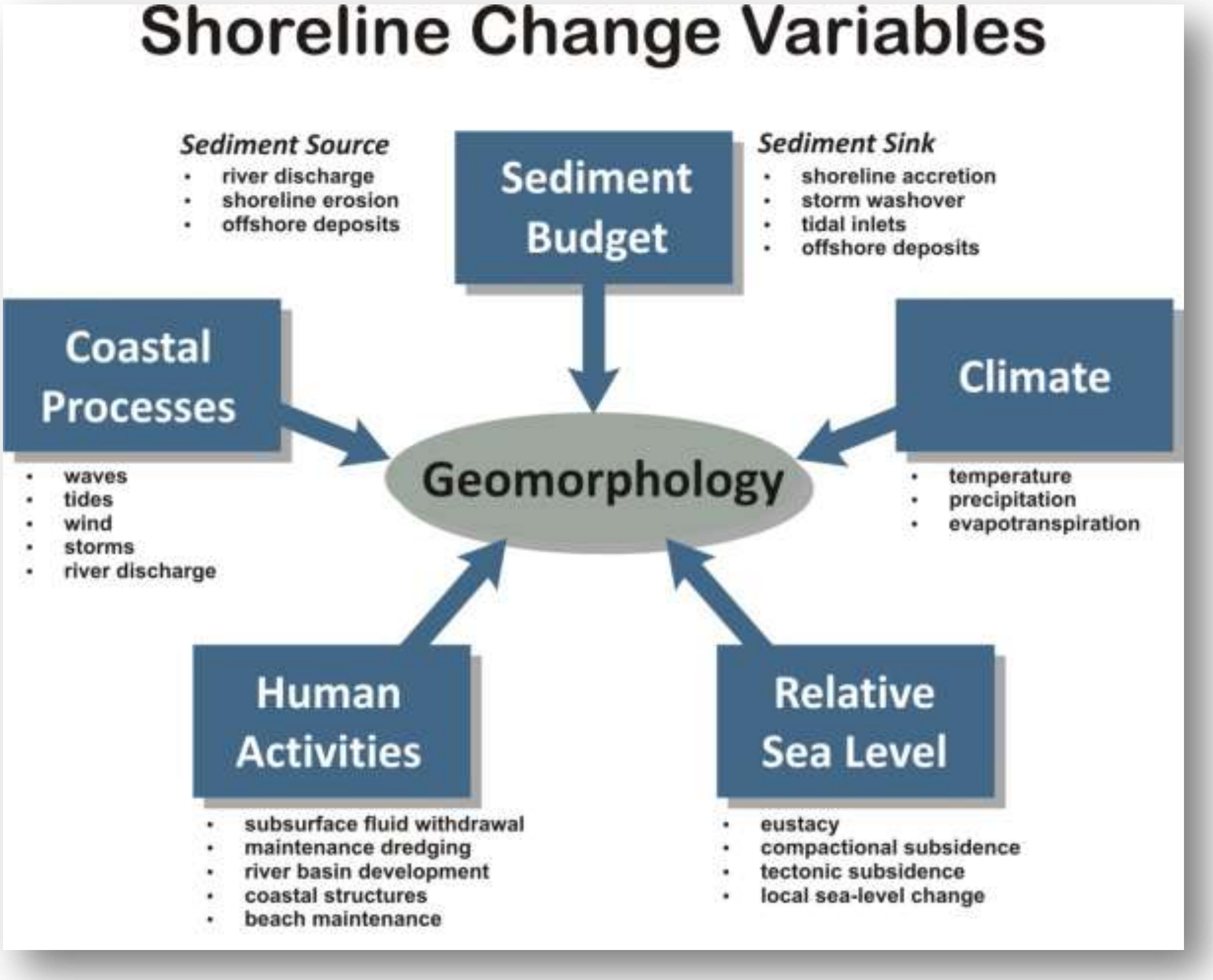


Figure 5.1: Drivers, processes and activities affecting shoreline "stability" or erosion.

The study on "Vulnerability and adaptation of the natural resources to the climate changes in Mozambique", a report prepared by MICOA under the United States Country Programme in 1999 (MICOA, 1999), identifies sea level rise as the main impact of global climate change in coastal areas of Mozambique. As was noted in IPCC (2001) and summarised in Table 2.1, climate change is expected to have a number of consequences which will detrimentally affect coastal resources. These are, amongst others: higher sea levels; higher sea temperatures; changes in precipitation patterns and sediment fluxes from rivers; changed oceanic conditions; as well as changes in storm tracks, frequencies and intensities. The apparent increase in storm activity and severity will be the most visible impact and the first to be noticed, since higher sea levels will require smaller storm events to overtop existing storm protection measures.

Changes in the shape of sandy coastlines depend on a number of factors of which the most important is the availability and distribution of sediment (sand). Sand along the coast is moved mostly by waves and currents, while the waves approaching the coast are in turn affected by bottom topography. As the sea level rises, existing topographic features will be located in deeper water and will have a different effect on waves approaching the coast. Features landward of the breaker zone will be in deeper water and will either have an amplified or dampened effect on the wave climate compared to the present. Deep water features may deepen to the degree that their effect on the wave climate is negligible. The points of wave energy convergence and divergence will change. The new locations of wave energy convergence could be expected to experience an increase in erosion while those locations currently subject to energy convergence could accrete if they are exposed to less energy in future. Changes in wave approach will change longshore currents and longshore sediment transport.

In conclusion, the primary hazards to physical (abiotic) coastal infrastructure related to sea storms and climate change are:

- Extreme inshore sea water levels resulting in flooding and inundation of low lying areas.
- Changes in cyclone characteristics, winds and local wave regime resulting in direct wave impacts.
- Coastal erosion and under-scouring of, for example, foundations and structures.
- System complexities, thresholds and non-linearities, for example related to sand transport.
- A combination of extreme events, such as sea storms during high tides plus sea level rise, will have the greatest impacts and will increasingly overwhelm existing infrastructure as climate change related factors set in time.

The main metocean drivers related to the above are thus waves and sea water levels (and to a lesser extent winds and currents). (The primary hazards listed above are discussed in detail in Sections 5.3 to 5.6 and 6.2.)

5.3 EXTREME INSHORE SEA WATER LEVELS

Significant drivers of high inshore sea water levels are tides, wind set-up, hydrostatics set-up, wave set-up and, in future, sea-level rise due to climate change (Theron, *et al.* 2010). These drivers all affect the still-water level at the shoreline.

The drivers/components of extreme inshore sea water levels most significant to the Southern African context are the tides (South African spring tides are about 1 m above mean sea level (MSL), but reach up to +3.7 m MSL in Mozambique), potential SLR, and wave run-up. Theron (2007) has estimated that in the South African setting during extreme events, these components could each contribute additional amounts (heights) of between about 0.35 m to 1.4 m to the inshore sea water level. Note that potential additional impacts of climate change (e.g. more extreme weather events) on wind-, hydrostatic- and wave set-up are not included in the above range of increase. These components of extreme inshore sea water levels as determined for the Mozambican coast are discussed in detail in Section 5.5.2

Recent observations from satellites, very carefully calibrated, are that global sea level rise over the last decade has been 3.3 +/- 0.4 mm/y (Rahmstorf *et al*. 2007)). The IPCC AR4 Report (IPCC

2007) concludes that anthropogenic warming and sea level rise would continue for centuries due to the timescales associated with climate processes and feedbacks, even if greenhouse gas concentrations were to be stabilised. Comparisons between about 30 years of South African tide gauge records and the longer term records elsewhere, show substantial agreement. A recent analysis of sea water levels recorded at Durban confirms that the local rate of sea level rise falls within the range of global trends (Mather 2008). Present SA SLR rates are: west coast +1.87 mm/y, south coast +1.47 mm/y, and east coast +2.74 mm/y (Mather *et al*. 2009).

The probability of sudden large rises in sea level (possibly several metres) due to catastrophic failure of large ice-shelves (e.g. Church and White 2006) is still considered unlikely this century, but events in Greenland (e.g. Gregory 2004, Overland, 2011) and Antarctica (e.g. Bentley 1997; Thomas *et al*. 2004) may soon force a re-evaluation of that assessment. In the longer term the large-scale melting of large ice masses is inevitable. Recent literature (since IPCC 2007) gives a wide range of SLR scenarios, as indicated in Figure 5.2.

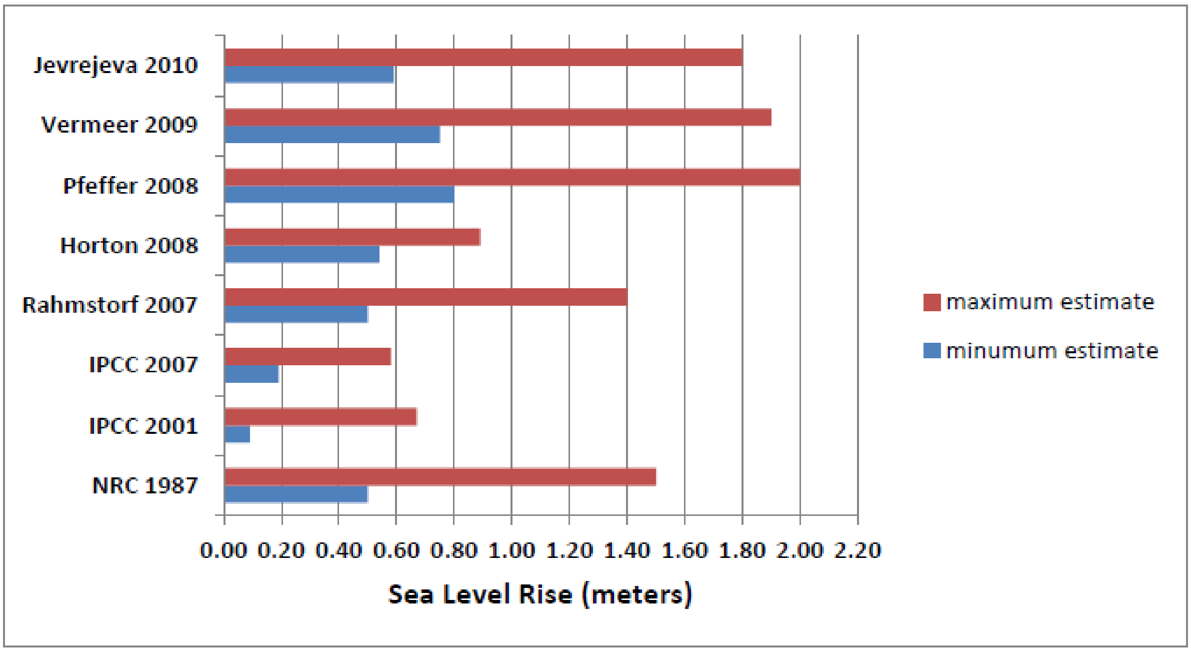


Figure 5.2: Comparison of minimum and maximum estimates of global SLR by year 2100 (USACE, 2011)
(Note, the post 2007 studies give an overall range of about 0.5 m to 2 m.)

Some projections and scenarios are even higher, but most "physics/process based" projections (e.g. Nicholls and Cazenave 2010; Pfeffer *et al.* 2008; Milne *et al.* 2009; SWIPA 2011) for 2100 are in the 0.5 m to 2 m range (Figure 5.4), as also concluded in various reviews (e.g. Theron and Rossouw 2009; Fletcher 2009). It is concluded that the *best estimate ("mid scenario")* of SLR by 2100 is around 1m, with a plausible *worst case scenario* of 2m, and a *best case scenario* of 0.5 m. The corresponding best estimate ("mid scenario") projection for 2050 is 0.3 m to 0.5 m.

The drivers of inshore water levels should not be confused with the added effect of wave run-up, which can reach even higher elevations. Wave run-up is the rush of water up the beach slope beyond the still-water level in the swash zone. A definition sketch of the various components leading to extreme inshore sea water levels (identifying the components of tide, barometric/hydrostatic setup, wind setup, wave setup, wave runup and sea level rise) is presented in Figure 5.3.

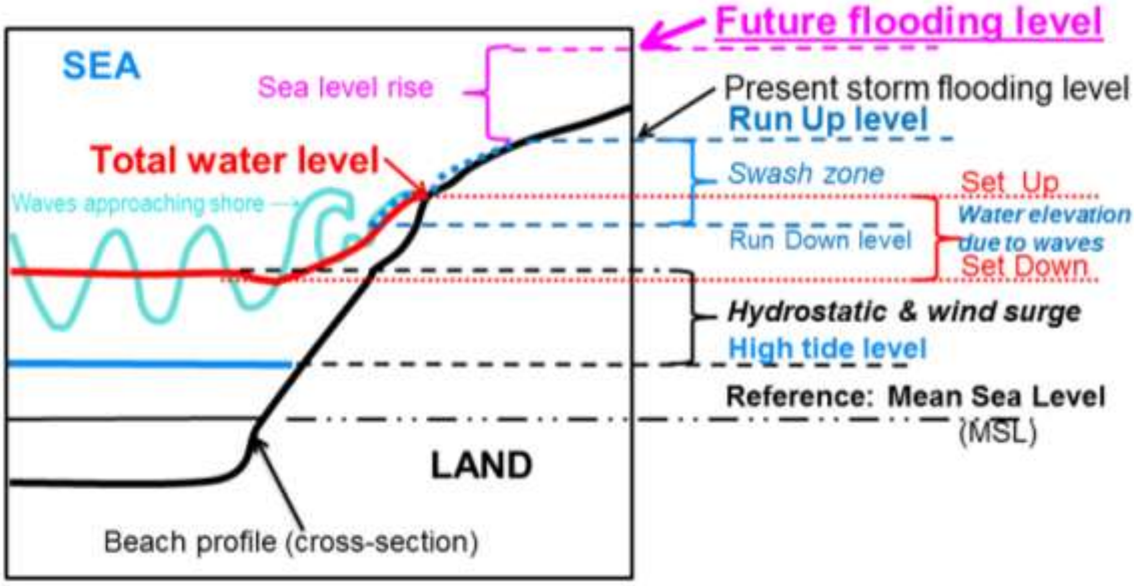


Figure 5.3: Definition sketch of the various components leading to extreme inshore sea water levels.

According to surveyed elevations (Smith *et al*. 2010), maximum run-up levels on the open Kwazulu-Natal (KZN) coast near Durban during the March 2007 storm (which coincided with highest astronomical tide) reached up to about +10.5 m MSL. Note that wave set-up and run-up are both accounted for in these levels. The maximum wave run-up alone during the 2007 KZN storm is estimated to have been up to about 7 m (vertical), resulting from significant nearshore wave heights of about 8.5 m. (The horizontal distance that the coastline retreated due to coastal erosion caused by this storm ranged from in the order of 0 m to 100 m resulting from local circumstances.)

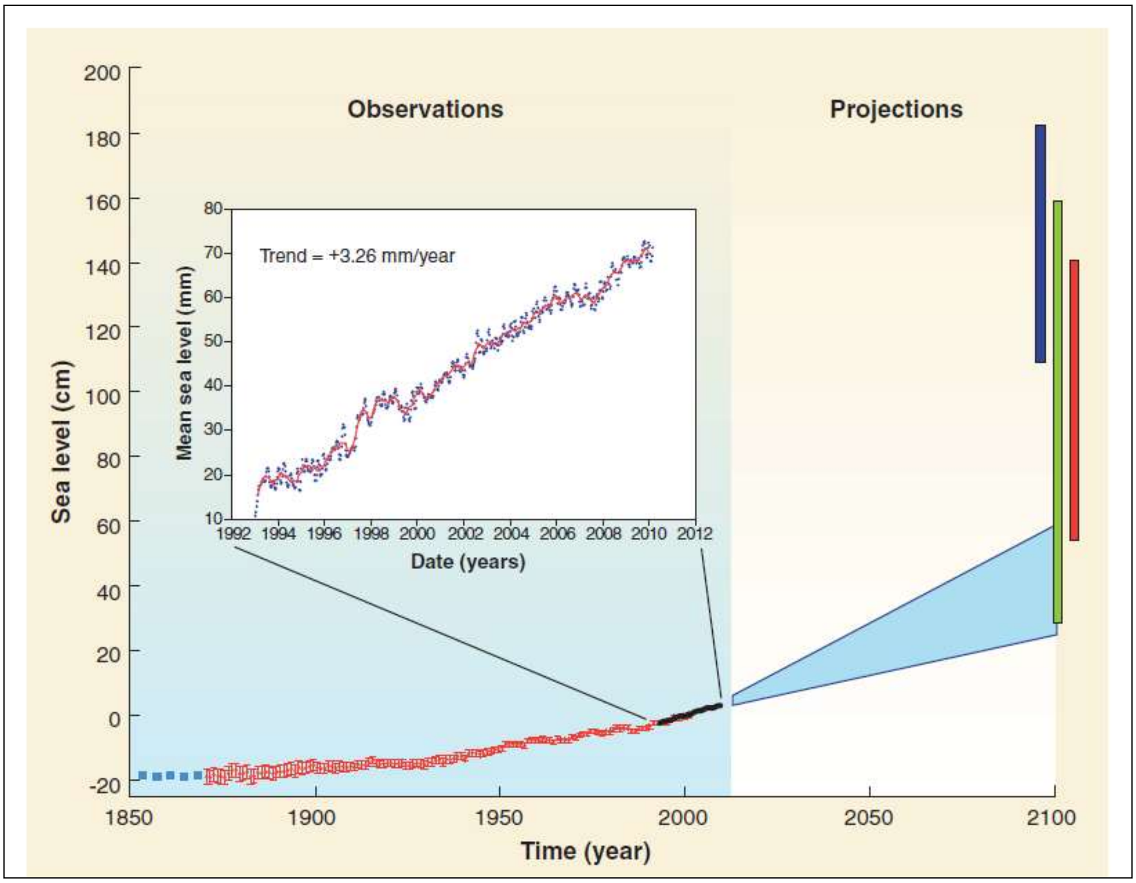


Figure 5.4: Measured and project sea level rise (Nicholls and Cazenave 2010). (The blue, green and red bars are projections from different authors.)

Around southern Africa, including Mozambique, wave run-up is thus an important factor, which may be considerably exacerbated by tides and future SLR (Theron, *et al.* 2010). Wave climate, resulting wave run-up prediction and the combined impact of waves, tides and SLR/climate change effects are addressed in the following sections of this chapter.

5.4 MOZAMBIQUE WAVE CLIMATE AND EXTREMES ANALYSES

5.4.1 Mozambican Offshore Wave Analysis

Introduction

This section presents a description of the wave climate derived for the Mozambican coast. Little recorded wave data are available for the Mozambican coast. Most of the wave analysis is based on the WaveWatch III information available from the National Centre for Environmental Prediction (NCEP), a division of NOAA, USA. Information on the cyclone-generated waves are also inferred from Cyclone data and other references.

Wind and Wave Climate Information

Offshore Wave Data

Data source

Archived NCEP data were available from February 1997 to June 2009. Data were extracted for 13 locations along the coast, as presented in Figure 5.4. The output includes three-hourly measurements of significant wave height (Hs), spectral peak wave period (Tp) and peak wave direction. In addition, the wind speed and direction were extracted.

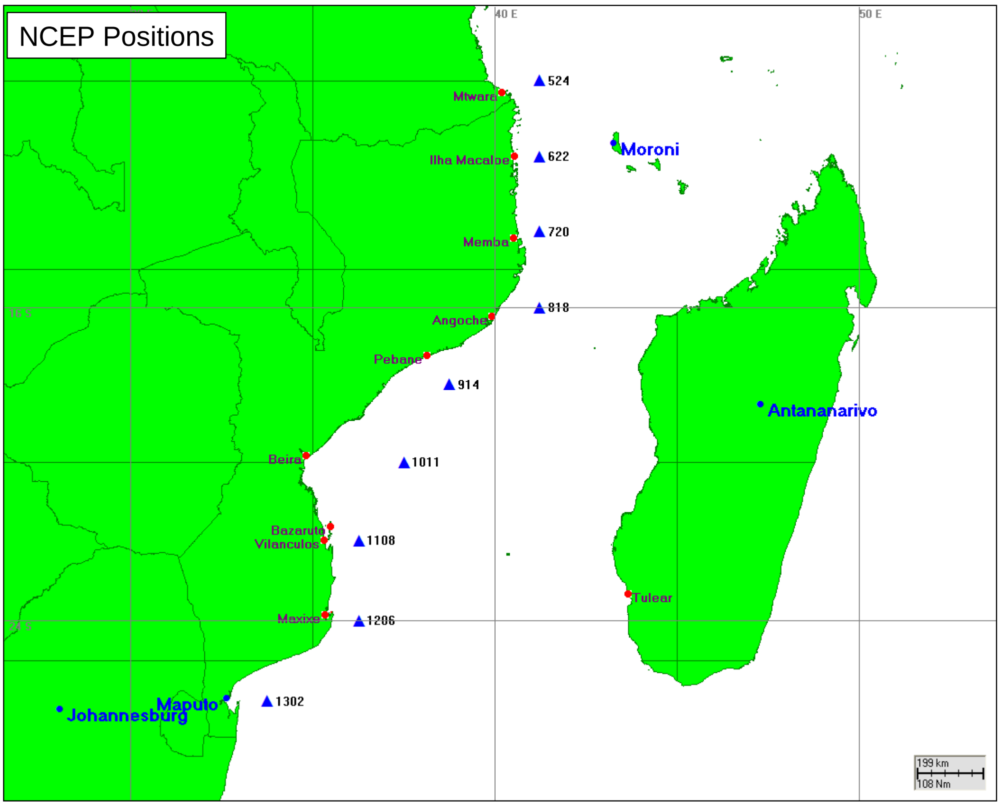


Figure 5.4: NCEP grid-point locations

The advantage of the NCEP data is that a data set of about 12 years is available. However since the data is derived from the global WaveWatch III Model, which predicts the wave conditions at a resolution of 1 x 1.25 degree resolution (approximately 110 km x 125 km grid size), the dynamic characteristics and scale of cyclones appear to be under-estimated by the model. A list of the grid-points used in this study is presented in Table 5.1. It is, however, worth noting that off the south coast of South Africa, the NCEP data compares well with measurements. The good comparison can most probably be attributed to the different wave generation mechanisms, i.e. the large low pressure or frontal systems passing the South African coast that can be well defined in the numerical atmospheric models.

Table 5.1: NCEP grid-points (as shown in Figure 5.4)

NCEP ID	Lat		Long		City/Town
	Deg	Min	Deg	Min	
1302	26	0	33	45	Maputo
1206	24	0	36	15	Maxixe
1108	22	0	36	15	Vilanculos
1011	20	0	37	30	Beira
914	18	0	38	45	Pebane
818	16	0	41	15	Angoche
720	14	0	41	15	Memba
622	12	0	41	15	Ilha Macaloe
524	10	0	41	15	Mtwara

Note that the output data are only representative of exposed offshore ocean waters with depths of 100m or greater

The NCEP grid-points offshore of Maputo, Beira, Maxixe and Vilanculos are given in greater detail in Figures 5.5a to 5.5d.

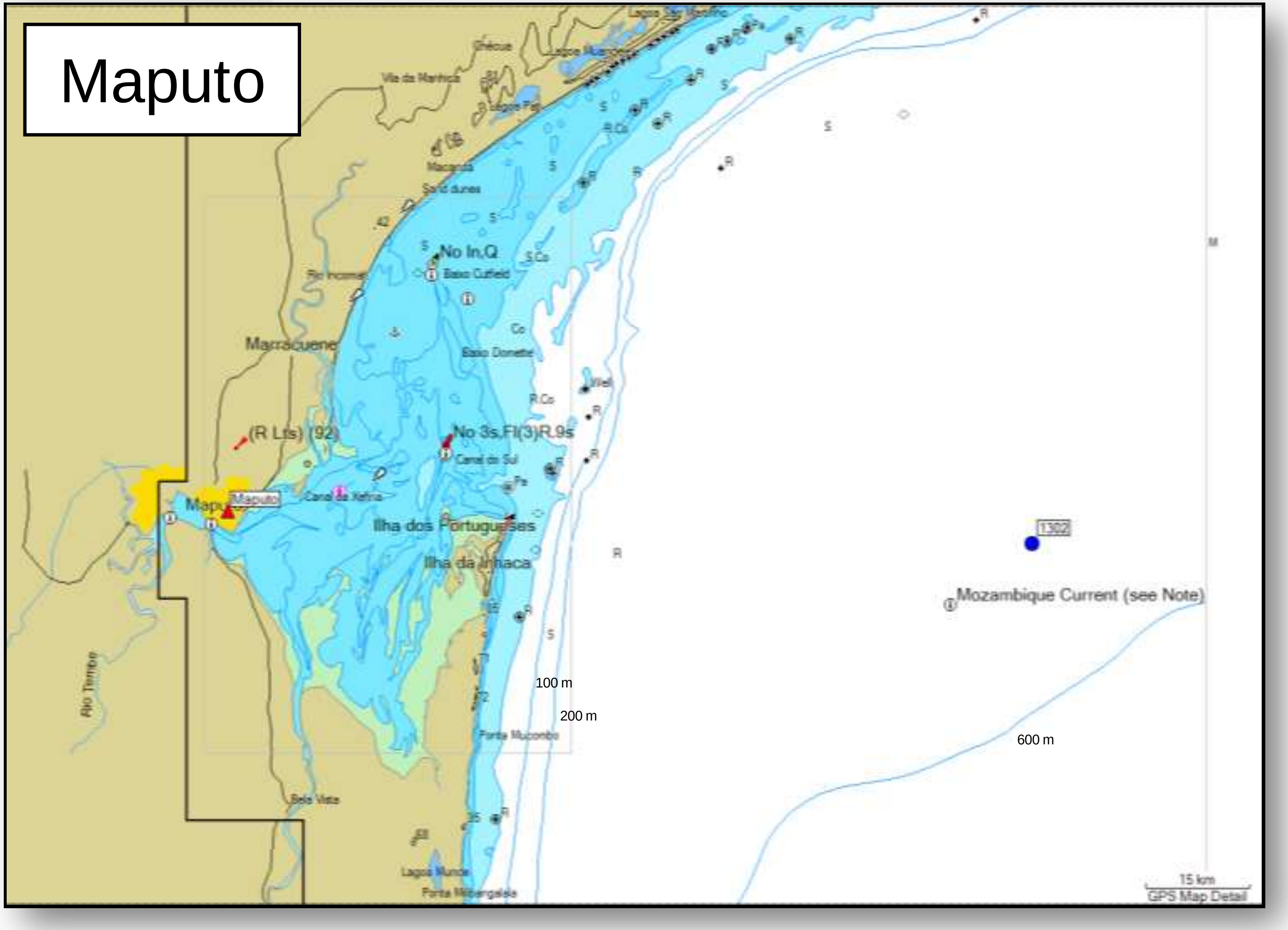


Figure 5.5a: NCEP grid-point location off Maputo

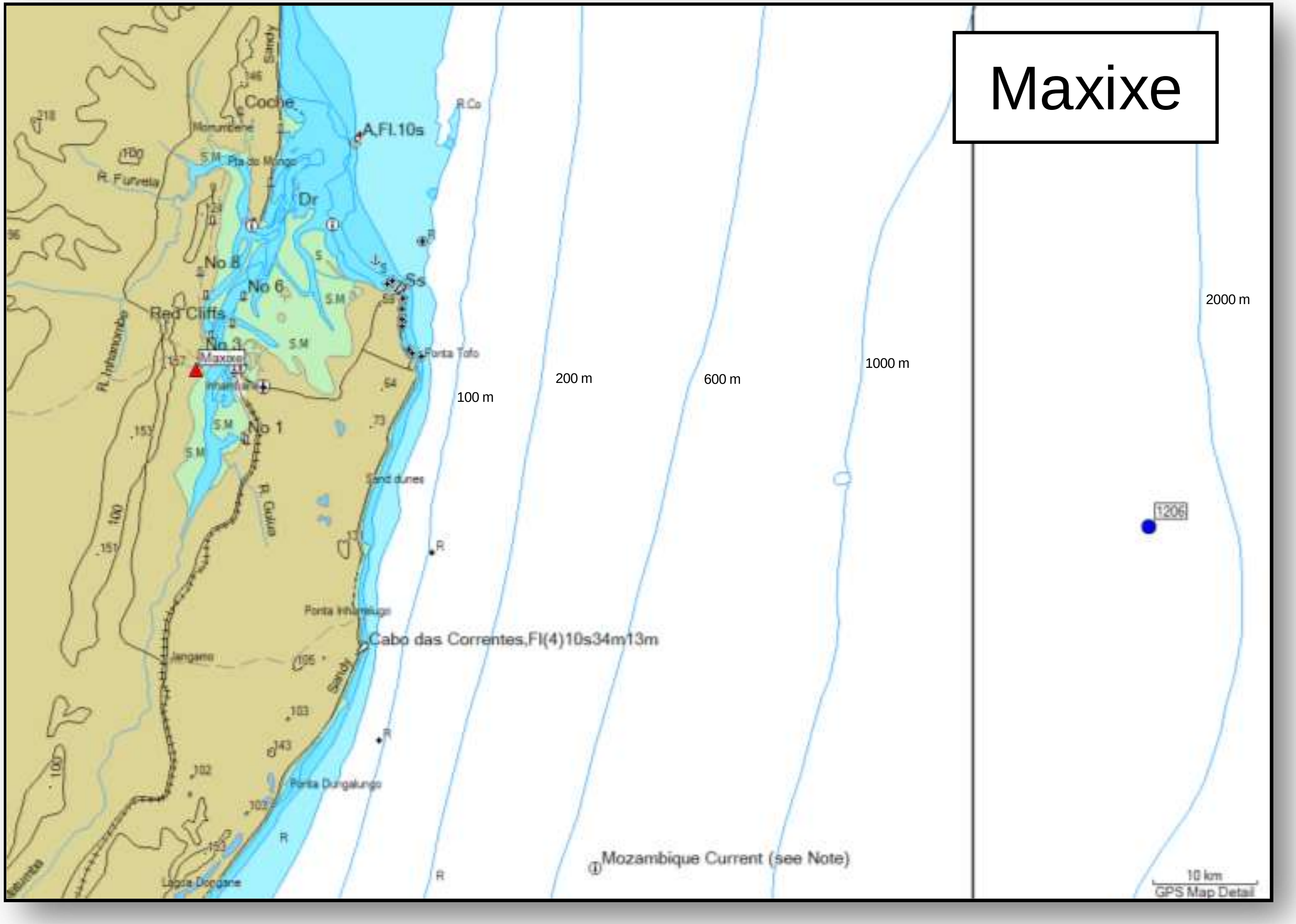


Figure 5.5b: NCEP grid-point location off Maxixe

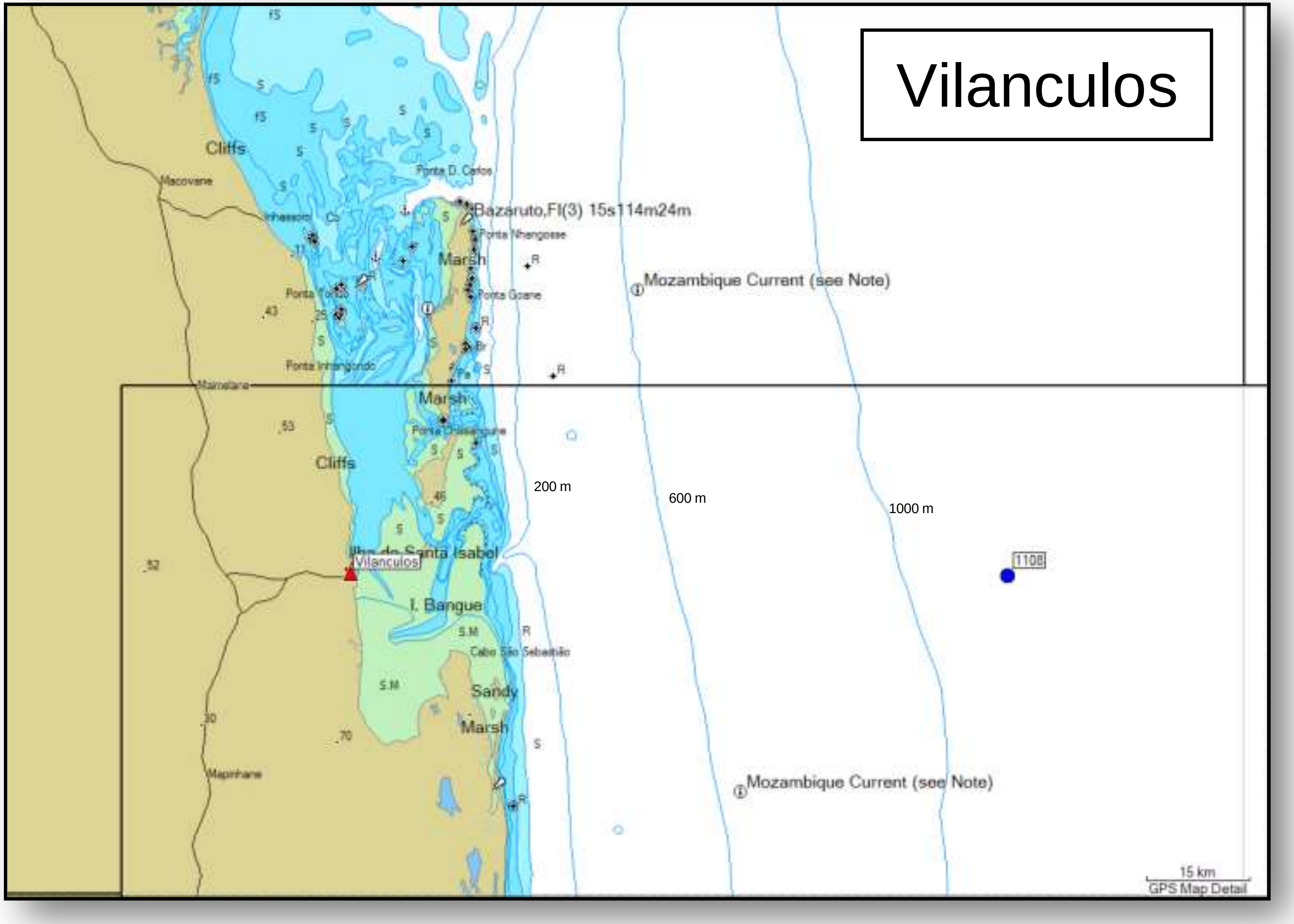


Figure 5.5c: NCEP grid-point location off Vilanculos

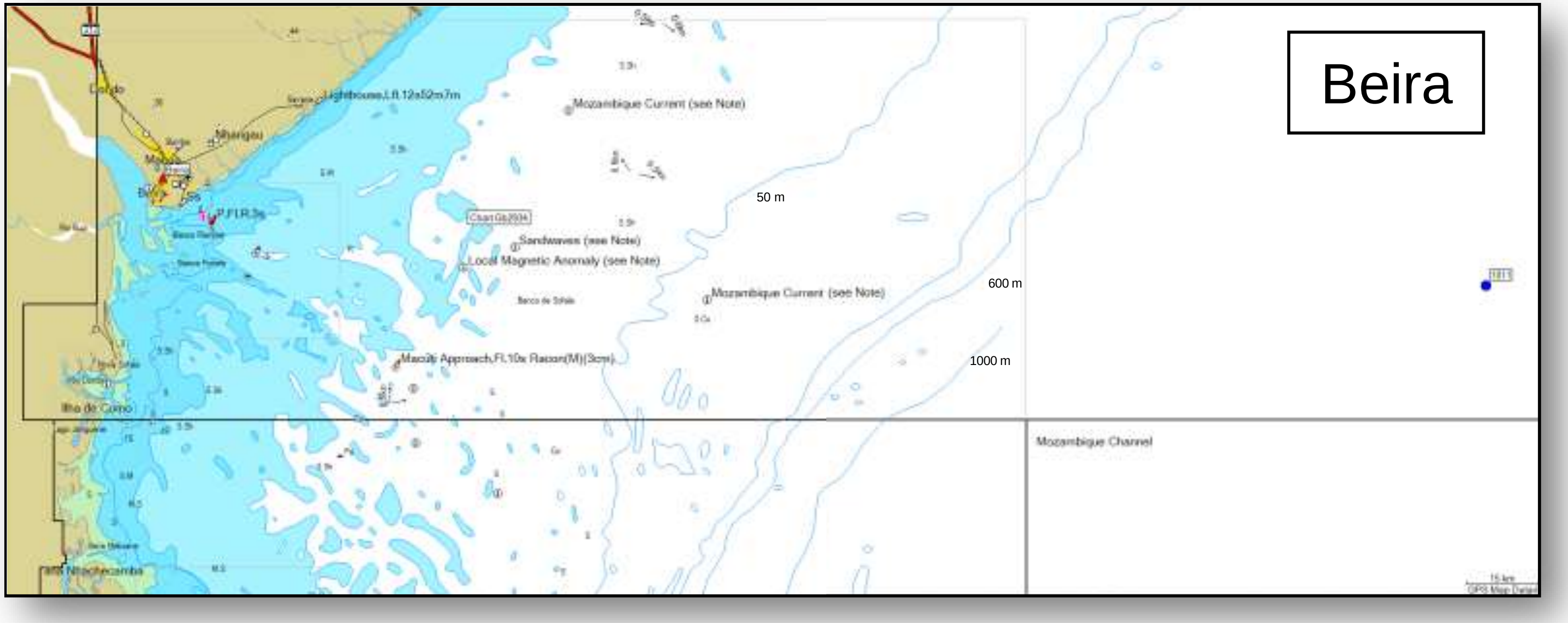


Figure 5.5d: *NCEP grid-point location off Beira*

Wave Climate

A summary of the general statistics per location is given in Table 5.2. This table presents the mean (average), the standard deviation, minimum and maximum, and selected exceedance percentiles. This table indicates that the wave height decreases to the northern part of Mozambique. The maximum registered wave height in the south was 6.2 m, decreasing to about 4.2 in the northern part. However, the waves appear to increase again in the southern part of Tanzania possibly as a result of the reduction of the sheltering effect of Madagascar.

The monthly distribution of mean wave height and standard deviation of wave height at each location are depicted in Figure 5.6. Thus, it can be seen that the highest waves occur during winter seasons, while calm conditions generally occur during November to February periods. Less seasonal variation is found in the south than in northern part of the Mozambican coast.

Table 5.2/…

Table 5.2: General wave height statistics

Station	Lat		Long		City/Town	NCEP ID	Average	Variance	Min	Max	0.01%	0.05%	0.10%	1%	5%	10%	25%	50%	75%	90%
	Deg	Min	Deg	Min																
ML01	26	0	33	45	Maputo	1302	1.8	0.5	0.5	6.2	6.0	5.7	5.4	4.2	3.2	2.8	2.1	1.7	1.4	1.2
ML03	24	0	36	15	Maxixe	1206	1.9	0.5	0.5	6.0	5.9	5.6	5.4	4.2	3.3	2.9	2.2	1.8	1.4	1.2
ML04	22	0	36	15	Vilanculos	1108	1.7	0.5	0.4	5.4	5.3	5.0	4.9	3.9	3.0	2.6	2.0	1.5	1.2	1.0
ML06	20	0	37	30	Beira	1011	1.6	0.5	0.4	5.3	5.3	4.9	4.8	3.8	3.0	2.6	1.9	1.4	1.1	0.9
ML08	18	0	38	45	Pebane	914	1.4	0.4	0.3	5.3	5.2	4.8	4.6	3.6	2.8	2.3	1.7	1.3	1.0	0.8
ML10	16	0	41	15	Angoche	818	1.4	0.4	0.3	5.3	5.2	4.7	4.3	3.4	2.5	2.2	1.6	1.2	1.0	0.8
ML11	14	0	41	15	Memba	720	1.1	0.2	0.2	4.2	4.1	3.8	3.5	2.6	2.0	1.8	1.4	1.0	0.8	0.6
ML12	12	0	41	15	Ilha Macaloe	622	1.1	0.2	0.2	4.2	4.1	3.7	3.6	2.6	2.0	1.8	1.4	1.0	0.8	0.6
ML13	10	0	41	15	Mtwara	524	1.4	0.3	0.3	4.2	4.3	3.8	3.7	2.8	2.3	2.0	1.7	1.3	1.0	0.8

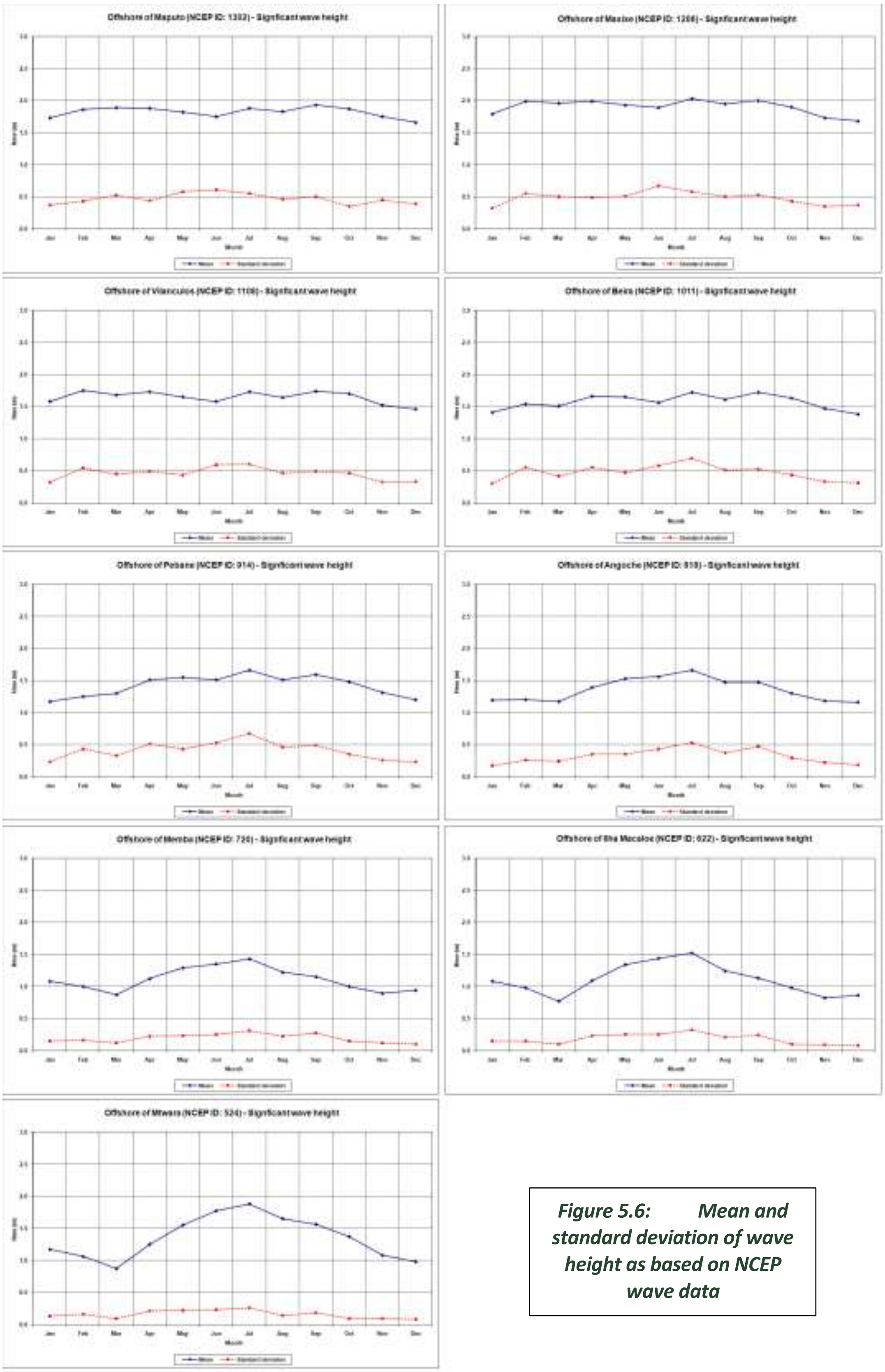
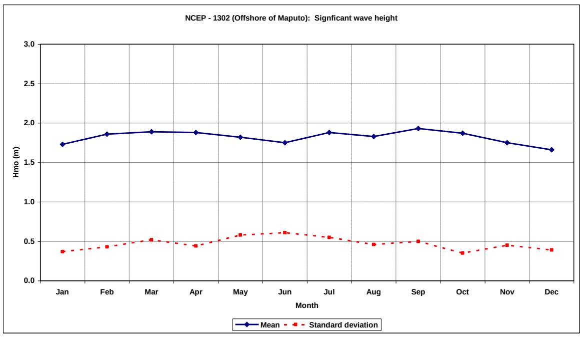
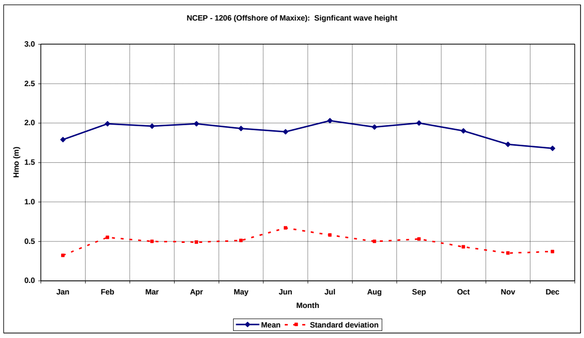
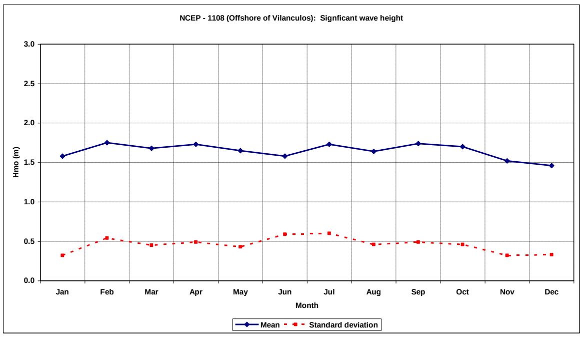
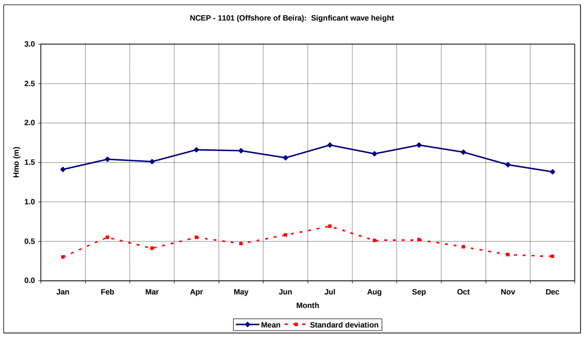


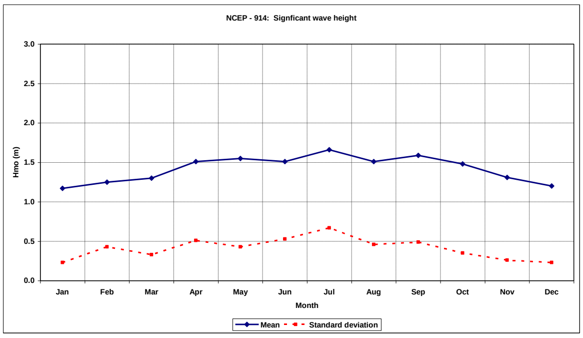
Figure 5.6: Mean and standard deviation of wave height as based on NCEP wave data

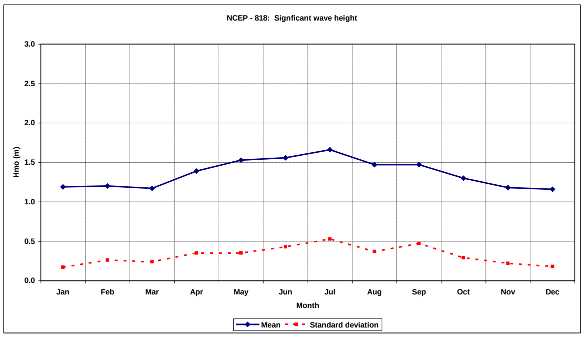

NCEP - 1302 (Offshore of Maputo): Signficant wave height

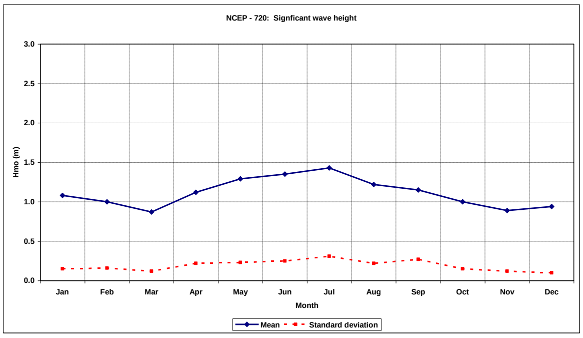

NCEP - 1206 (Offshore of Maxixe): Signficant wave height

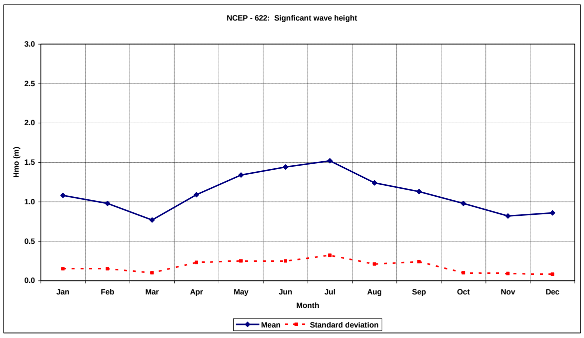

NCEP - 1108 (Offshore of Vilanculos): Signficant wave height

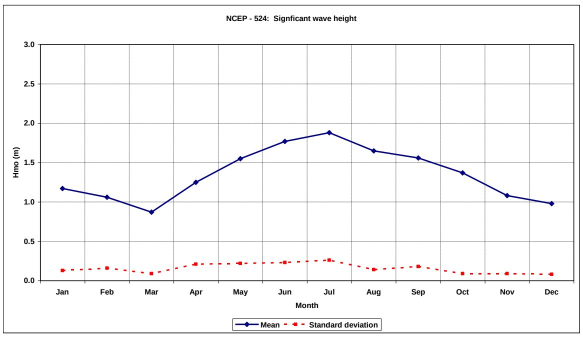

NCEP - 1101 (Offshore of Beira): Signficant wave height


NCEP - 914: Signficant wave height


NCEP - 818: Signficant wave height


NCEP - 720: Signficant wave height


NCEP - 622: Signficant wave height


NCEP - 524: Signficant wave height

The annual joint distributions of wave height versus direction for each of the locations are presented in Figure 5.7 in the form of wave roses. The roses indicate that in the southern part of Mozambique (from southern border to Vilanculos), a bi-modal wave direction with waves approaching from the S and SE/ESE is indicated. In the central part (from Vilanculos to Angoche), a SSW'ly component also becomes prominent, together with the SSE'ly component. However, the SSW'ly component is more prominent towards the northern section. In the northern part of the Mozambican coast, the wave direction is predominantly S. However, it appears that in the coastal area between Mozambique and Tanzania, the direction changes to a more E'ly direction as the effect of Madagascar is less.

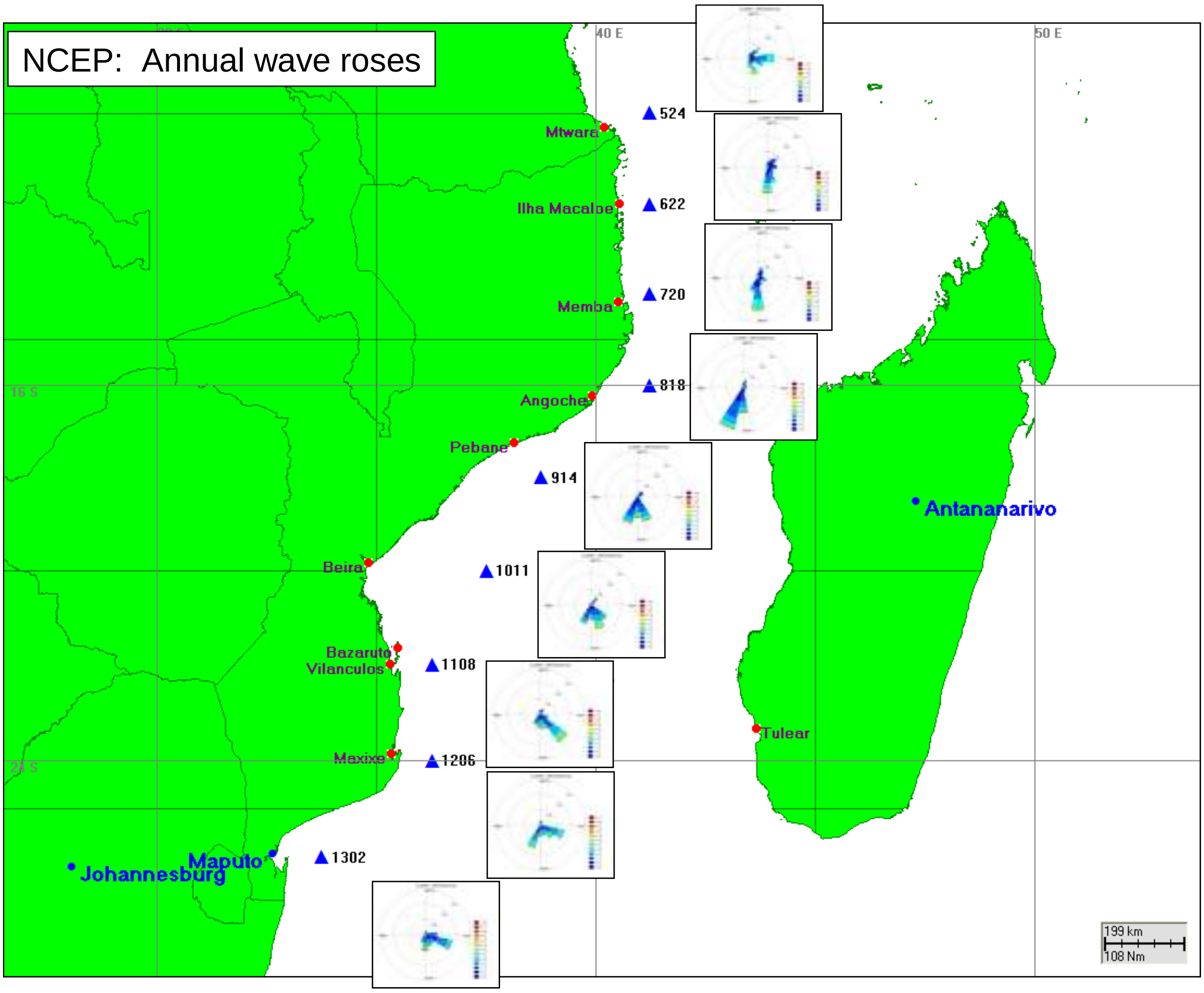
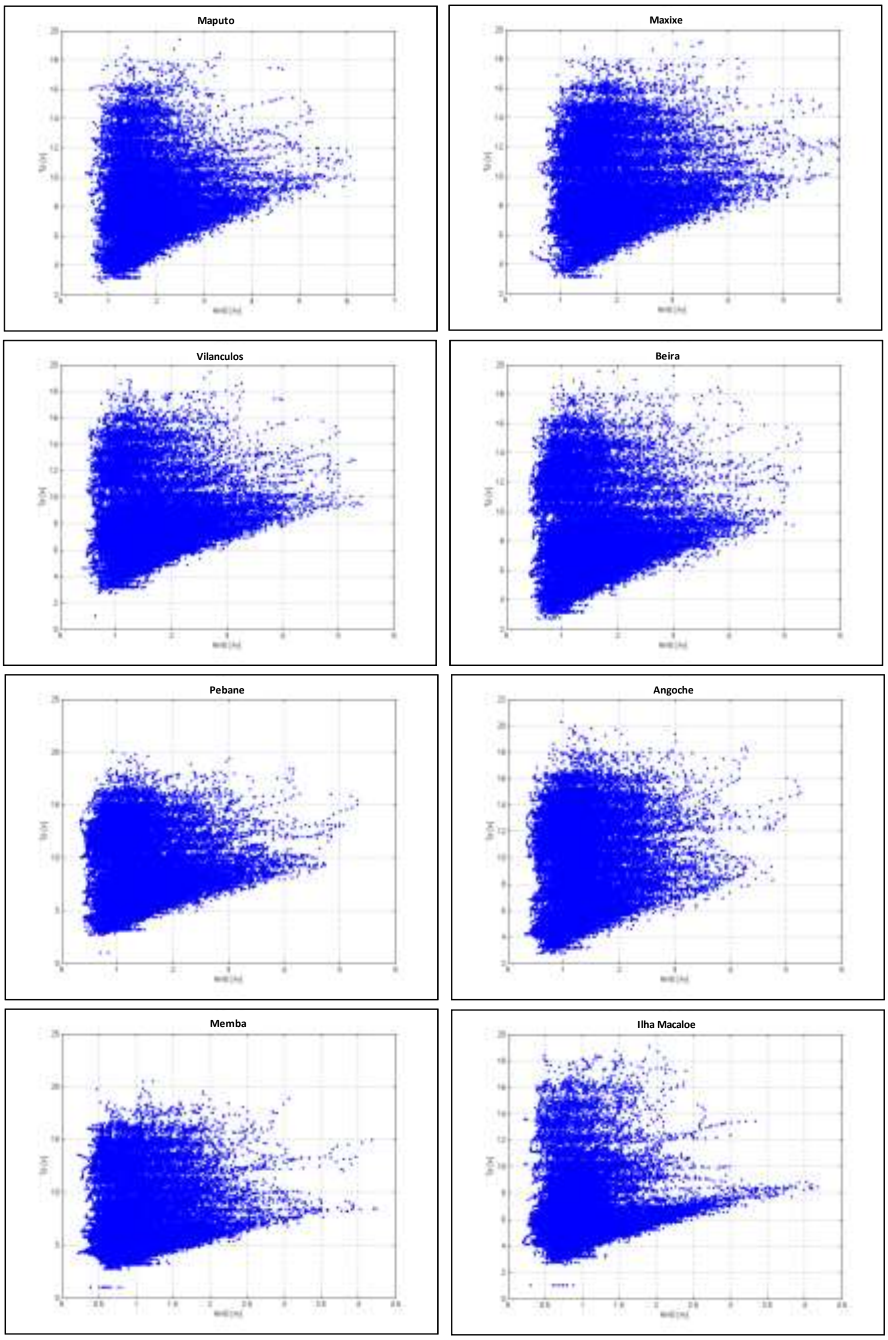


Figure 5.7: Annual wave roses as based on 12 years of NCEP wave data

The NCEP wave data also provides information on the wave periods. Figure 5.8 presents the scatter-plots of the significant wave height (Hmo) versus peak wave period (Tp).



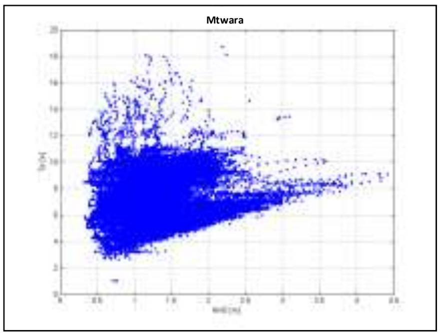


Figure 5.8: Scatter-plot of Hmo versus Tp for 9 NCEP wave stations

The peak periods (Tp) of the smaller waves varies mostly between 3 s and about 20 s off the Mozambican coast. The period for the larger waves varies mostly between periods ranging from 8 s to about 18 s.

Cyclone Information

The NCEP data are derived from the global Wavewatch III model. Therefore, since tropical cyclones are fairly small and dynamic atmospheric phenomena, the cyclone-generated waves are not well represented by the NCEP data. There is also little measured data to verify the cyclone-generated wave data. It was therefore necessary to examine the available information on cyclones. For this study, the Annual Tropical Reports from the Joint Typhoon Warning Centre (JTWC) were utilized (JTWC 1997, 2009). From these reports, four tropical cyclones were identified for inspection of the corresponding NCEP data. During TC Eline (Feb 2000) with wind speeds of about 200 km/h, the closest grid-point off Beira indicated offshore waves of about 4 m. During TC Jahpet (March 2003), NCEP indicated waves of about 4 m offshore of Beira and about 3 m offshore of Vilanculos. TC Favio passed over the Vilanculos region with wind speeds of more than 150 km/h. The offshore wave height was indicated to be in the order of 2 m. Therefore, it appears the NCEP model may be under-estimating the magnitude of these waves.

In this study, only cyclone information from 1997 onwards (as obtained from JTWC, 2009) was extracted, to coincide with the NCEP data. An evaluation of the estimated cyclone tracks indicated that cyclones travelled through the Mozambican Channel during the period November to April. Based on the period 1997 to 2008, approximately three cyclones had moved across the Mozambican Channel on an annual basis, which may have had an impact on the wave data.

During this period a number of tropical cyclones of significance impacted on the Mozambican coast. Tropical cyclones that made landfall since 1994, as summarised by INGC Climate Change Report (INGC Phase 1 Report, 2008), are presented in Table 5.3. Unfortunately no wave data were readily available for these cyclones, except for the CSIR measurements made off Beira during TC Lisette in February 1997. The wave buoy deployed in 20 m water depth, registered a peak of about 4 m (Hs) with a corresponding peak period of about 10 s.

Table 5.3: Tropical cyclones , and tropical storms (TS) making landfall on the coast of Mozambique for the period 1994-2008 (source: INGC report, 2009)

Year	Category and Name	Landfill	Date	Strength	Wind speed
1994	(Cat 4) Nadia	North	24 March	Cat 1	139 km/h
1995	(TS) Fodah	Central	22 Jan	TD	37 km/h
1996	(Cat 4) Bonita	Central	14 Jan	Cat 1	130 km/h
1997	(Cat 1) Lisette	Central	2 March	TS	111 km/h
1998	(TS)	North	17 Jan	TD	56 km/h
2000	(Cat 4) Eline	Central	22 Feb	Cat 4	213 km/h
2000	(Cat 4) Hudah	Central	8 April	Cat 1	148 km/h
2003	(Cat 4) Japhet	South	2 March	Cat 2	167 km/h
2003	(TS) Atang	North	13 Nov	TD	46 km/h
2004	(TS) Delfina	Central	1 Jan	TS	93 km/h
2007	(Cat 4) Favio	South	22 Feb	Cat 3	185 km/h
2008	(Cat 4) Jokwe	North	08 Mar	Cat 3	180 km/h

It is worth noting that remote sensing satellite wave data are available for the area. These satellites (e.g. Jason, Envisat) have fixed tracks (i.e. geo-orbiting). Therefore, more detailed studies could be conducted to find the satellite-tracks that coincide with the occurrence of cyclones.

Extreme Wave Analysis

Introduction

As the wave conditions are a primary driver of extreme sea water levels and potential flooding/inundation of areas, it is necessary to quantify the extreme wave conditions encountered around the coast. Two procedures were applied in this study to derive the extreme wave conditions. The first procedure involved fitting a statistical distribution to the NCEP data, while the second procedure focussed on determining the wave height generated by the extreme cyclone wind conditions. Both approaches were applied to the full Mozambican coast. The sections below give an overview of the procedures and the results. (These results, in conjunction with other drivers of extreme inshore water levels, were considered in the assessment of coastal flooding in Sections 5.5, 5.6 and 6.2.)

NCEP Extreme Wave Analysis

The NCEP wave climate was analysed and appropriate statistical distributions (e.g. Fisher-Tippet and Weibull) were tested to find those most applicable to the Mozambican coast. (An article by Rossouw and Rossouw (1999) provides a description of these distributions and their application to wave statistics.) The final procedure was based on the POT method (Rossouw & Rossouw, 1999) and by fitting Weibull and Gumbell statistical distributions to all directional data. A summary of the results are provided in Table 5.4. Note that the corresponding peak period (Tp) were based on the relationship of Tp^2 versus wave height. By determining the average wave period per wave height bin (of 0.5 m), a linear relationship could be assumed.

The derived Tp for each extreme wave height is therefore an estimate of the corresponding period. Since longer wave periods are indicated in the data (Figure 5.8) than presented in Table 5.4, more detailed analyses will be necessary when focussing on a particular site. The longer period waves will influence the wave energy that will arrive at the particular location.

Table 5.4: NCEP extreme wave analysis for 9 Locations off the Mozambican coast

Site	Dir	Return period															
		1		5		10		20		30		40		50		100	
		Hm0 [m]	Tp [s]	Hm0 [m]	Tp [s]	Hm0 [m]	Tp [s]	Hm0 [m]	Tp [s]	Hm0 [m]	Tp [s]	Hm0 [m]	Tp [s]	Hm0 [m]	Tp [s]	Hm0 [m]	Tp [s]
Maputo (M01)	All	5.2	10.1	6.3	10.7	6.7	11.0	7.1	11.2	7.4	11.3	7.6	11.4	7.7	11.5	8.1	11.7
	N	2.4	5.0	2.6	5.2	2.7	5.2	2.7	5.3	2.8	5.3	2.8	5.3	2.9	5.3	2.9	5.4
	NE	2.4	5.5	2.5	5.6	2.6	5.6	2.7	5.7	2.8	5.7	2.8	5.7	2.8	5.7	2.9	5.8
	E	3.8	10.1	4.6	10.8	4.9	11.0	5.3	11.3	5.5	11.4	5.6	11.5	5.7	11.6	6.1	11.9
	SE	4.7	10.6	5.6	11.3	6.0	11.5	6.3	11.8	6.5	12.0	6.7	12.1	6.8	12.2	7.2	12.4
	S	5.9	10.1	6.9	10.4	7.3	10.5	7.7	10.6	7.9	10.7	8.1	10.7	8.2	10.7	8.6	10.8
	SW	4.0	-	4.7	-	5.0	-	5.3	-	5.4	-	5.6	-	5.6	-	5.9	-
	W																
	NW	2.3	5.0	2.5	5.1	2.6	5.1	2.7	5.1	2.7	5.2	2.8	5.2	2.8	5.2	2.9	5.2
Maxixe (M03)	All	5.3	11.2	6.5	12.1	7.0	12.4	7.5	12.8	7.7	12.9	7.9	13.1	8.1	13.2	8.6	13.5
	N	3.5	7.3	4.0	7.8	4.2	8.0	4.3	8.1	4.5	8.3	4.5	8.3	4.6	8.4	4.8	8.6
	NE	3.6	8.3	4.2	8.9	4.4	9.2	4.7	9.4	4.8	9.5	4.9	9.6	5.0	9.7	5.3	9.9
	E	4.5	9.2	5.5	9.7	5.9	9.9	6.3	10.2	6.6	10.3	6.8	10.4	6.9	10.4	7.4	10.7
	SE	5.1	10.0	6.3	10.7	6.7	11.0	7.2	11.3	7.5	11.4	7.7	11.6	7.9	11.6	8.3	11.9
	S	5.7	11.5	6.8	12.0	7.2	12.1	7.6	12.3	7.8	12.4	8.0	12.5	8.1	12.5	8.5	12.7
	SW	4.7	12.7	5.4	12.7	5.7	12.7	6.0	12.7	6.2	12.7	6.3	12.7	6.4	12.7	6.7	12.7
	W																
	NW																
Vilanculos (M04)	All	4.8	10.3	6.0	11.1	6.4	11.5	6.9	11.8	7.2	12.0	7.4	12.1	7.5	12.2	8.0	12.5
	N	3.1	6.9	3.5	7.4	3.7	7.6	3.9	7.8	4.0	7.9	4.1	8.0	4.2	8.0	4.4	8.2
	NE	3.3	7.4	3.9	7.9	4.2	8.2	4.4	8.4	4.6	8.5	4.7	8.6	4.8	8.6	5.0	8.8
	E	3.8	9.0	4.5	9.7	4.8	10.0	5.1	10.3	5.3	10.4	5.4	10.5	5.5	10.6	5.8	10.9
	SE	4.5	9.5	5.5	10.1	5.9	10.3	6.2	10.5	6.5	10.7	6.6	10.8	6.7	10.8	7.1	11.1
	S	5.5	10.3	6.6	10.4	7.1	10.5	7.6	10.5	7.9	10.6	8.1	10.6	8.3	10.6	8.7	10.7
	SW	3.5	-	4.2	-	4.5	-	4.7	-	4.9	-	5.0	-	5.1	-	5.4	-
	W																
	NW																
Beira (M06)	All	4.5	10.6	5.4	11.3	5.7	11.5	6.1	11.8	6.3	12.0	6.4	12.0	6.5	12.1	6.9	12.4
	N	3.0	6.6	3.5	7.0	3.7	7.2	3.9	7.4	4.0	7.5	4.1	7.6	4.2	7.6	4.4	7.8
	NE	3.3	9.0	3.9	9.9	4.2	10.3	4.5	10.6	4.7	10.8	4.8	10.9	4.9	11.0	5.1	11.4
	E	3.3	7.2	3.8	7.7	4.0	7.8	4.3	8.0	4.4	8.1	4.5	8.2	4.6	8.3	4.8	8.5
	SE	4.4	9.4	5.0	9.9	5.3	10.1	5.6	10.3	5.8	10.4	5.9	10.4	6.0	10.5	6.2	10.7
	S	4.9	10.9	5.7	11.2	6.1	11.4	6.4	11.5	6.7	11.6	6.8	11.6	6.9	11.7	7.2	11.8
	SW	4.1	-	5.0	-	5.4	-	5.8	-	6.1	-	6.2	-	6.4	-	6.8	-
	W																
	NW																
Pebane (M08)	All	4.3	11.4	5.1	12.2	5.5	12.6	5.8	12.9	6.0	13.0	6.1	13.2	6.2	13.3	6.6	13.6
	N	1.7	4.4	1.8	4.5	1.8	4.5	1.8	4.5	1.8	4.5	1.8	4.5	1.9	4.5	1.9	4.6
	NE	2.6	6.4	3.0	6.8	3.2	6.9	3.3	7.0	3.4	7.1	3.5	7.2	3.5	7.2	3.7	7.3
	E	2.8	7.5	3.3	8.2	3.6	8.5	3.8	8.7	4.0	8.9	4.1	9.0	4.2	9.0	4.4	9.3
	SE	3.8	8.4	4.4	8.8	4.7	9.0	5.0	9.2	5.1	9.3	5.2	9.4	5.3	9.4	5.6	9.6
	S	4.5	11.5	5.4	12.2	5.7	12.4	6.0	12.7	6.2	12.8	6.4	12.9	6.5	13.0	6.8	13.2
	SW	3.9	-	4.9	-	5.3	-	5.8	-	6.0	-	6.2	-	6.3	-	6.8	-
	W																
	NW																
Angoche (M10)	All	4.1	11.7	5.2	12.8	5.6	13.3	6.0	13.7	6.2	13.9	6.4	14.1	6.6	14.2	7.0	14.6
	N	2.9	6.8	3.4	7.2	3.6	7.3	3.8	7.5	3.9	7.5	4.0	7.6	4.0	7.6	4.2	7.8
	NE	2.6	6.2	3.0	6.5	3.2	6.6	3.4	6.7	3.5	6.7	3.5	6.8	3.6	6.8	3.8	6.9
	E	3.1	7.2	3.7	7.7	4.0	7.9	4.3	8.1	4.5	8.2	4.6	8.3	4.7	8.4	5.0	8.5
	SE	2.6	6.9	3.0	7.2	3.1	7.3	3.3	7.4	3.4	7.5	3.4	7.5	3.5	7.6	3.6	7.7
	S	4.3	11.9	5.2	12.8	5.6	13.1	5.9	13.4	6.2	13.6	6.3	13.7	6.4	13.8	6.8	14.1
	SW	3.4	12.8	4.0	12.8	4.2	12.9	4.5	12.9	4.6	12.9	4.7	12.9	4.8	12.9	5.1	12.9
	W																
	NW																
Memba (M11)	All	3.2	9.1	3.9	9.8	4.2	10.0	4.5	10.3	4.7	10.4	4.8	10.5	4.9	10.6	5.2	10.8
	N	3.0	7.4	3.5	8.0	3.7	8.2	4.0	8.4	4.1	8.6	4.2	8.6	4.3	8.7	4.5	8.9
	NE	2.0	6.8	2.3	7.0	2.4	7.1	2.6	7.2	2.6	7.3	2.7	7.3	2.7	7.3	2.8	7.4
	E	2.6	7.4	3.2	8.0	3.4	8.2	3.7	8.4	3.8	8.5	4.0	8.6	4.0	8.7	4.3	8.9
	SE	2.5	7.1	2.9	7.5	3.0	7.6	3.2	7.7	3.3	7.8	3.4	7.9	3.4	7.9	3.6	8.1
	S	3.5	9.3	4.2	9.5	4.5	9.6	4.8	9.7	5.0	9.8	5.1	9.8	5.2	9.9	5.6	10.0
	SW																
	W																
	NW																
Ilha Macaloe (M12)	All	3.3	7.8	4.0	8.3	4.4	8.4	4.7	8.6	4.8	8.7	5.0	8.8	5.1	8.8	5.4	9.0
	N	3.0	7.2	3.5	7.8	3.7	8.0	3.9	8.2	4.0	8.3	4.1	8.4	4.2	8.4	4.4	8.6
	NE	2.0	7.8	2.4	8.2	2.6	8.3	2.8	8.5	2.8	8.6	2.9	8.7	3.0	8.7	3.1	8.9
	E	2.1	8.0	2.6	8.3	2.9	8.4	3.1	8.6	3.3	8.7	3.4	8.7	3.5	8.8	3.8	8.9
	SE	2.5	6.9	2.9	7.2	3.1	7.3	3.3	7.5	3.4	7.6	3.4	7.6	3.5	7.7	3.7	7.8
	S	3.7	7.6	4.4	7.6	4.7	7.5	5.0	7.5	5.2	7.5	5.3	7.5	5.4	7.4	5.7	7.4
	SW																
	W																
	NW																
Mtwara (M13)	All	3.5	8.1	4.2	8.5	4.5	8.6	4.8	8.8	5.0	8.9	5.1	8.9	5.2	9.0	5.5	9.1
	N	3.0	6.8	3.5	7.3	3.8	7.4	4.0	7.6	4.1	7.7	4.2	7.8	4.3	7.8	4.5	8.0
	NE	2.3	8.1	2.7	8.5	2.8	8.6	3.0	8.8	3.1	8.9	3.2	8.9	3.2	9.0	3.4	9.1
	E	2.5	9.2	2.8	9.5	2.9	9.6	3.0	9.7	3.1	9.7	3.1	9.8	3.2	9.8	3.3	9.9
	SE	3.0	6.9	3.3	6.9	3.4	6.9	3.6	7.0	3.6	7.0	3.7	7.0	3.7	7.0	3.9	7.0
	S	4.0	8.0	4.7	8.2	5.0	8.3	5.3	8.4	5.5	8.4	5.6	8.5	5.7	8.5	6.0	8.6
	SW																
	W																
	NW																

As concluded from the discussion above, the NCEP data do not sufficiently represent or contain the cyclone-generated waves, less emphasis is placed on the results of the extreme analysis based on this data set (Table 5.4).

Offshore wave heights corresponding to return periods from 1 to 100 years applicable to the various sectors of the Mozambican coast are also indicated in Table 5.4. For the deep sea off the Maputo and Beira areas, for example, the calculated return periods for various extreme wave heights can be depicted graphically as indicated in Figure 5.9.

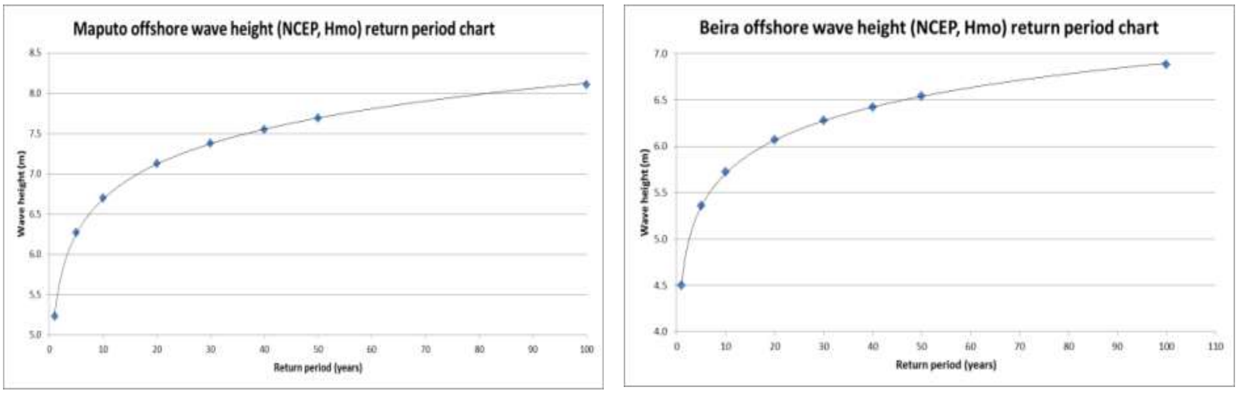


Figure 5.9: Extremes wave heights (NCEP wave data) versus return periods offshore of Maputo (left) and Beira (right)

The norm for the engineering design of marine/coastal structures is the 1-in-100 year wave condition. It may be argued that residential dwellings or less important structures could be designed for a reduced design period of say 50 years. However, based on the calculated wave return periods (Figure 5.9) the 1-in-50 year condition is only 5% less than the 1-in-100 year condition for both Maputo and Beira. Therefore, the results for the 1-in-100 year wave height (the design norm) are applied further.

Cyclone-generate Extreme Waves

Information on the extreme wind intensity of tropical cyclones was obtained to estimate extreme cyclone generated waves, as a better alternative to focussing on the analysis of the NCEP wave data. By deriving or estimating extreme wind intensities, the corresponding wave condition can be calculated. This procedure was also followed since no long-term measurements and no high resolution hindcast data were available along the Mozambican coast for this study.

Rossouw (1999) used data obtained from JTWC and applied Monte Carlo techniques to derive the number and average maximum intensity of tropical cyclones to be expected in a 100 years. Estimates of the extreme wind conditions were derived for the entire Mozambican coast, as a function of latitude. These estimates are presented in Table 5.5.

Table 5.5: Estimated average maximum wind speed intensity in 100 years as a function of latitude (based on Rossouw, 1999)

Latitude (Deg)	Onshore City/Town	Vm (knots)
26.0	Maputo	96
24.0	Maxixe	116
22.0	Vilanculos	132
19.8	Beira	120
17.3	Pebane	142
16.2	Angoche	134
14.2	Memba	132
12.0	Ilha Macaloe	138
10.3	Mtwara	106

Using the estimate maximum intensities, Rossouw (1999) applied the following procedure to determine the extreme wave height. Note that the estimation of the significant wave height (Hs) and associated peak wave period (Tp) is described in the SPM (USACE, 1984).

$$Hs = 5.03e^{\frac{R\Delta P}{4700}}\left[1+\frac{0.29\alpha V_f}{\sqrt{U_R}}\right] \quad \{\text{m}\} \tag{1}$$

$$Tp = 8.6e^{\frac{R\Delta P}{9400}}\left[1+\frac{0.145\alpha V_f}{\sqrt{U_R}}\right] \quad \{\text{s}\} \tag{2}$$

Where:

$$\text{R (radius to maximum winds)} = 11.671 + 0.014487 * Latitude * 10^{-5} * Vm^{3} \quad \{\text{km}\} \tag{3}$$

with Vm, the average 1-minute wind speed, in m/s

$$\Delta\text{P (pressure gradient)} = e^{\frac{1}{0.6797}\left[\ln\left(\frac{Vm}{4.4548}\right)\right]} \quad \{\text{mb}\} \tag{4}$$

with Vm in knots

a = forward motion factor, estimated to be 1.0

V_f = forward celerity of the tropical cyclone {m/s}

$$U_R = 0.865 * Vm + 0.5V_f \tag{5}$$

with *Vm* and V_f in m/s

For the purposes of this study, the forward celerity (V_f) was taken as 7 m/s. This value was based on Rossouw (1999) and a review of the cyclone tracks obtained from the JTWC reports. The results of this procedure are presented in Table 5.6. The 100-year wave conditions, represent the offshore wave condition in the same areas as presented in Table 5.1. A summary of the wave conditions is schematically presented in Figure 5.10, giving the wave height and period along the Mozambican coast. For example, based on the wind speed expected to occur only once in a 100 years as result of the presence of a tropical cyclone, the estimated wave height offshore of Beira would be in the order of 8.7 m. The corresponding wave period is estimated to be 12 s.

Table 5.6: Estimated offshore and nearshore 100-year wave condition

Onshore City/Town	Latitude (deg)	100-year wave condition		Water depth = 14 m (from 200 m); Slope = 1:50					
				0° (orthogonal)			45° (orthogonal)		
		Hs	Tp	Hs	Dir	L	Hs	Dir	L
Maputo	26.0	**8.2**	**11**	7.8	0.0	122.0	7.0	27.0	122.0
Maxixe	24.0	**8.6**	**12**	8.4	0.0	135.0	7.4	25.0	135.0
Vilanculos	22.0	**9.0**	**12**	8.8	0.0	135.0	7.8	25.0	135.0
Beira	19.8	**8.7**	**12**	8.5	0.0	135.0	7.5	25.0	135.0
Pebane	17.3	**9.3**	**12**	9.1	0.0	135.0	8.0	25.0	135.0
Angoche	16.2	**9.1**	**12**	8.9	0.0	135.0	7.9	25.0	135.0
Memba	14.2	**9.0**	**12**	8.4	0.0	135.0	7.8	25.0	135.0
Ilha Macaloe	12.0	**9.2**	**12**	9.0	0.0	135.0	8.0	25.0	135.0
Mtwara	10.3	**8.4**	**11**	8.0	0.0	122.0	7.2	27.0	122.0

Furthermore, since the derived waves represent deep water conditions, a linear wave transformation was applied to estimate the wave height in a water depth of 15 m. Two wave heights were determined. The wave height was determined assuming the waves approach the coast orthogonally as well as from a 45° angle. These results are also presented in Table 5.6. Thus, the offshore 100-year wave condition ranges in height from 8.2 m to 9.3 m with a mean of 8.8 m. It is interesting to note that the largest deviation from the mean is only about 7%. These estimated extreme wave conditions were applied in the rest of the study, except where superseded by wave modelling, as discussed in Section 5.4.3.

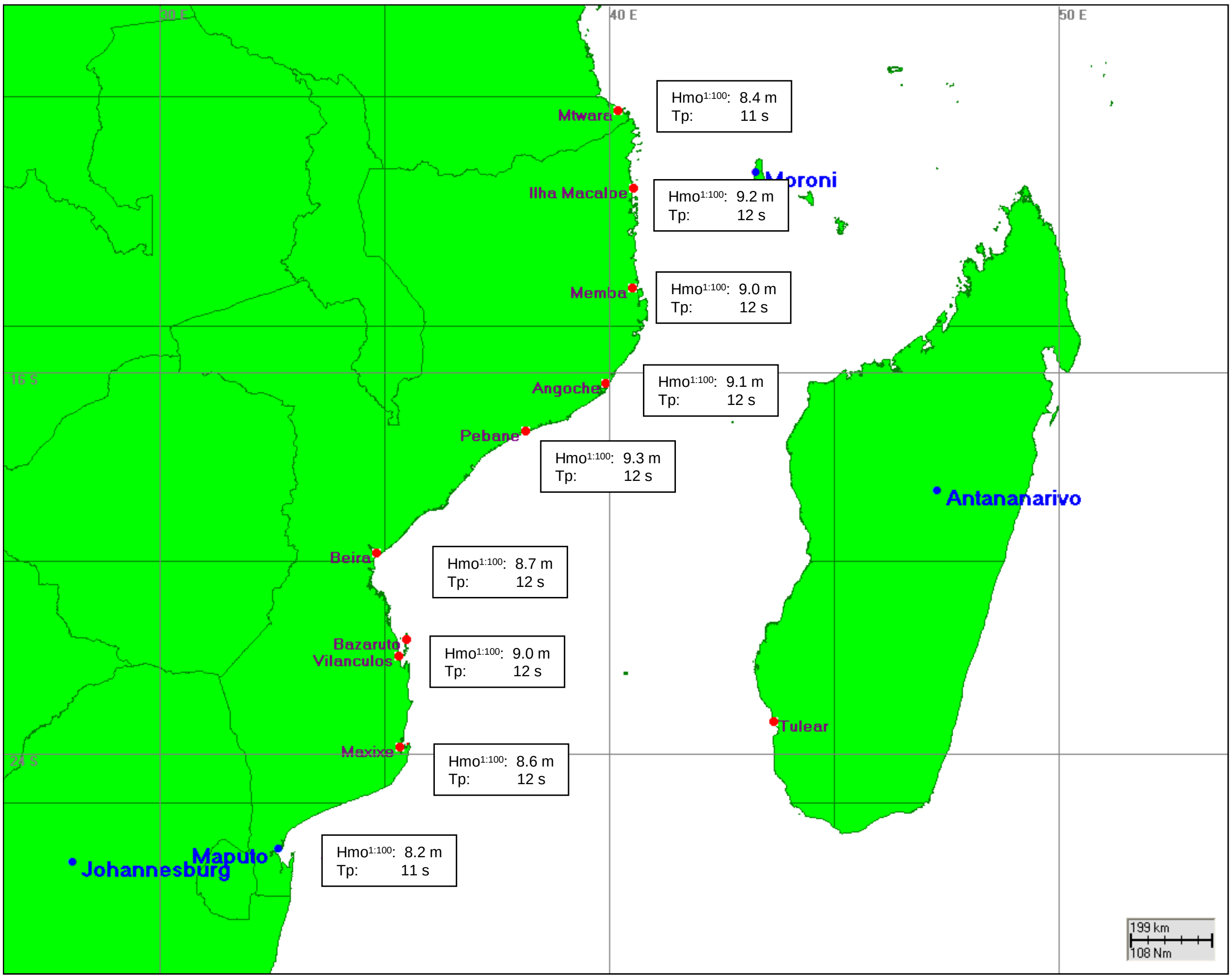


Figure 5.10: 100-year wave condition along Mozambican coast

5.4.2 Trends in wave climate and future conditions

Preliminary findings indicate that there may be long-term trends in regional marine weather (metocean) climates, while sea level rise alone will greatly increase the risks and impacts associated with extreme sea-storm events (Theron 2007). The regional variation in the global wave climate was demonstrated by Mori *et al*. (2010), who predicted that the mean wave height might generally increase in the regions of the mid-latitudes (both hemispheres) and the Antarctic ocean, while decreasing at the equator. Their study was based on simulating future trends. Further evidence of a general wave height increase in the northern Atlantic, along the North American East coast was provided by Wang *et al*. (2004). Komar and Allan (2008) also found an increase in the wave height generated by hurricanes along the East coast of the United States using wave data from the National Data Buoy Center (NDBC) wave buoy data. Investigations done by Ruggerio *et al*. (2010) with buoy data also indicate increasing storm intensities along both the West and East coast of Northern America. Such changes in the regional metocean climates are expected to have significant impacts on local coastal areas. It is therefore important to also investigate possible future climatic changes off the southern African coastline as well as the expected associated impacts.

As can be anticipated, a more severe wave climate (or indirectly a more severe oceanic wind climate) will have greater impact on run-up and flooding levels, and will thus necessitate the prediction of future trends in the wave climate. Although the available southern African wave record is shorter than ideally required to determine long-term trends, a preliminary analysis was conducted. It was found that the annual mean significant wave height (H_{m0}) and corresponding standard deviation for the wave data set collected off Richards Bay (some 230 km south of Mozambique) and the annual mean wave height (H_{m0}) for the long-term data set, collected offshore of Cape Town (SA), indicate no real progressive increase. This may appear to contradict the findings of the IPCC as presented in PIANC (2008). However, the SA results may reflect a regional aspect of the impact of climate change. Since no long-term data are available for the Mozambican waters and given the different weather climate, or rather the different wave generating mechanisms, the patterns or trends in wave climate found along the SA east coast can not be transferred directly to the Mozambican coast.

Although the averages of the SA data appear to remain constant, the individual storm data shows some change. For example, considering the peaks of individual storms during the more extreme South African winter period (June to August), an increase of about 0.5 m over 14 years can seemingly be observed (Figure 5.11). The trend could potentially be indicative of a significant increase in the 'storminess' over the next few decades, but such a large trend is considered unlikely at this stage. It is also worth noting that the opposite occurs during summer: there seems to be a general decreasing trend over the last 14 years with regard to individual storms.

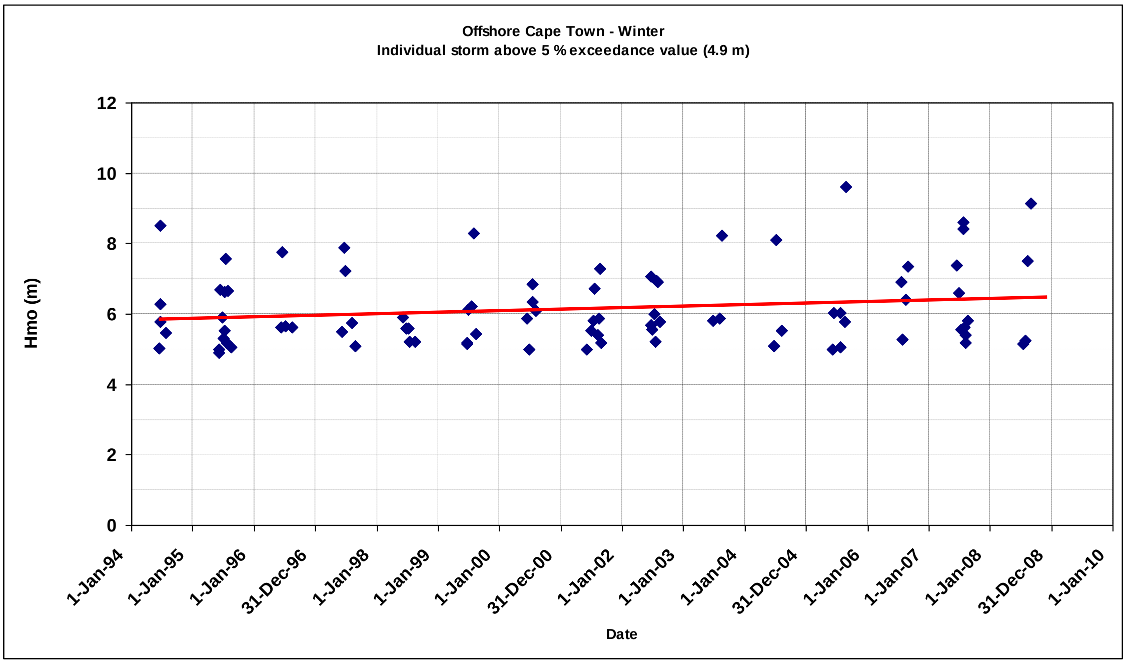


Figure 5.11: Peaks of individual storms over 14 year-period – offshore Cape Town (based on recordings by CSIR on behalf of Transnet National Ports Authority, South Africa).

If the recorded increase is indeed indicative of a trend, storminess (in terms of intensity) may be on the increase. (A number of aspects need further study though, including reviewing the trends in energy flux and not just the wave height.) *An extrapolation into the future of the previous 0.5 m wave height increase over 14 years, is however considered to be unrealistically high.* To some extent it could be said that an increasing trend (as possibly indicated by the SA wave data) is supported by the model predictions of Mori *et al*. (2010), which appear to show an increase for the southern Indian Ocean of roughly 6% (at exceedance probability < 10^-5) (Figure 5.12).

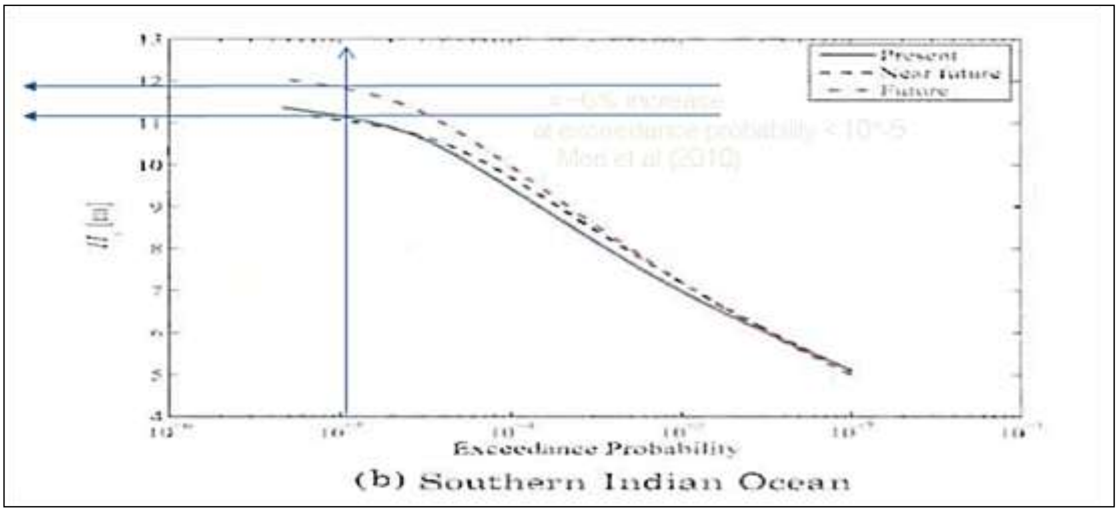


Figure 5.12: Future wave climate changes from model predictions by Mori et al. (2010)

In lieu of a sufficiently long record of wave data and consequently on wave climate trends, the main driver of the waves, namely the ocean winds, can be examined to derive possible trends. Wave climate and conditions are determined by ocean winds (through parameters such as, e.g. velocity, duration, fetch, occurrence, decay, depth), as indicated in Figure 5.13. Modelling of the southern African metocean climate i.t.o. present versus future wind conditions and barometrics, is currently being conducted (by CSIR). Analyses of the outputs (i.t.o. factors such as ocean wind statistics and trends) are still required to inform future projections of oceanic weather and resultant wave conditions.

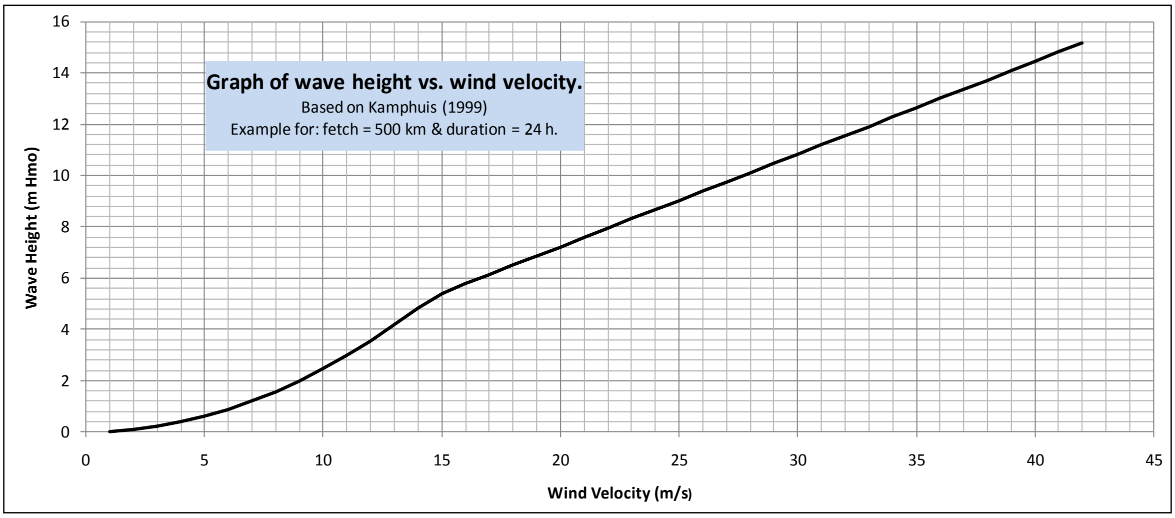


Figure 5.13: Example of wave height determined from wind velocity through a wind/wave model

Despite the possibility of stronger oceanic winds (e.g. IPCC 2007, Joubert and Hewitson 1997), predicted values for potential changes in wind regimes off the southern African coastal region are currently still largely lacking. In view of this shortcoming, and to enable an assessment of the potential impacts of stronger winds, a relatively modest increase of 10% could be assumed. (This is also in line with assumptions made for the German coast (Brinkmann, 2010)). Wave height (in the fully developed state) is proportional to the square of the wind stress factor (UA). UA can be related to the wind speed (U) according to the following expression (US Army, Corps of Engineers 1984): $UA = 0.71\ U^{1.23}$. Thus, a modest 10% increase in wind speed, means a 12% increase in wind stress and a 26% increase in wave height (Theron, 2007).

Some Global climate models seem to predict an increase in frequency and intensification of cyclones (e.g. Carter at all, 1994), but there does not seem to be general scientific consensus on such future cyclone changes/trends. While about two to three cyclones per year currently enter the Mozambique Channel, a possible southward shift of the cyclone belt due to climate change (see Phase I and Theme 8 report), would mean an increase in the occurrence of cyclones impacting southern Mozambique's coastal regions. However, although this is a projected future outcome of climate change effects, the confidence placed in this projection is low at this stage. This potential effect of CC is also not expected to occur within the next few decades, but is possible in the long-term, perhaps only beyond 2100.

Based on the foregoing information and discussion, it is concluded that the main scenario for future wave climate off Mozambique should be a 6% to 10% increase in wave height by 2100, with the best estimate at 6% increase as derived from Mori *et al.* 2010. This might seem insignificant, but the effect on for example sediment transport can be significant, as discussed in Section 5.5.4. However, in terms of only wave height it is indeed somewhat insignificant, in that the uncertainly of the predicted cyclone wave heights is probably more than 6%. In addition, the water depth was increased in the cyclone wave modelling according to the predicted SLR scenarios, thus accounting for the possibly largest CC effect on the waves. Therefore, the possible additional effect of the small 6% increase was not explicitly incorporated in the cyclone modelling. (If better wave data becomes available for the Mozambique region, it may be warranted to re-evaluate this issue.)

5.4.3 Modelling cyclone wind-generated waves

Approach and cyclone wave modelling background

Numerical wave modelling is powerful tool to understand and determine the wave conditions in an area where no data are available. The CSIR has been using the SWAN model for many years now to simulate the evolution of a wave field from the offshore area to the coast (the shore). This includes the development of the CSIR Virtual Buoy System, which is operational in Table Bay and Saldanha Bay (Rossouw *et al*., 2005). SWAN is the acronym for Simulating WAves Nearshore (Booij *et al*. 1999). SWAN also has the ability to take the local wind into account by generating the waves over the model domain. Furthermore, SWAN allows spatial and temporal variability of the wind.

In this part of the study the focus was on the varying wind field and propagation due to cyclones and the resulting wave generation and propagation towards the shoreline. Therefore, using the estimated 100 year extreme winds, the corresponding wave conditions could be derived for specific locations along the coast. The application of SWAN in this study is described below.

Background on SWAN numerical wave model

The SWAN model is based on the discrete spectral action balance equation and is fully spectral (in all directions and frequencies). More detail can be found in Deltares (2010). Being a spectral model, it implies that short-crested random wave fields can be simulated. These wave fields propagate simultaneously from different directions (e.g. a wind sea with super-imposed swell). Note that the SWAN model represents the processes of wave generation by wind, dissipation due to white-capping, bottom friction and depth-induced wave breaking and non-linear wave-wave interactions.

Verification of cyclone wave modelling

To evaluate and verify the cyclone wind-wave modelling ability, a test case was set up, where an actual tropical cyclone was modelled. The CSIR collected wave data with wave buoys off Beira in 1997 at the time that Tropical Cyclone (TC) Lizette passed over the area. This event gave a unique opportunity to simulate the cyclone-generated waves and to compare the results to measured data. The locations of the two wave buoys are shown in Figure 5.14.

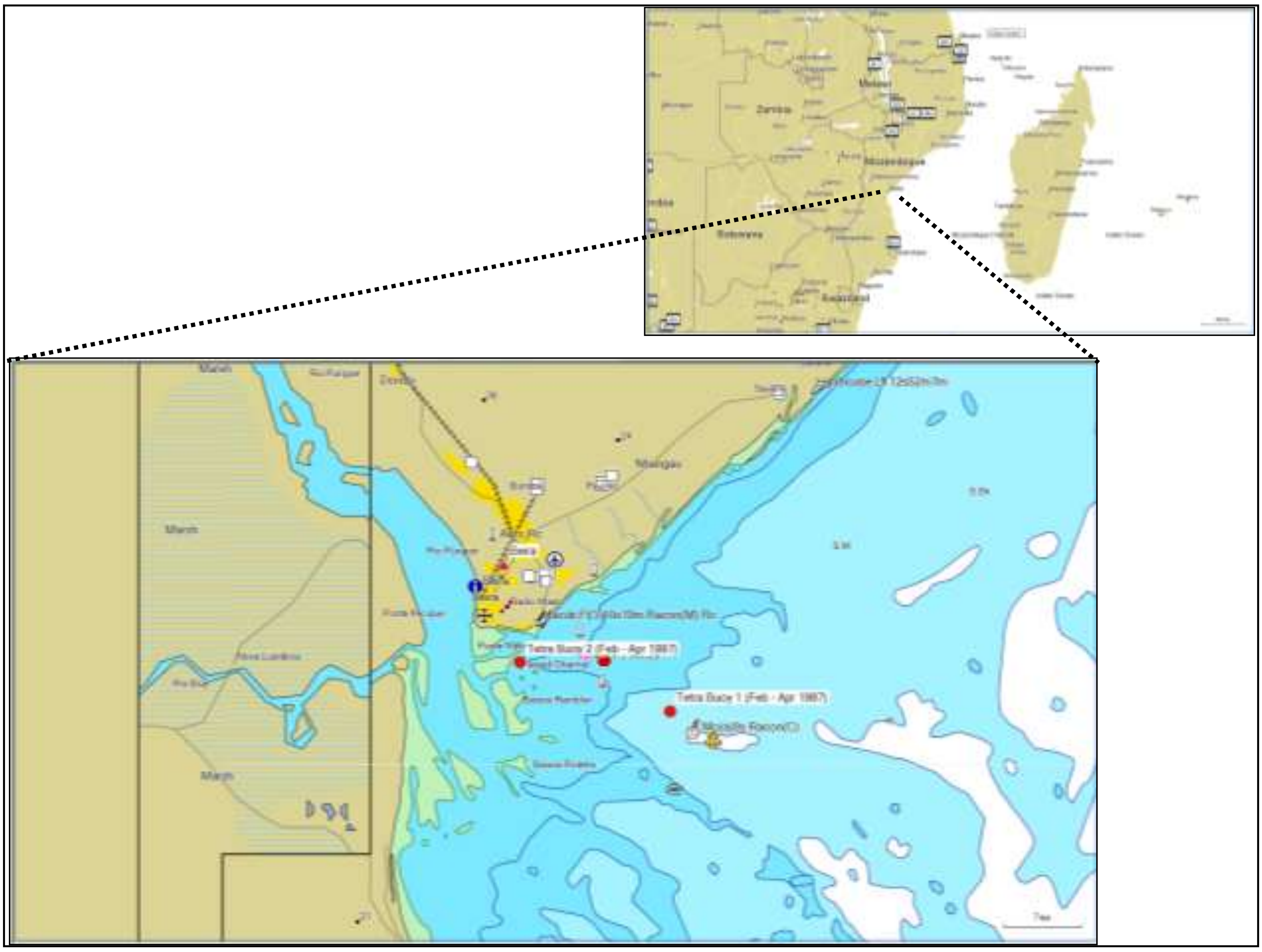


Figure 5.14: Location of wave buoys off Beira, Mozambique

Although sufficient wave information was available at the two buoys, little detail information on TC Lizette, was available. The most useful information was obtained from the 1997 Annual Tropical Cyclone report of the Joint Typhoon Warning Center (JTWC, 1997). This center uses observations and satellite imagery to estimate the magnitude and tracks of cyclones. The track of TC Lizette over Mozambique is shown in Figure 5.15. The estimated maximum wind speed intensity of the cyclone was 39 m/s, which represented in the 1 min average speed.

An image of the Scatterometer onboard the ERS-2 satellite of TC Lizette on the morning of 27 February 1997 in the Mozambican channel, is shown in Figure 5.16. The Scatterometer provides information on the wind speed and direction. The structure of the cyclone is shown; in particular one can note the sensitivity of each Scatterometer's antenna to the wind direction. The eye of the cyclone, where the wind speed falls dramatically is clearly illustrated by the wind vectors.

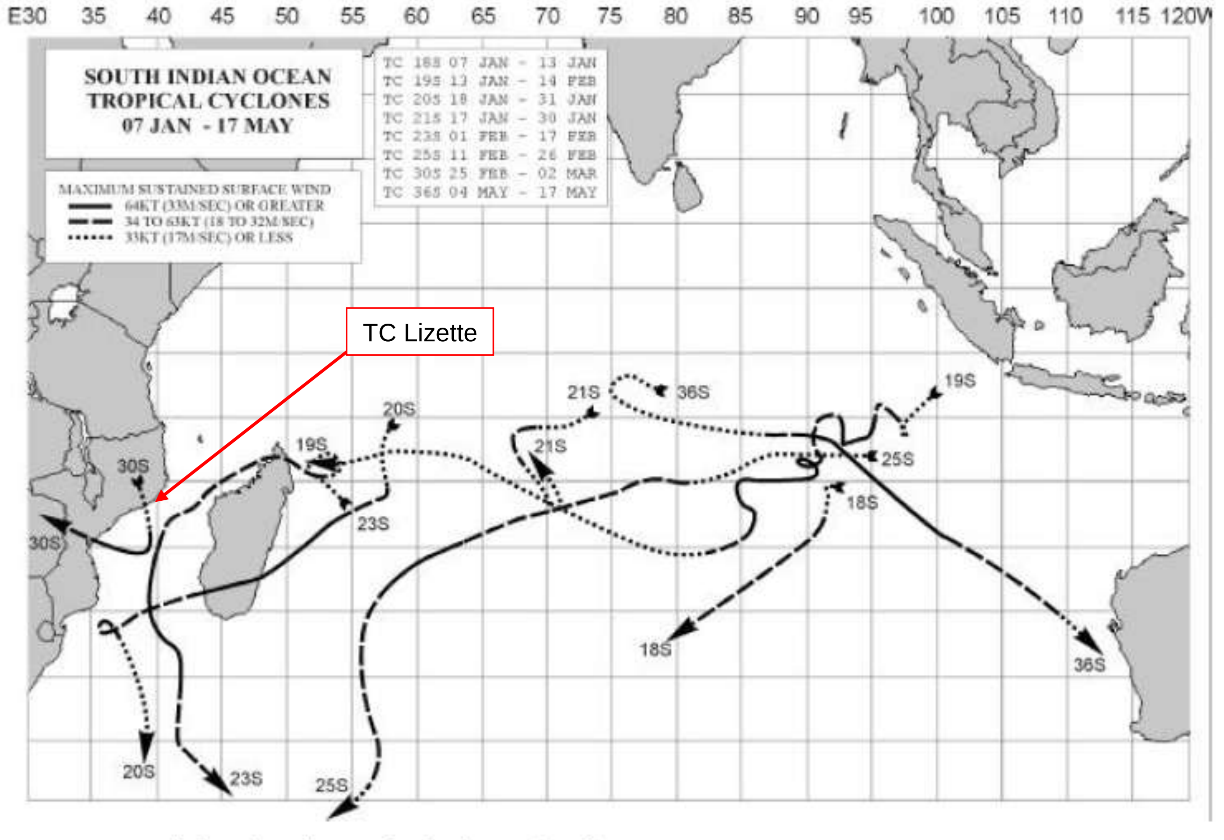


Figure 4-3 Tropical Cyclone best tracks for the South Indian Ocean

Figure 5.15: Track of TC Lizette over Mozambique (JTWC, 1997).

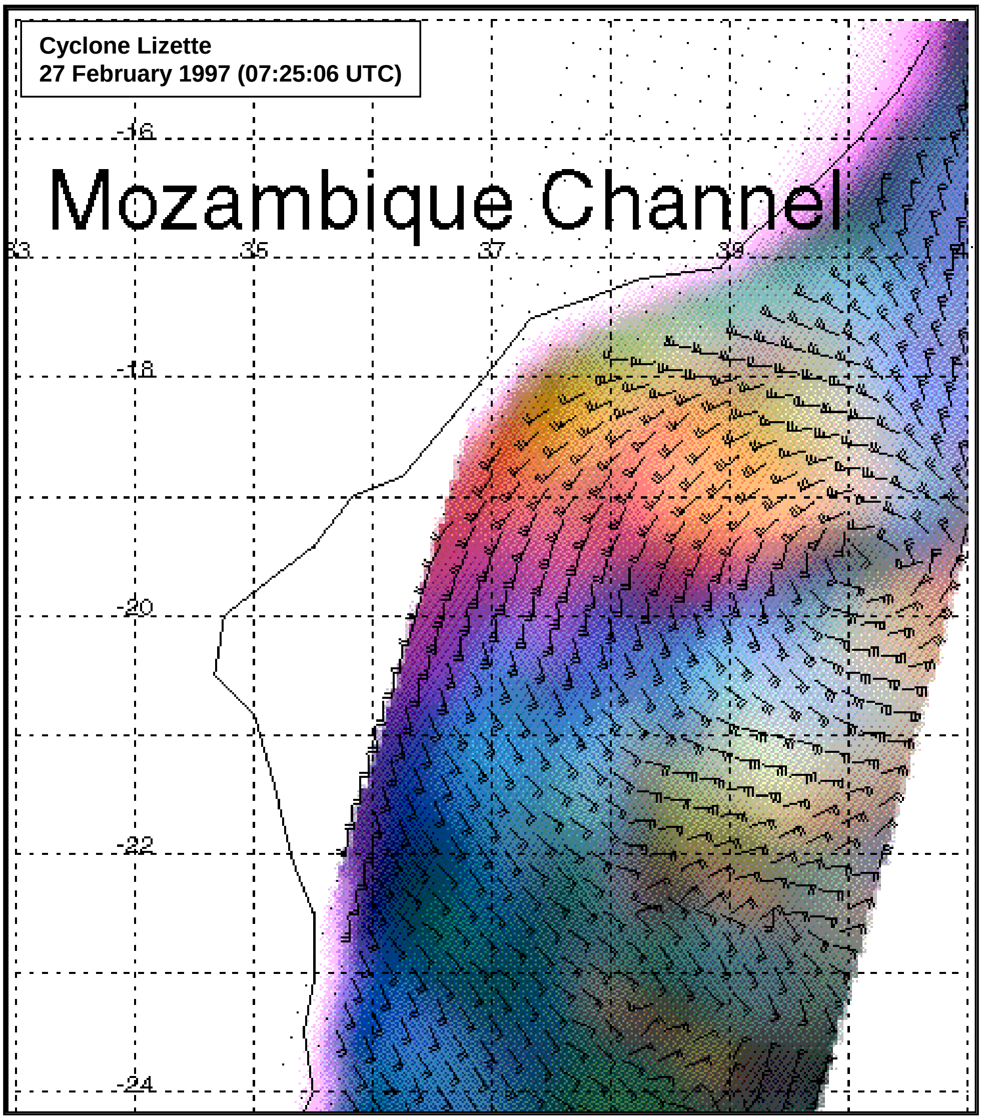


Figure 5.16: ERS-2 Scatterometer image of TC Lizette showing the cyclonic wind vectors
(Source: ESA)

In order to represent the cyclone (or wind field) in time and space in the SWAN model, a wind field was generated with a MatLab procedure over the entire model domain. A schematized wind distribution was used to describe TC Lizette, based on what little information about the structure of the cyclone could be obtained. The wind field was generated on a 30 minute time-step over a period of about 2 days. Examples of these wind fields, at certain time-steps, are presented in Table 5.7. These wind fields follow the trajectory of the cyclone over time. Note that a separate MatLab procedure was developed to generate the cyclone trajectory.

Table 5.7: The main input parameters for TC Lizette (March 1997)

Estimated mean pressure (MSLP):	968 MB
Max wind speed (1 min average):	39 m/s
Max wind speed (1 hr average – SWAN input):	31 m/s
Radius to maximum wind speed:	12 km
Forward celerity of cyclone (estimated from JTWC tracks):	5 m/s
Water level (based on CSIR water level measurements at Beira):	+ 5.5 m to CD

Using these wind fields as input, a SWAN model was set up for the Mozambican coast off Beira. In general, the model domain of a typical SWAN set-up would cover an area of about 50 km by 100 km. In this particular case, the model domain covered an area of about 700 km by 800 km, which included the Mozambican channel. The model domain is shown in Figure 5.17. This is a very large area and therefore, a computationally intensive exercise.

The SWAN model consisted of two model domains, namely the coarse domain as shown in Figure 5.17 and a high resolution domain. The high resolution domain covered a small area at Beira, taking the depth-varying bathymetry into account.

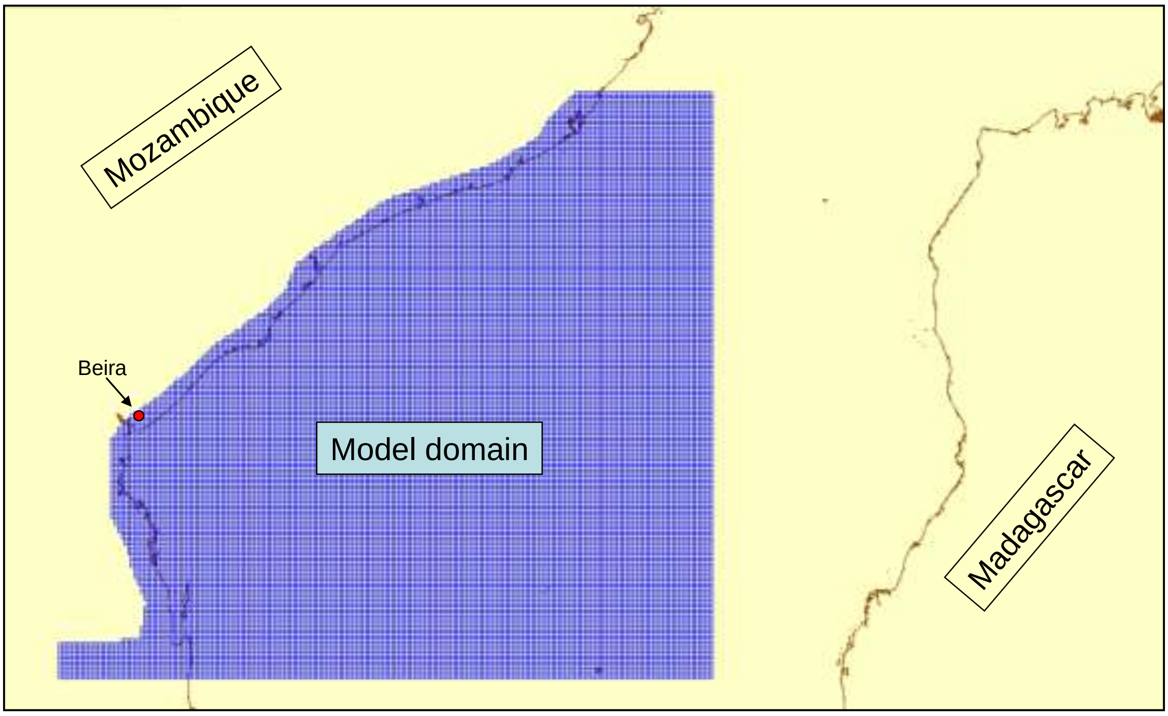
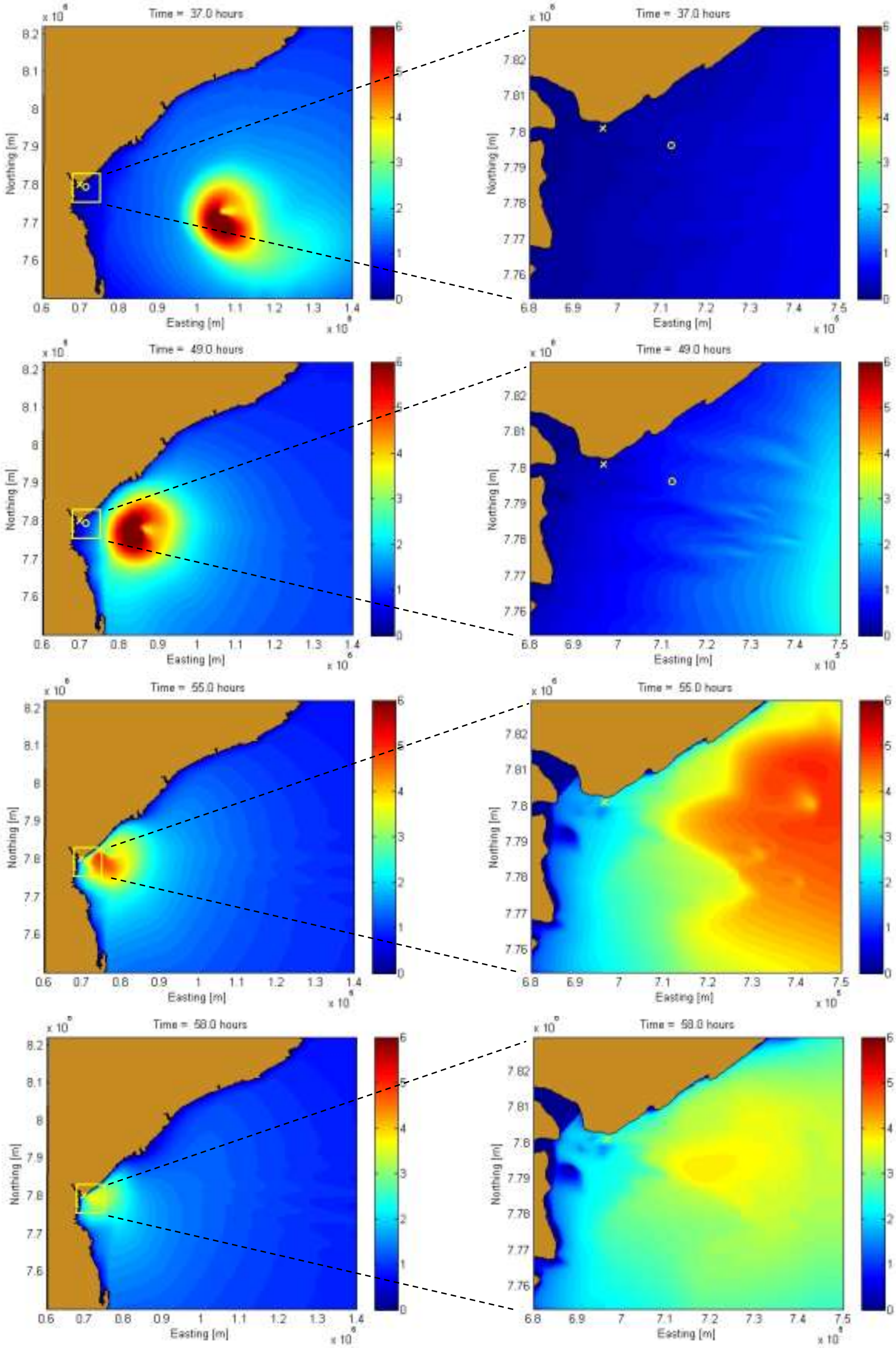
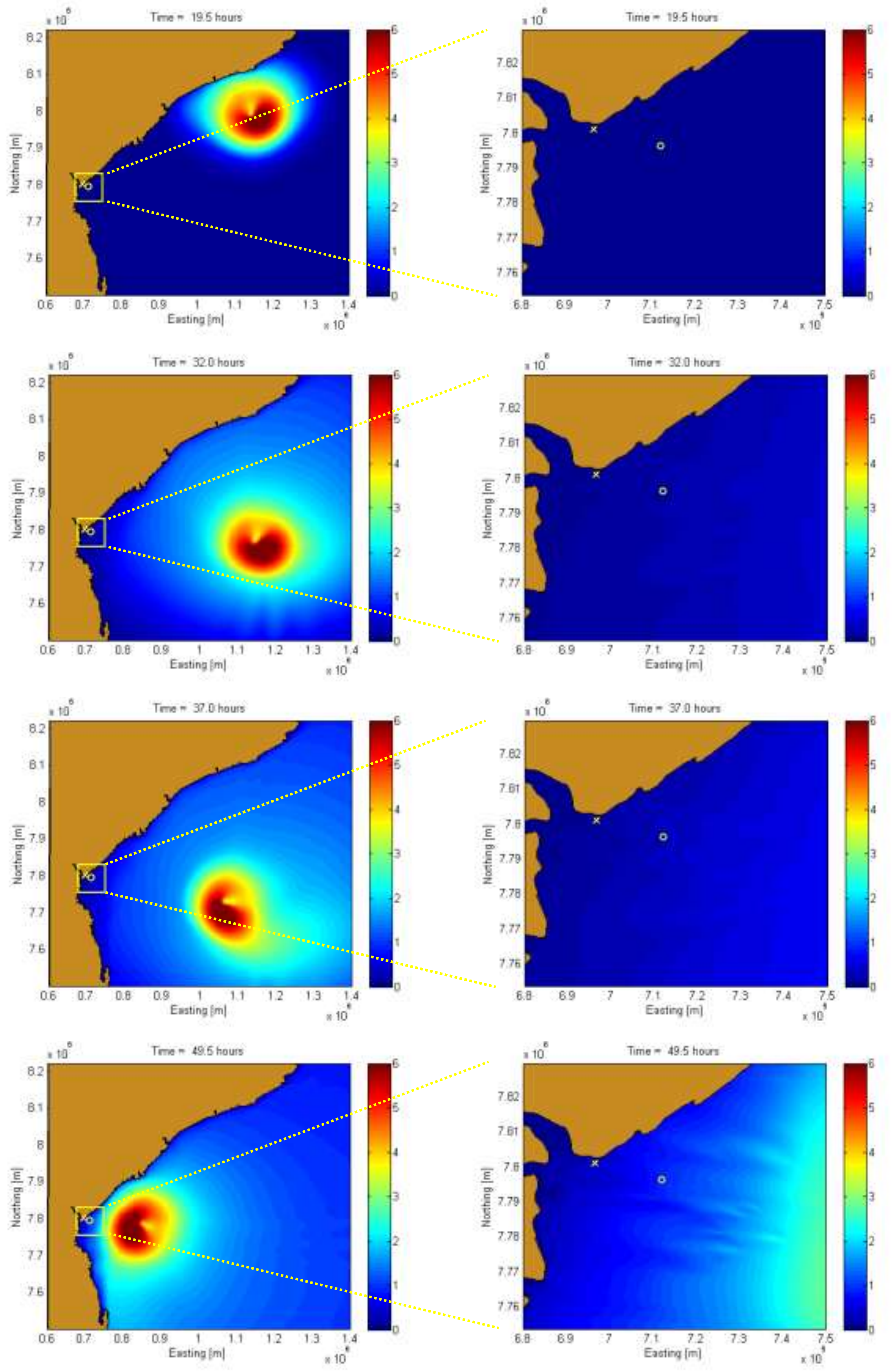


Figure 5.17: SWAN model domain

The wave simulation was done using these model domains and the wind field set-up. The wind-generated wave fields, which correspond to the wind field given in Table 5.7, are presented in Figure 5.18. The wave fields are presented for a larger area and for the area close to Beira, where the wave data were collected.

Figure 5.18: Example of cyclone wind-generated wave fields showing wave height in the Mozambique Channel and near Beira at particular time-steps. Note, the locations where wave data were collected are also shown.




Time = 19.5 hours
Time = 32.0 hours
Time = 37.0 hours
Time = 49.5 hours
x 10^6
Northing [m]
Easting [m]
x 10^6
x 10^5
8.2
8.1
8
7.9
7.8
7.7
7.6
0.6
0.7
0.8
0.9
1
1.1
1.2
1.3
1.4
7.82
7.81
7.8
7.79
7.78
7.77
7.76
6.8
6.9
7
7.1
7.2
7.3
7.4
7.5
0
1
2
3
4
5
6

A comparison of the simulated wave height with the measured data is shown in Figure 5.19. Taking the sparse information on the cyclone into account, and considering that no additional boundary conditions or local wind conditions were taken into account, the model simulations compare very well with the measured wave height data at both of the locations. (Note that the measured wave height, as recorded 24 hours prior to the cyclone storm event, was subtracted (hence the flat line on the y-axis at 0 m), since the background swell and historic wind-generated waves were not taken into account – only the cyclone-generated waves.)

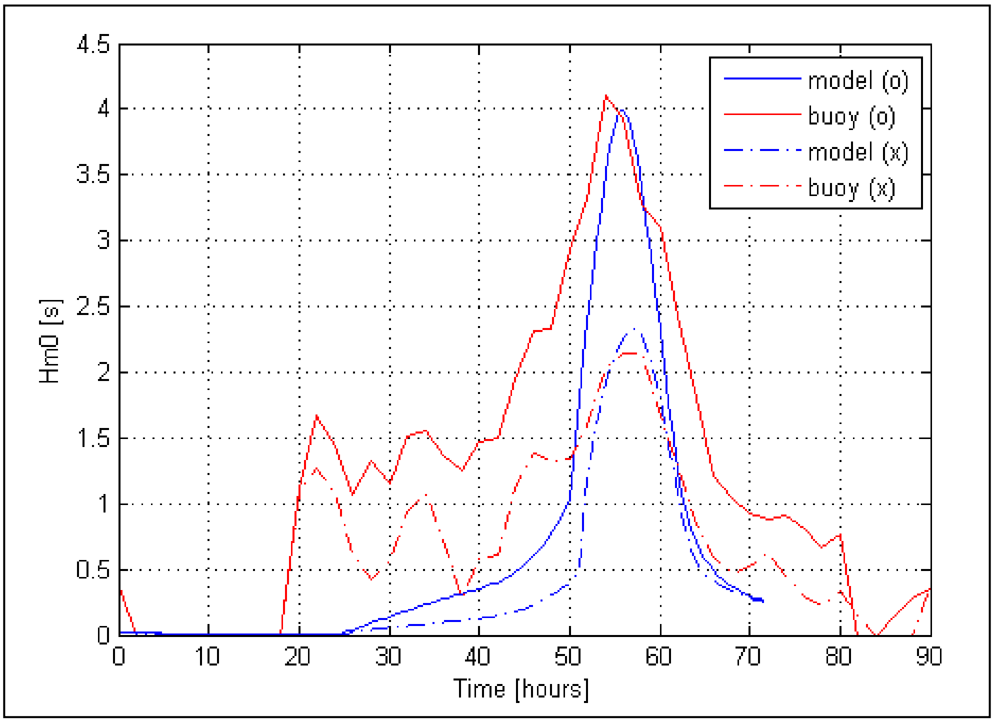


Figure 5.19: Time-series of measured and simulated wave height – for both wave buoy locations

The results of the simulation exercise indicated that SWAN provided a reasonably good description of the cyclone event in terms of the wave conditions. The modelling methodology developed can thus be applied with some confidence to simulate cyclone wind and wave conditions.

Extreme cyclone generated waves along the Mozambican coast

Analyses of the input offshore wave climate, extreme conditions and future projections off Mozambique, have been dealt with in the previous sections. However, to assess coastal wave run-up and wave related impacts, the inshore wave conditions have to be determined for design offshore wave conditions. Therefore, based on available bathymetric data and selected offshore input cyclone conditions, numerical wave modelling was conducted to determine the required inshore conditions.

Limited wave modelling was conducted for three locations along the Mozambican coast, namely Maputo, Beira and Pemba areas. Since a cyclone can approach from a wide directional range, a number of selected propagation-directions were investigated. The selected locations did, however, dictate which directions were simulated with SWAN. The three offshore cyclone propagation directions which could result in the most severe wave conditions along the Mozambique coast included south-east, east and north- east. In line with the norm for engineering design, the 1-in-100 year condition was selected.

A summary of the simulation details for the three locations, as applied in this study, is presented in Table 5.8. Note, the radius to maximum wind speed (R) was based on the procedure presented in Rossouw (1999). The total radius of the cyclone was taken as 150 km.

Table 5.8: Cyclone simulation details for Mozambican locations

Simulation parameter	Location		
	Maputo	Beira	Pemba
Wind speed – hourly average (m/s)	42	48	56
V_f - forward celerity (m/s)	7	7	7
Radius to max wind speed (km)	12	12	12
Approach directions simulated with SWAN	ENE & E	E & SE	NE & E

Examples of the wave fields, as generated by a cyclone with a 1-in-100 yr wind condition, are presented in Figures 5.20 to 5.22 for three locations. The wave fields are presented in terms of the wave height contours (i.e. the colour range) and wave vectors. These wave vectors show the mean wave direction while the wave height is represented by the length of the vector.

The wave field depicted in Figure 5.20 is the result of the cyclone approaching Maputo from an East-north-easterly direction. The largest waves prevail in the open waters (white colour) and decrease rapidly closer to the shore, as a result of the decreasing water depth.

A similar wave field is presented for the Beira area in Figure 5.21c. The waves are larger in the open waters and smaller near the shore. Figure 5.21 also presents the wave field of the entire cyclone as it is travelling towards the coast from a south-easterly direction.

The wave field generated by a cyclone approaching Pemba from an easterly direction is illustrated in Figure 5.22. Figure 5.22a (left side) shows the waves when the cyclone is offshore of Pemba. Note that the centre of the cyclone is northward of Pemba, to ensure the maximum impact of the approaching waves. Figure 5.22b (right side) shows the wave field when the cyclone is already over land.

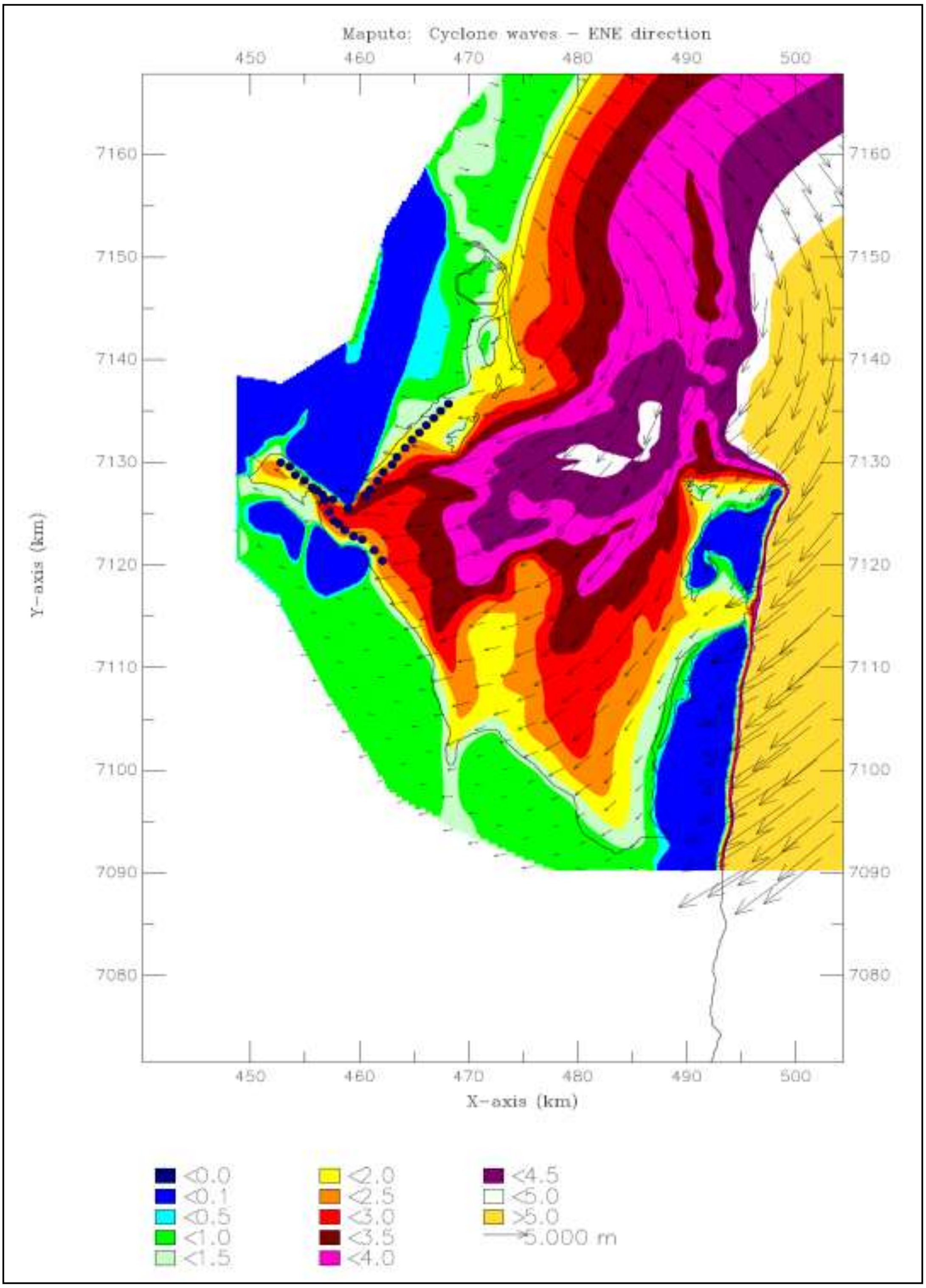


Figure 5.20: Example of wave modelling to derive inshore conditions at Maputo (east-north-easterly cyclone direction)

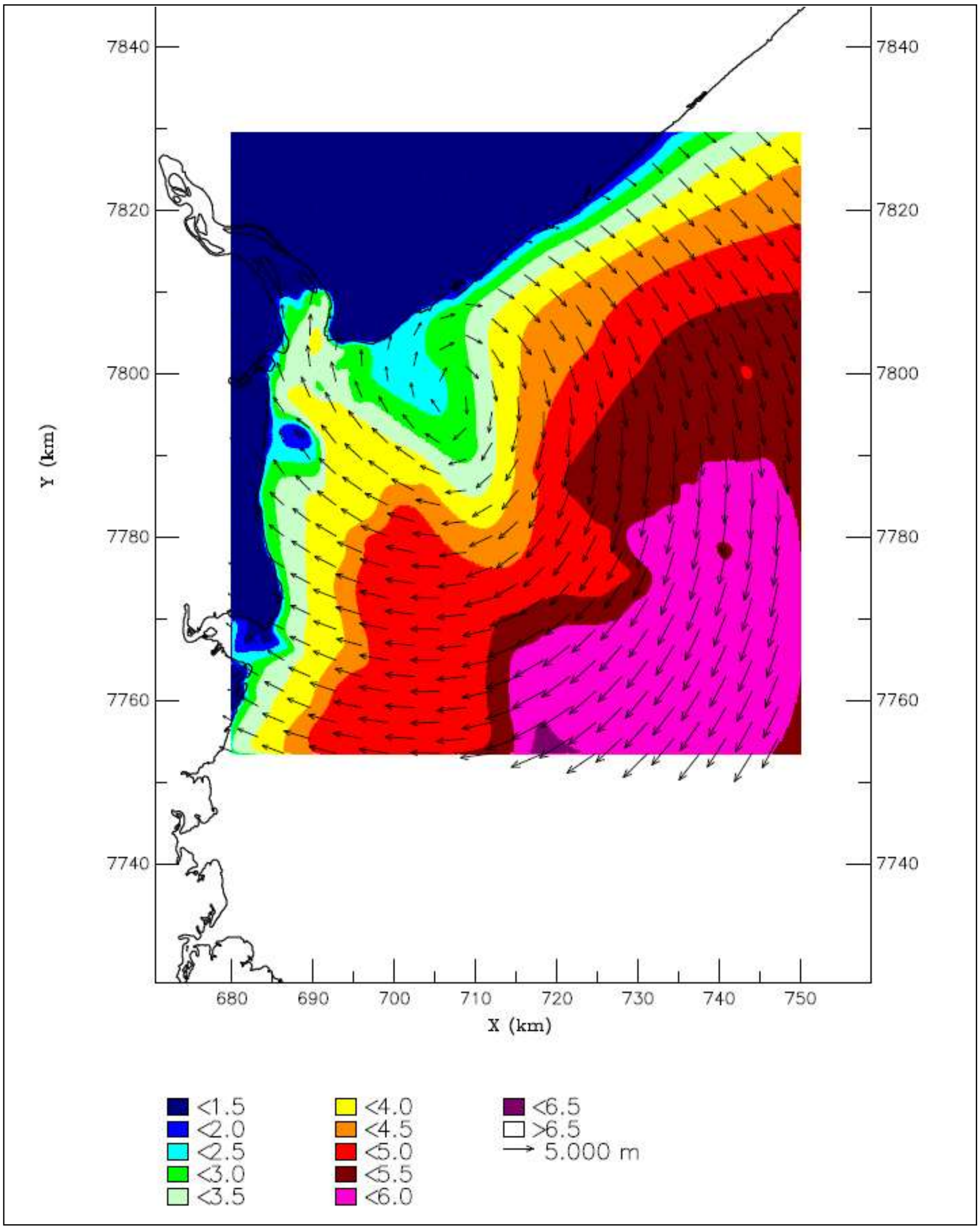


Figure 5.21a, b & c: Example of wave modelling to derive inshore conditions at Beira (south-easterly cyclone direction)

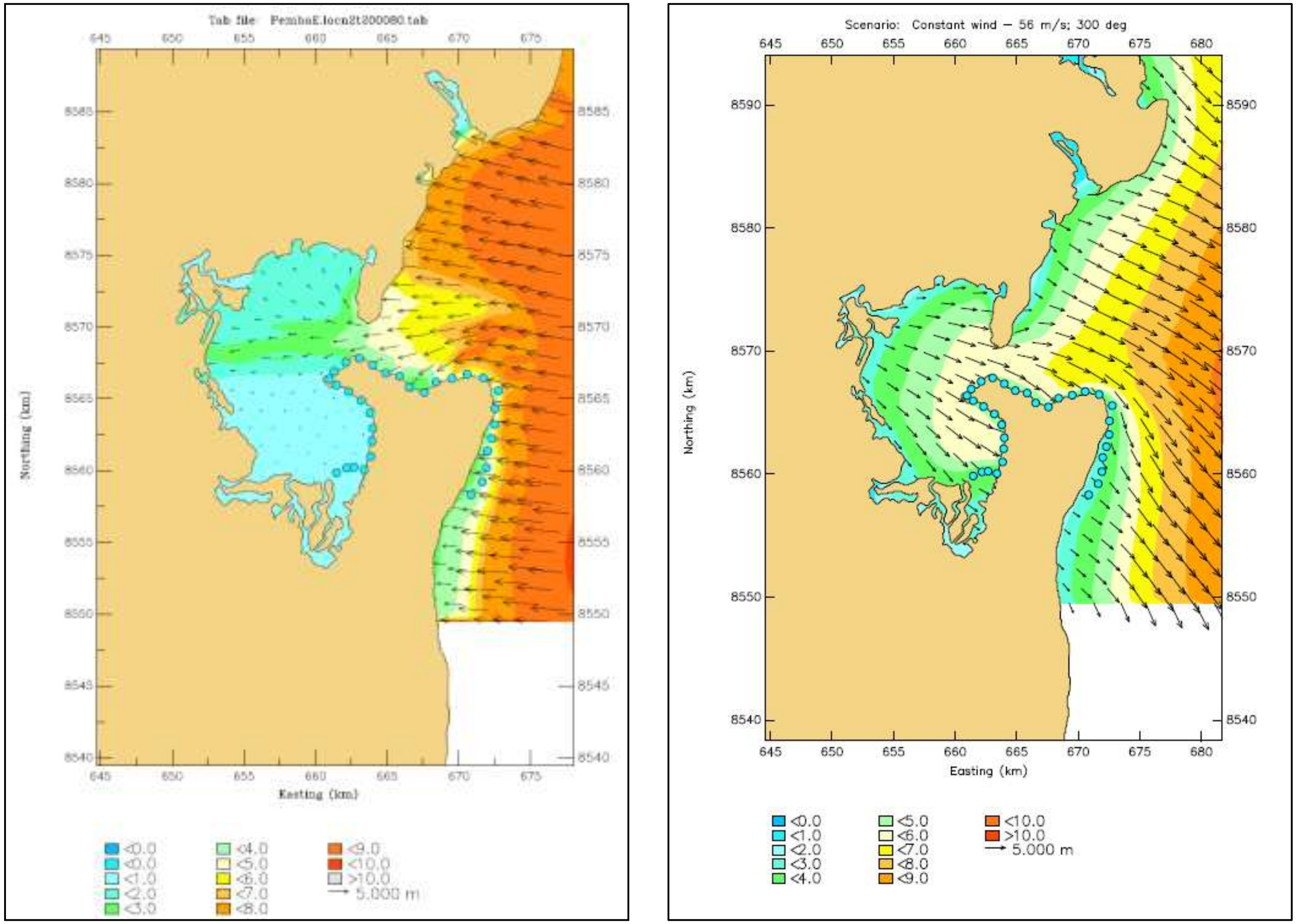


Figure 5.22a and b: Example wave cyclone modelling output for Pemba; (a) easterly offshore cyclone direction; (b) cyclone on land / over bay

It is perhaps worth noting that the derivation of the nearshore waves using a numerical model, provides a more realistic estimation of the extreme waves than merely deriving the nearshore wave from the estimated offshore extreme wave using a simple refraction/shoaling equation. The mild bathymetric slopes/features have a significant impact on wave dissipation (e.g. through frication and shoaling) which can be better estimated with a numerical model.

Following the SWAN simulations, the relevant wave parameters were extracted at a number of positions for each of the three areas. These parameters were incorporated in the derivation of the coastal inundation and erosion levels for particular areas. The derivation approach/methodologies and results are described in the following section.

5.5 COASTAL FLOODING/INUNDATION AND EROSION

5.5.1 Basic concepts and approach

As found in the literature review, probably the most significant driver of deleterious impacts in the Mozambican coast is sea storms (e.g. due to cyclones) combined with high water levels (Section 5.2). Thus, the remainder of this chapter is focussed on the quantification of these specific aspects/drivers of coastal hazard. Process based models are now applied to these specific drivers which have greatest effect on the coastal impacts.

The shoreline response and flooding impact is influenced by coastal parameters/processes such as: topography, geology, inshore wave action, sea level rise, bathymetry and foredune volume. To be of more use in hazard quantification and ultimately in finding ways of reducing risks, it is necessary to be able to predict or forecast the coastal response and severity of impacts. This is addressed in the following sections.

5.5.2 Prediction of high inshore sea water levels

As mentioned, significant drivers of high inshore sea water levels are tides, wind set-up, hydrostatics set-up, wave set-up and, in future, sea-level rise (SLR, due to climate change). These drivers all affect the still-water level at the shoreline. The drivers/components of extreme inshore sea water levels most significant to the southern African context are the tides, potential SLR, and wave run-up. Refer to Figure 5.3 for a schematic definition of the various components referred to below.

<u>Tides</u>

Spring tides reach up to about 3.7 m above mean sea level (MSL) in Mozambique. The tidal levels at locations along the Mozambican coast are given in Table below.

Table 5.9: Tidal levels based on UK Hydrographic Office (2007).

Location (south to north)	Mean high water spring level (m to MSL)
Richards Bay	1.1
Maputo	1.5
Inhambane	1.4
Bazaruto	1.9
Beira	2.9
Chinde	1.8
Quelimane	2.1
Maquivale	2.2
Pebane	1.9
Moma	1.4
Port Angoche	1.9
Port Mozambique	1.8
Nacala	3.3
Pemba	3.3
Mocimboa da praia	3.7
Palma	3.2

Wind and wave set-up

Wind set-up is usually a smaller component of combined extreme inshore sea water levels, and along open coasts it can be insignificant (the amount is dependent on the shape of the coast). It is also difficult to separate out the wind set-up from the usually more dominant wave set-up and especially the wave run-up. Various authors do not clearly distinguish between the wind set-up and other wave related set-ups and some assume that the combined determination/calculation of wave set-up and wave run-up includes the often smaller component of wind set-up. If specific additional allowance is made for wind set-up, the combined total set-up tends to be somewhat over estimated. For these reasons the wind set-up is included in the calculation of wave run-up as discussed in Section 5.5.3.

Various guidelines are provided in the literature to estimate the amount of wave set-up at the coast. According to FEMA (2000) the set-up is 10-20% of the breaker wave height. Karsten (2008) puts the set-up at 20% of the offshore wave height (Hmo). WMO (1988) states that: "As a general rule of thumb, wave set-up at the coast is about fifteen to twenty per cent of the incident root-mean square wave height." The wave set-up factor (Ws), which is a function of the wave height, period and direction, can also be estimated using an approach presented by Goda (2000) for the following wave period range:

Ws = 0.13 for $Tp \leq 11$ s
= 0.15 for $11 \text{ s} < Tp \leq 12$ s
= 0.16 for $Tp > 12$ s
Where Tp = Wave period

Thus, based on these published guidelines and the distribution of wave periods versus wave heights off Mozambique (Section 5.4), the wave set-up factor is taken as 0.16.

To estimate the increase in the water level as a result of wave set-up, the following relationship is proposed:

wave set-up = $H'_0 * Ws$
where H'_0 = "equivalent" unrefracted off-shore significant wave height
Ws = Wave set-up factor (according to Goda)

For the purposes of this estimation, the "equivalent" unrefracted off-shore significant wave height (H'_0) is related to the observed off-shore wave height through the following relationship:

$H'_0 = Kr * Hs^{offshore}$
where Kr = refraction coefficient
$Hs^{offshore}$ = the off-shore significant wave height
(from e.g. NCEP or cyclone modelling)

The refraction coefficient is mainly a function of wave direction, wave period and the orientation of the coastline. Simplified refraction coefficients (Kr) for regions around the southern African coast almost all fall within the range of 0.4 to 0.98 (Rossouw pers com). The design wave conditions off Mozambique have been determined to range from 8.2 m to 9.3 m (Section 5.4.3). Thus, the "equivalent" unrefracted off-shore significant wave height (H'_0) ranges from approximately 3.3 m to 9.1 m. By application of Goda's wave set-up factor, the wave set-up is therefore estimated to range from approximately 0.5 m to 1.5 m, or about 1 m on average. In terms of regional differences in the offshore wave climate, as indicated in Section 5.4 and Table 5.6, the largest wave height deviation from the mean (100-year wave condition) is only about 7%. This would result in only a 7 cm deviation from the average 1 m set-up, which is insignificant, and therefore means that regional differences in the wave climate can rightfully be neglected (w.r. t. set-up). The larger differences in wave set-up indicated above (with set-ups ranging from 0.5 m to 1.5 m), are due to local wave exposure/sheltering effects (i.e. the refraction coefficients mentioned above), but even these differences are 0.5 m or less from the 1 m average set-up. Differences in the tidal ranges, SLR scenarios and wave run-up (Section 5.5.3) are larger and thus more significant. More accurate location specific wave set-ups can only be determined by means of numerical wave modelling requiring detail bathymetry data at each site, which in virtually all instances are not available. In view of all of these factors, it is deemed acceptable to use the average wave set-up of 1 m for all the study sites.

Hydrostatic set-up

Raised inshore sea water levels result from the effects of low local atmospheric pressure over the ocean. The pressure set-up can be estimated by using the inverse barometer approximation, which translates to an increase of about 1cm for every 1hPa decrease in atmospheric pressure (Van Ballegooyen, 1996). Annual minimum pressures off the Mozambican coast (due to cyclones) are in the order of 100 hPa below the average sea level pressure (estimated from the Joint Typhoon Warning Center data; JTWC, 1997). Thus, the annual maximum hydrostatic set-up along the Mozambican coast is usually about 1 m. Cyclone occurrence statistics in the Mozambique offshore region, at present show an occurrence of about 1/3 less in southern Mozambique relative to central Mozambique (INGC Phase 1, 2009). In Section 5.4.2 the possibility is mentioned of a southward shift of the cyclone belt due to climate change (see Phase I and Theme 8 report). This would mean a relative increase in the occurrence of cyclones impacting southern Mozambique's coastal regions. (Although this is a projected future outcome of climate change effects, the confidence placed in this projection is low at this stage.) In any case, very strong cyclones (with very low central pressures) have been recorded along the southern Mozambique region. For these reasons, it is deemed acceptable to use one value for hydrostatic set-up along the whole Mozambican coast, with the annual maximum usually being usually about 1 m.

Based on these calculations, the combined wave and "barometric" set-up is estimated to be about 2 m (respectively 1 m each).

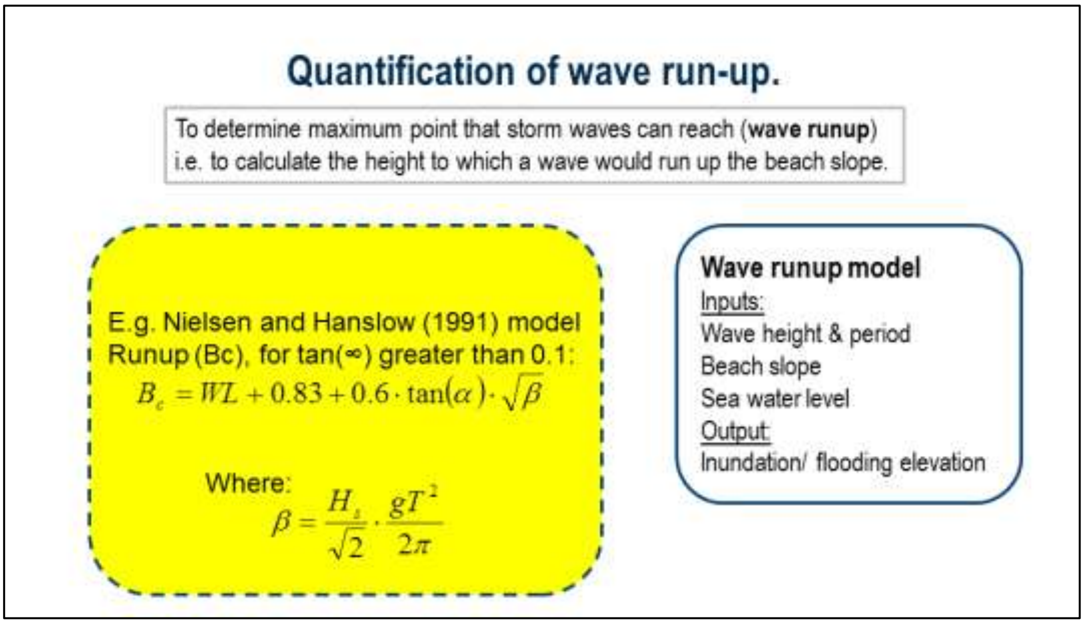
Sea-level rise (SLR)

In Section 5.3 it is concluded that the *best estimate (or "central" estimate)* of SLR by 2100 is around 1m, with a plausible *worst case scenario* of 2m, and a *best case scenario* (low estimate) of 0.5 m. (The corresponding best estimate ("mid scenario") projection for 2050 is 0.3 m to 0.5 m.)

5.5.3 Prediction of wave run-up

One of the impacts of sea level rise is that waves will reach further inland than at present which implies that present coastal development setback lines (of which few exist) have to be adapted. A coastal development setback line should be a line landward of which fixed structures (e.g. houses, roads, etc.) may be built with reasonable safety against the physical impacts of the coastal processes (e.g. sea storms, wave erosion and run-up). Factors which co-determine the location of setback lines are storm wave run-up elevations and how far the shoreline will retreat due to erosion, which are in turn affected by the amount of sea level rise that is expected and the projected increases in storminess. Therefore, realistic scenarios of sea level rise and potential increases in wave heights were determined, as well as calculations to estimate the resulting effects on erosion and run-up.

As mentioned, an important step in calculating setback lines (i.e. adequate development setback distances) is the determination of wave run-up, i.e. the maximum point that storm waves can reach (Figure 5.3). In a literature review of wave run-up prediction methods, 15 such methods were considered of which 7 were evaluated in more detail. These were: Battjes (1971); Nielsen & Hanslow (1991); three formulations by Ahrens and Seelig (2001); two formulations by Ruggiero *et* *al*. (2001); Guza and Thornton (1982); and Stockdon *et al*. (2006). Of the more empirical formulations, Nielsen and Hanslow (1991) and Ruggiero *et al*. (2001) appear to be most suitable; with the former being easier to apply. The Nielsen and Hanslow (1991) model requires the wave height and period, beach slope and water level. Their set of formulations was therefore used in the compilation of a computer routine, which was then verified and tested against an available set of southern African field data. The results are considered surprisingly good (R^2 = 0.79) if the relatively few parameters included in the formulation are kept in mind. (Most recently a promising formulation for SA has been proposed by Mather *et al.* (2011), but this was not available at the time when the Mozambican modelling was conducted.)



Quantification of wave run-up.

To determine maximum point that storm waves can reach (**wave runup**) i.e. to calculate the height to which a wave would run up the beach slope.

E.g. Nielsen and Hanslow (1991) model Runup (Bc), for tan(∞) greater than 0.1:

$$B_c = WL + 0.83 + 0.6 \cdot \tan(\alpha) \cdot \sqrt{\beta}$$

Where:

$$\beta = \frac{H_s}{\sqrt{2}} \cdot \frac{gT^2}{2\pi}$$

Wave runup model
Inputs:
Wave height & period
Beach slope
Sea water level
Output:
Inundation/ flooding elevation

Figure 5.23: Description of (part of) the Nielsen and Hanslow (1991) coastal wave run-up model

Having found the Nielsen and Hanslow (1991) model to be sufficiently valid and applicable to local conditions, the same methodology was applied to investigate the impact of SLR on run-up return periods and occurrences.

To clearly illustrate the large effect that SLR has, a low SLR value is first applied. The mean value of the IPCC Fourth Assessment Report SLR predictions is about 0.4 m by 2100 (AR4 Report, IPCC 2007). Using this prediction of future sea levels it was found that the same extreme wave run-up elevations as occurred during the extreme 2007 KZN storm in South Africa, would be reached by waves 10% lower (H_{m0}) than those recorded during the peak of the 2007 storm. This means that, based on the calculated return period of the 2007 storm (and assuming that the statistical distribution of extreme waves remains about the same over the next 100 years), the return period for the same extreme run-up heights is effectively halved. In other words, the probability of such extreme conditions occurring again is basically doubled, or statistically, such situations are likely to occur about twice as often over the long term for a SLR of only 0.4 m. (Note, that as discussed in the next paragraph, SLR of 0.4 m is not considered to be a suitable scenario for planning in this report.)

In Section 5.3 it was concluded that the best estimate (or "central" estimate) of SLR by 2100 is around 1m (with a plausible worst case scenario of 2m, and a best case scenario (low estimate) of 0.5 m). Therefore, in view of the newer SLR predictions (post IPCC 2007), the effects of a 1 m SLR (best estimate) on run-up levels were also quantified. It was thus calculated that a wave height of 24% less than the 2007 KZN storm would result in similar run-up elevations if sea level rose by 1 m. The results are alarming, in that the return period of the 2007 event (i.t.o. of high run-up elevations) would effectively be subject to a six-fold reduction. In other words, the probability of such extreme events (i.t.o. of high run-up elevations) as those experienced during 2007 happening again would be six times greater, or statistically, such impacts are likely to occur six times as often in the long run due to SLR of 1 m.

As illustrated above, it is of utmost importance to take seriously the issue of wave run-up when determining development setback parameters,

5.5.4 Coastal erosion due to climate change

Calculation of shoreline erosion due to climate change

Another important issue to predict is how areas that are already vulnerable to erosion may become more prone to damage in the future due to the effects of climate change. It is well known that the prime factor leading to damages in the past and increased risk in the future, are developments located too close to the sea. Thus, there is a need to determine areas of low vulnerability, which requires prediction of future shoreline locations. Studying the risks due to climate change in coastal areas will aid design and location of new developments and infrastructure in low risk areas, and will also help to identify other adaptation options for existing developments that are at risk.

The Mozambican coastline includes many sandy areas, which mostly have no hard protection (and where upon cyclone generated waves could impact). This leads to a high potential for erosion of these sandy coastlines. The most widely known (and applied) formula for estimating erosion as a result of sea level rise was proposed by Bruun (Bruun, 1988; Figure 5.24). The main parameters that are taken into account in Bruun's unsophisticated rule are the amount of sea level rise and the slope of the nearshore. The accuracy of the absolute results obtained through use of the Bruun rule can certainly be questioned, but the rule can be applied to give a first estimate of possible erosion of 'soft' sandy beaches. In some cases, broad dunes and wide beaches could mitigate such erosion to some degree. In other situations narrower beaches backed by *hardened* dunes will resist erosion resulting in less erosion than predicted by the Bruun rule.

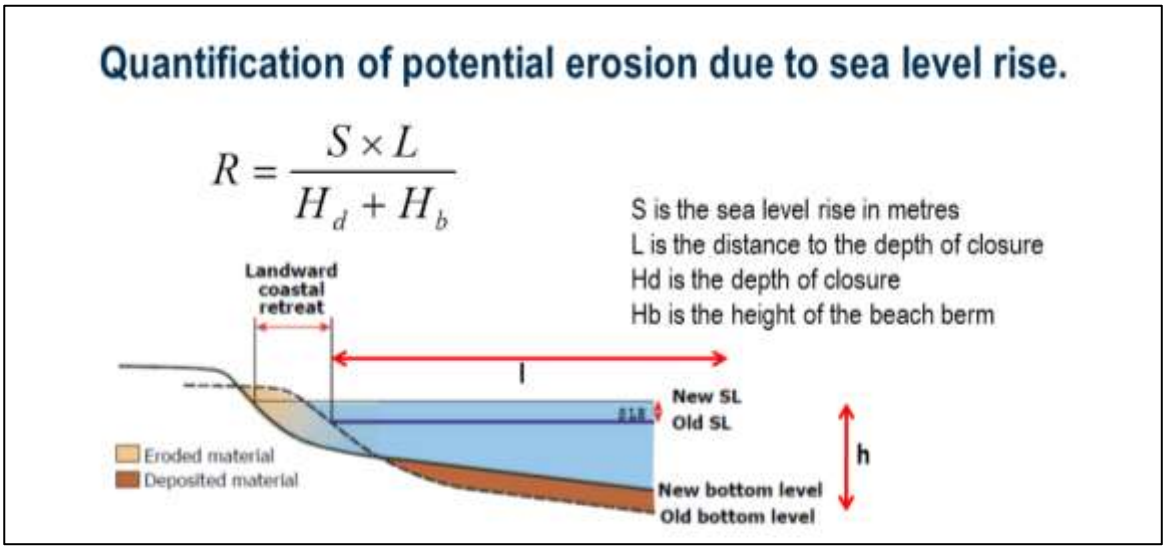


Figure 5.24: Schematic illustration of the Bruun model of profile response to rise in sea level showing erosion of the upper beach and nearshore deposition. (From Davidson-Arnott, 2005).

The Bruun rule is sensitive to the chosen values of the input parameters and the values of these parameters are also sometimes difficult to determine (Theron 1994; Theiler *et al.* 2000). Many other factors besides the amount of sea level rise and the slope of the nearshore need to be taken into account to accurately predict future coastal evolution on longer time and space scales. Site specific aspects such as local geology, hydrology and sedimentology, near and offshore bathymetry, exposure to waves, currents and general climatology, and local geographical features as well as human influences should all be considered. The Bruun rule remains, however, generally useful for coasts with little data or information about past morphological change and can be used as a useful spatial indicator of where future impacts may be a problem.

Effects of climate change on sediment transport

Wave energy is proportional to the square of the wave height (which in itself, in the fully developed state, is proportional to the square of the wind stress factor). The wave power is proportional to the wave energy and the wave period. Therefore, with the wave period directly proportional to the wind stress factor, an increase of only 10% in wind speed can mean as much as an 80% increase in wave power (Theron, 2007). (In lieu of more comprehensive site specific sediment transport calculations or modelling, wave power or wave energy can provide a rough indication of sediment transport potential.) This means that a modest 10% increase in wind speed could also result in a potential significant increase in coastal sediment transport rates and consequently impacts to the shoreline. (Coastal sediment transport rates are especially sensitive to changes in wave/storm direction.) The response (increase) of wave height versus wind velocity increase, and the resultant non-linear (power law) increase in wave energy and even further accelerated wave power, are illustrated in Figure 5.25.

In lieu of more complex/sophisticated sediment transport and/or beach morphology modelling, wave energy can be calculated to give an indication of coastal erosion potential. Thus, it can for example, be determined for the different wave return period conditions (Section 5.4), that the 1-in-1 and 1-in-50 year waves have respectively about 10 and 20 times the energy of the mean wave. In other words, the wave erosion potential of 1-in-1 and 1-in-50 year waves is respectively in the order of 10- of 20 times greater than for the mean condition, which is a significant change.

Since the current coastal geomorphology (of especially the soft coasts) is a direct result of the long term coastal processes (i.e. the mean condition over time) a change in the wave erosion potential can significantly alter the coastal configuration.

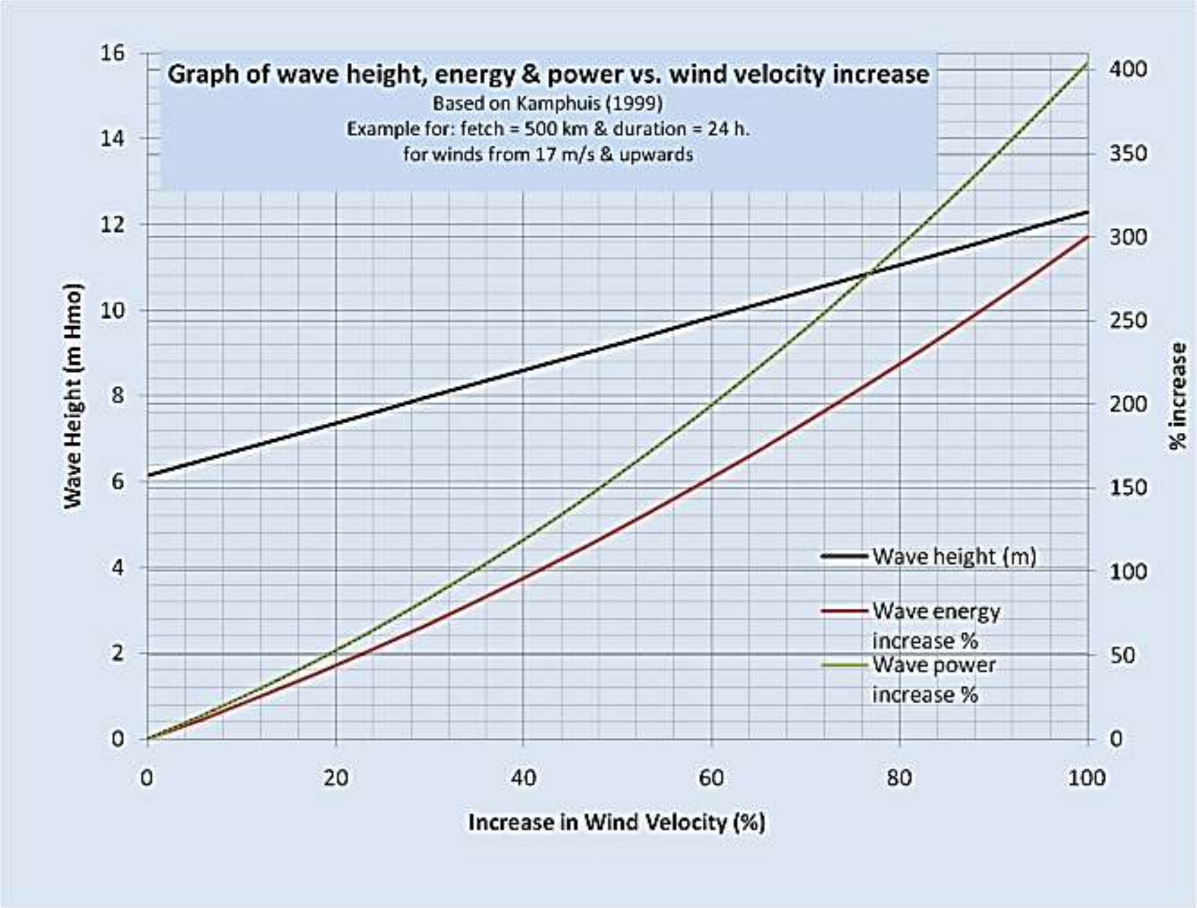


Figure 5.25: Example of proportional wave height growth versus wind velocity increase, also indicating resultant non-linear increase in wave energy and power (Kamphuis model).

5.5.5 Coastal Flooding/Inundation and Erosion Model

A conceptual description of the combined coastal flooding/inundation and SLR erosion model which explains the functional relationships between components of the model is presented in Figure 5.26 below. (*Note*, the figure relates to processes related to Climate Change and does not include any consideration of long term beach erosion and/or short term storm erosion. These are also important and such allowance is made in the setback line discussion for Beira and Maputo in Section 5.5.6.)

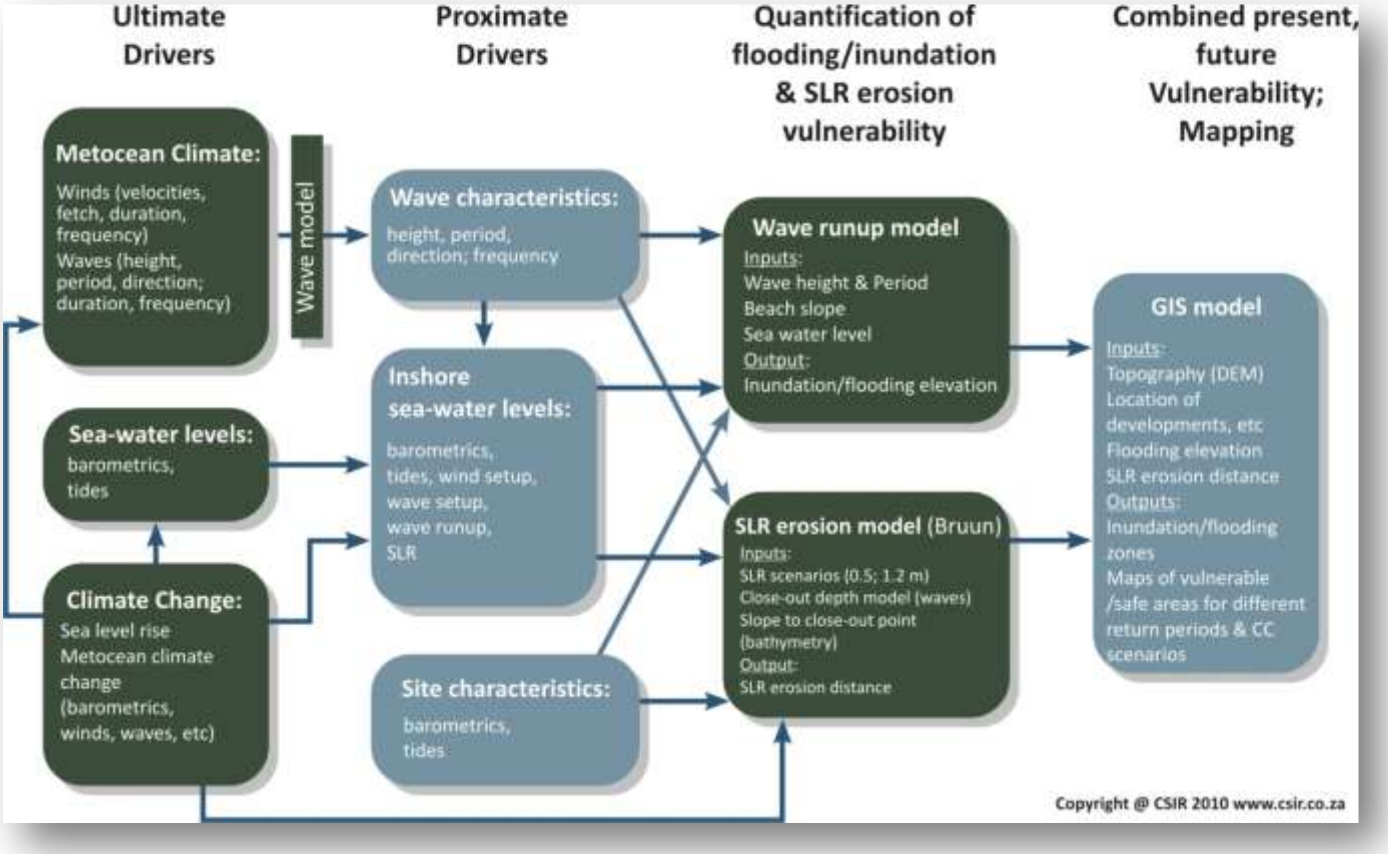


Figure 5.26: Conceptual description of the combined coastal flooding/inundation and SLR erosion model with functional relationships between components. (SLR = Sea Level Rise; DEM = Digital Elevation Model)
(Note, the figure relates to Climate Change and excludes other erosion drivers. These should also be allowed for in setback lines.)

Having determined the inshore wave conditions, the wave run-up and SLR coastal erosion models (as described in Sections 5.5.2 and 5.5.3) can be employed to quantify specific coastal impacts. Thus, for example, wave run-up elevations can be calculated at each coastal point along the coast for various tidal levels combined with different wave heights. Spring high tides (see Section 5.5.2) occur once every 14 days along the southern and eastern African coast and are therefore selected as a realistic scenario to consider in conjunction with selected sea storms. The same methods can be employed to predict and assess the conditions and impacts in the future by including climate change effects, in this case sea level rise and/or increased storminess. The extreme wave climate off Mozambique has been forecast to increase by about 6% by 2100, as discussed in Section 5.4, while the best estimate for SLR is 1 m by 2100 (Section 5.5.2).

An example of the calculated amount of wave run-up at each location point along the Beira shoreline is presented in Figure 5.27. These are the predicted amounts of wave run-up for the modelled inshore cyclone wave conditions.

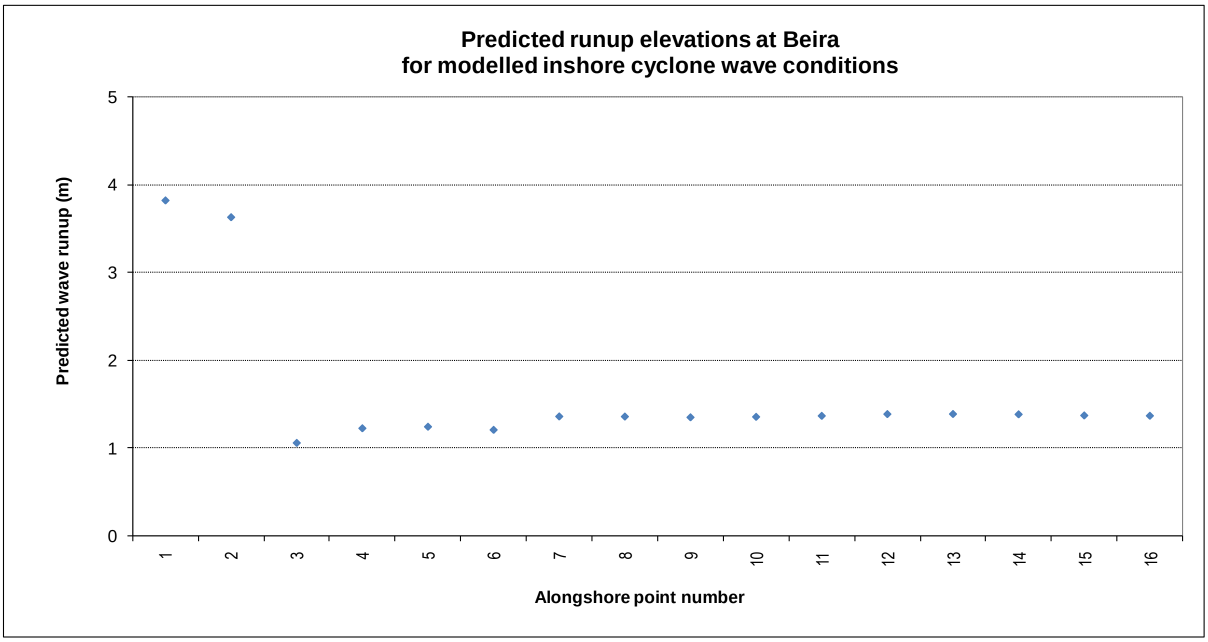


Figure 5.27: Example of predicted run-up amounts at Beira

From the figure it can be seen that the wave run-up amounts range from about 1 m to 4 m. The alongshore variations in predicted run-up heights are mainly related to the differing wave exposure and slope of each location. (Note, however, that where the beach slopes were found to be flatter than 0.1, they were taken to be 0.1. This was done for two reasons: (1) It has been found that the Nielsen and Hanslow model is less reliable for slopes flatter than 0.1, and (2) more importantly, extreme run-up occurs during storms, which means that the beach profiles are also subject to erosion at the same time. The effect is that the beach slopes will in fact steepen during the storm, leading to higher run-up on the steeper profile. Thus, it is assumed that the milder profile slopes (< 0.1) are likely to be steeper during a storm than at present, which is a conservative assumption.

Similar run-up predictions were made for Maputo and Pemba (thus incorporating a wide variety of cyclone wave conditions and shoreline characteristics). It was found that wave run-up amounts range from about 1 m to 6 m. Taking all three areas into account (and rounding up to the nearest decimetre), it was found that for most of the input conditions at most of the coastal point locations, the run-up in fact ranges between about 1.5 m to 3 m. (At first hand this may appear to be lower run-up amounts than expected, but the wave modelling shows that this is due to the dampening effect of the wide shallow inshore areas, as found in many parts of Mozambique.)

Appropriate combinations of present and future components of extreme inshore water levels (including wave run-up) are discussed in detail in Section 5.5.6.

5.5.6 Calculation of potential erosion due to SLR at Beira and Maputo

The focus here is on Maputo and Beira as they are the two major coastal cities in Mozambique with by far the most extensive infrastructure and development within the coastal zone potentially subject to climate change impacts. (They are also both major sources of income for the government and contain the main Mozambican ports.) For each of the two cities, and for each of the scenarios and input conditions, the SLR coastal erosion model (Section 5.5.4) was also employed to quantify the potential erosion due solely to SLR. To allow for normal shoreline variability (e.g. erosion during storms and accretion recovery thereafter) an additional setback distance of 40 m is added to derive an acceptable total setback distance, as indicated in the last row of the table.

Detailed and comprehensive investigations are sometimes conducted to better determine setbacks required for local shoreline variations, but then only for small study areas and where extensive input data is available. On large scale studies (such as this project), it is not practical or affordable to conduct many such detailed local setback investigations. The 40 m distance is based on extensive experience in southern Africa and adapted for average Mozambican conditions. This is also the distance specified in some Australian and US states. An example of the calculated potential erosion and setback line recommended at each location along the Beira shoreline, is given in Table 5.10. Some of the results for predicted erosion potential (due to SLR) shown in this example (Table 5.10) are very low (Points 2451 to 2455). These results are correct however, and are due to these points being located on non-erodible (rocks or hard structures) and/or very steeply sloped sections of the Beira coast. Where the coast cannot erode, the high-water line simply moves directly up and landward with the slope according to the amount of SLR; the Bruun rule is not applicable at these locations.

Table 5.10: Example of quantification of erosion potential and erosion setback for SLR

POINT	BEIRA - SUMMARY		
	Sea level rise (SLR) (m)	Erosion due to SLR (m)	Erosion setback including SLR (m)
2440	0	0	40
2440	0.5	130	170
2440	1	260	300
2440	2	530	570
2444.5	0	0	40
2444.5	0.5	50	90
2444.5	1	110	150
2444.5	2	120	260
2450	0	0	40
2450	0.5	110	150
2450	1	220	260
2450	2	450	490
2451 to 2455	0	0	40
2451 to 2455	0.5	10	50
2451 to 2455	1	20	60
2451 to 2455	2	30	70

A graphical output of all of these results for each coastal point at Beira is mapped in Figure 5.28. The total SLR erosion setback thus ranges from 40 m to 570 m depending on the alongshore location. The alongshore variations in erosion potential (due to SLR) are mainly related to the differing wave exposure, but especially slope and "erodibility/hardness" of each location. Some of the *potential* erosion distances are very large (e.g. around Point 2440). These may be considered somewhat unrealistic, as it should be remembered that the unsophisticated Bruun rule cannot take account of changing landward characteristics and processes where potentially large inland erosion is predicted. (Recent Australian coastal guideline documents provide a modified Bruun rule methodology which may give smaller erosion distances that might be more realistic, but the applicability of this method has not yet been verified for Mozambique.) It should also be noted that application of such methods and all of the results are dependent on the accuracy of the input data. In particular, detailed topographic data was only available at some towns (and even where it was available, significant errors were found in some of the data). Thus, elevations, slopes and landward horizontal distances were calculated or interpolated on this relatively coarse data. Where the topography is very complex and uneven or large abrupt changes occur in reality, the results could be affected significantly. <u>This underscores the need for good topographic input data if more detailed or accurate results are required.</u> The potential setback line for SLR erosion at Beira, as mapped in Figure 5.27, can only be recommended as a conservative first order estimate to consider for long-term planning of new development or major redevelopment of the coastal strip.

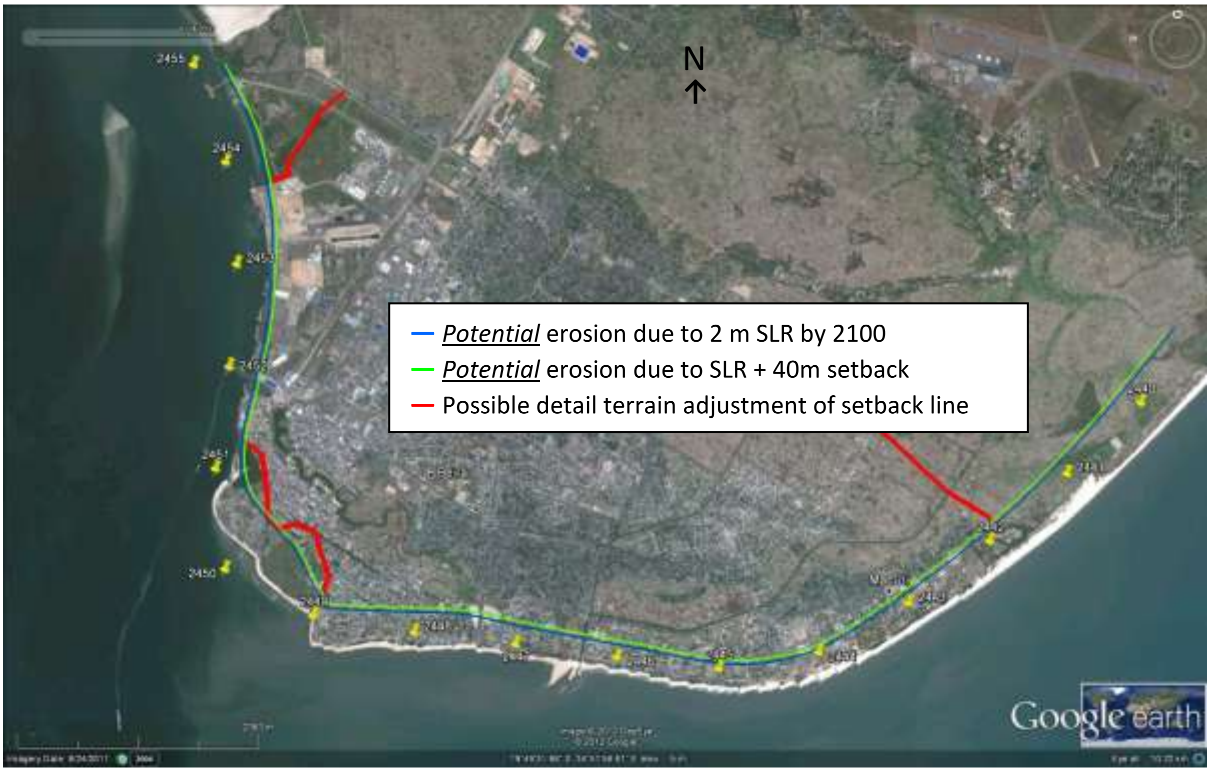


Figure 5.28: Map of potential erosion and recommended setback line for SLR – Beira

The increase in potential erosion over time, due to the increasing SLR, is illustrated in Figure 5.29. The potential additional impact of a relatively low background erosion trend (which could e.g.

result from other human impacts) is also illustrated in the figure. Poor coastal zone management practises (e.g. disruption of sand transport or removal of sand) can easily lead to such or higher erosion rates. (Note, that such an existing erosion trend has not been observed at Beira.)

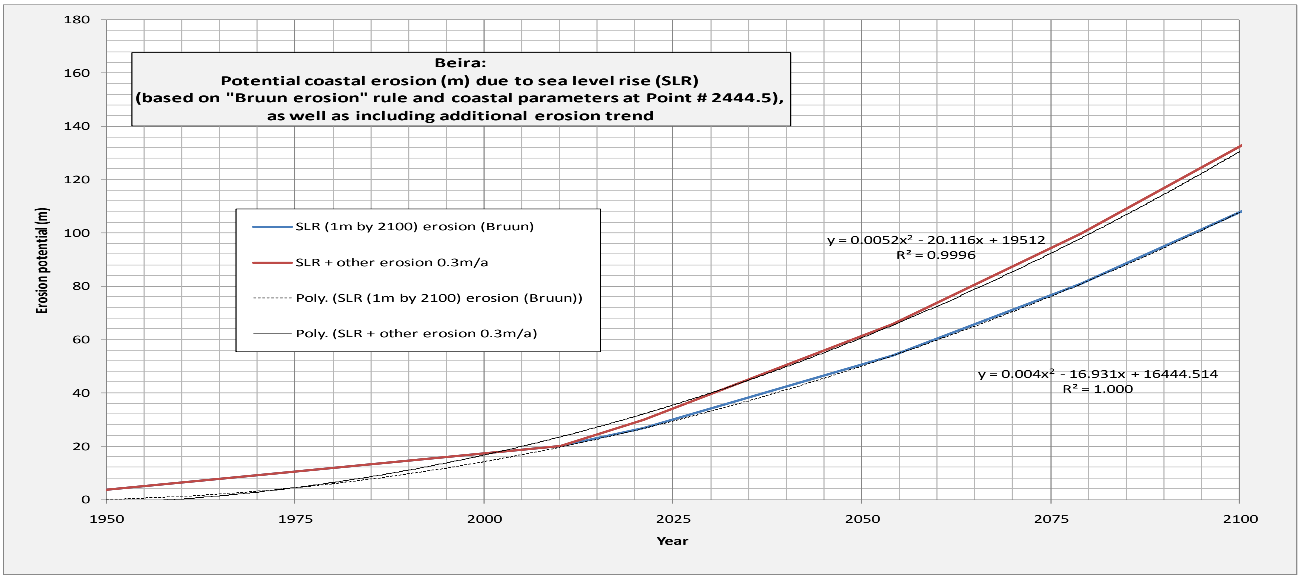


Figure 5.29: Increase in potential erosion over time at Beira, due to the increasing SLR up to 1m by 2100

Taking the example depicted in Figure 5.29 (at Beira location # 2444.5), for the scenario of 1 m SLR by 2100 and assuming no other ("background") erosion trends, by 2050 (i.e. in the next ~40 years) some 30 m (more) of the coast at this location may be eroded (compared to perhaps not more than 10 m of erosion in the past 40 years). (Note, good data on possible historical erosion trends was not available.) Major problems due to possible historic erosion at Beira have not been observed. However, coastal erosion due to SLR is likely to become significant in a few decades. The onset of such coastal erosion should be a "red flag", triggering a reassessment of the likelihood of the more extreme SLR scenarios, as the potential impacts (in conjunction with the impacts of extreme events) will be severe at Beira. Such reassessment should consider all vulnerable areas along the Mozambican coast.

Following the same procedure as applied for Beira, the potential erosion setback line (due to SLR effects and shoreline variability) has been determined for Maputo as indicated in Figure 5.30.

Figure 5.30: Map of potential erosion and setback line for SLR - Maputo

The potential erosion and setback lines indicate in the foregoing maps do, however, not explicitly make allowance for coastal flooding/inundation. The areas subject to extreme flooding events could in several instances extend significantly further landward than the potential setback lines indicated in the foregoing maps (despite these being considerable distances in some locations due to the potential erosion indicated by the Bruun rule). Areas/locations subject to coastal flooding/inundation should also be an important consideration in identifying vulnerable areas and in planning coastal developments (and ICZM). For each of the 10 towns / cities the areas that are vulnerable to coastal flooding/inundation are identified and discussed in detail in Section 6.4.

5.6 QUANTIFICATION OF FLOODING LEVELS FOR MOZAMBICAN COASTAL TOWNS

To illustrate how the components of the inshore sea water levels have been calculated for each location, Beira is used as an example in Figure 5.31 below.

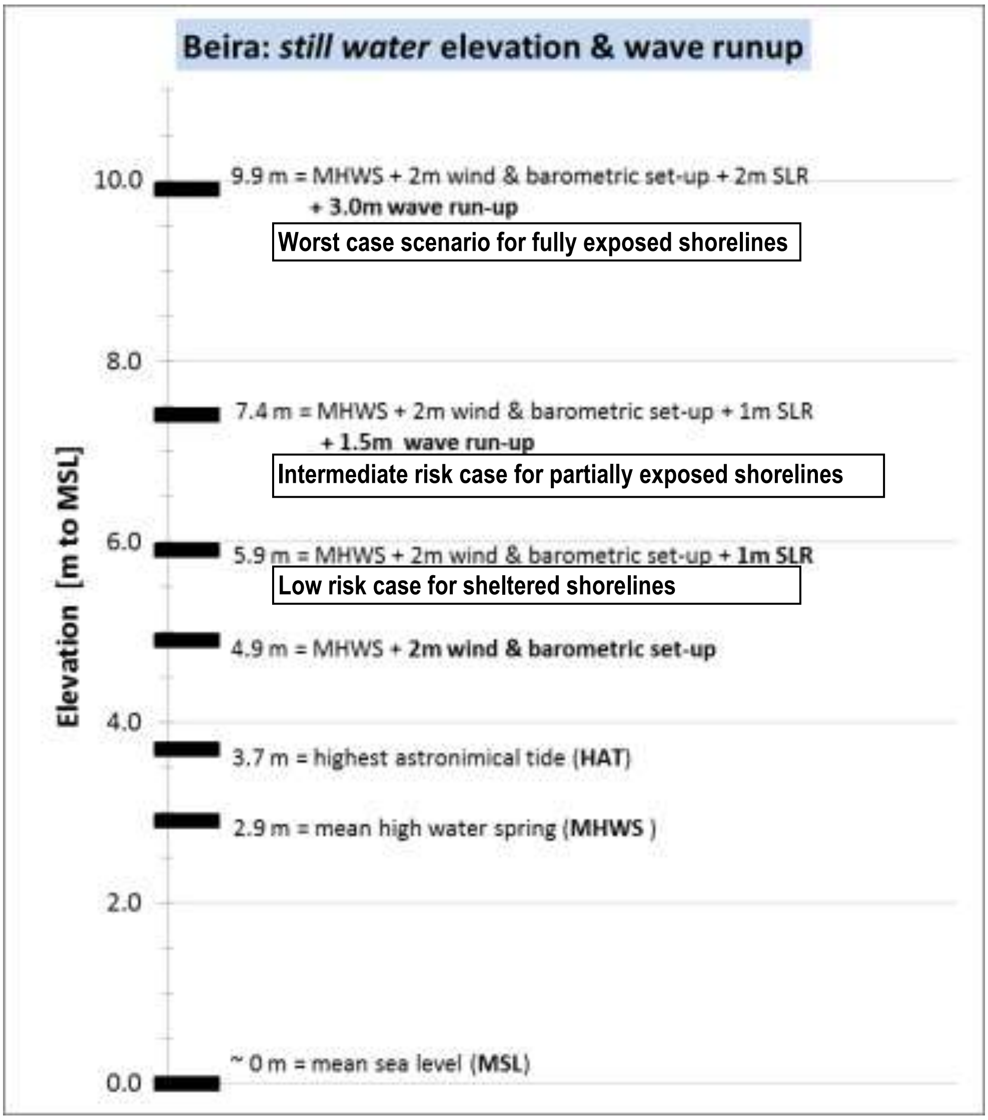


Figure 5.31: Beira coastal flooding and wave run-up levels.

The figure shows the extreme inshore sea water levels calculated for Beira due to the combination of the various contributing components. Thus, the figure shows the increasing water levels all relative to Mean Sea Level (MSL) which is at approximately 0 m elevation, for:

- Mean High Water Spring tide (MHWS, occurring every 14 days) = 2.9 m above MSL
- The crest elevation of existing coastal structures (according to INGC Phase 1,, 2009) = 3.46 m above MSL.
- Highest Astronomical Tide (HAT, highest level that *ordinary* tides will reach under average meteorological conditions, which has a 19 yr cycle) = 3.7 m above MSL
- A cyclone approaching the coast results in an additional local set-up (increase) of the sea water level due to strong onshore winds (wind-waves) and low barometric pressure. The combined wave and "barometric" set-up is estimated at an additional 2 m. Thus, at present, a cyclone approaching Beira during spring tides (which occur every 2 weeks) could result in flooding levels of about 2.9 m (MHWS) + 2 m (wind & barometric set-up) = 4.9 m above MSL.

- The mid scenario (best estimate) for Sea level Rise (SLR, due to Climate Change) is 1 m by 2100. Thus, the extreme future scenario (2100) for a cyclone occurring during spring tide could result in flooding levels of about 4.9 m + 1 m (SLR) = 5.9 m above MSL. In lieu of better extreme water level data, it is recommended that this be taken as the "design" flooding level for low risk infrastructure (<50 year lifespan) within sheltered locations.
- The above elevations all relate to the "still-water" level at the shoreline. This should not be confused with the additional effect of wave run-up, which can reach even higher elevations along partially and fully exposed shorelines. (Wave run-up is the rush of water in the swash zone up the beach slope above the still-water level, Figure 5.3.) A cyclone approaching Beira would also cause waves, resulting in even higher elevations being reached by the wave run-up along partially and fully exposed shorelines. Based on the wave and run-up modelling, the additional height reached by wave run-up along partially and fully exposed shorelines would be from 1.5 m and upwards. Thus, the total elevation reached by waves along partially and fully exposed shorelines during a cyclone and spring tides is from 5.9 m + 1.5 m = 7.4 m above MSL and upwards.
- Depending on the specific site and circumstances (e.g. profile slope, exposure to incident waves, etc.), the wave runup during extreme events could be significantly more than just an additional 1.5 m, up to about 3 m along fully exposed shorelines. The worst case scenario for Sea level Rise (SLR, due to Climate Change) is 2 m by 2100. In this case, the total elevation reached by waves along fully exposed shorelines during a cyclone and spring tides could be about 4.9 m + 2 m + 3 m = 9.9 m above MSL. Note, no accurate recurrence levels can be attributed to such a combination of events. The joint probability of spring high tides (occurring for approximately say 18 h in total over 14 days) with a 1-in-100 year cyclone (with possible extreme local effect of say 3 days) and a long-term 2 m SLR scenario by 2100, could be more severe and less frequent than a true 1:100 year extreme coastal flooding event. Relatively long-term water level recordings, *which include sufficient cyclone events and resulting set-ups*, are required to calculate statistically accurate extreme events and occurrences. Unfortunately, such data for Mozambique is insufficient; therefore, following the precautionary approach, plausible scenario combinations were robustly applied, which is considered an appropriate first level approximation.

Similar calculations of the components of the inshore sea water levels have been made for each coastal town, examples for Maputo and Pemba are indicated in Figures 5.32 and 5.33.

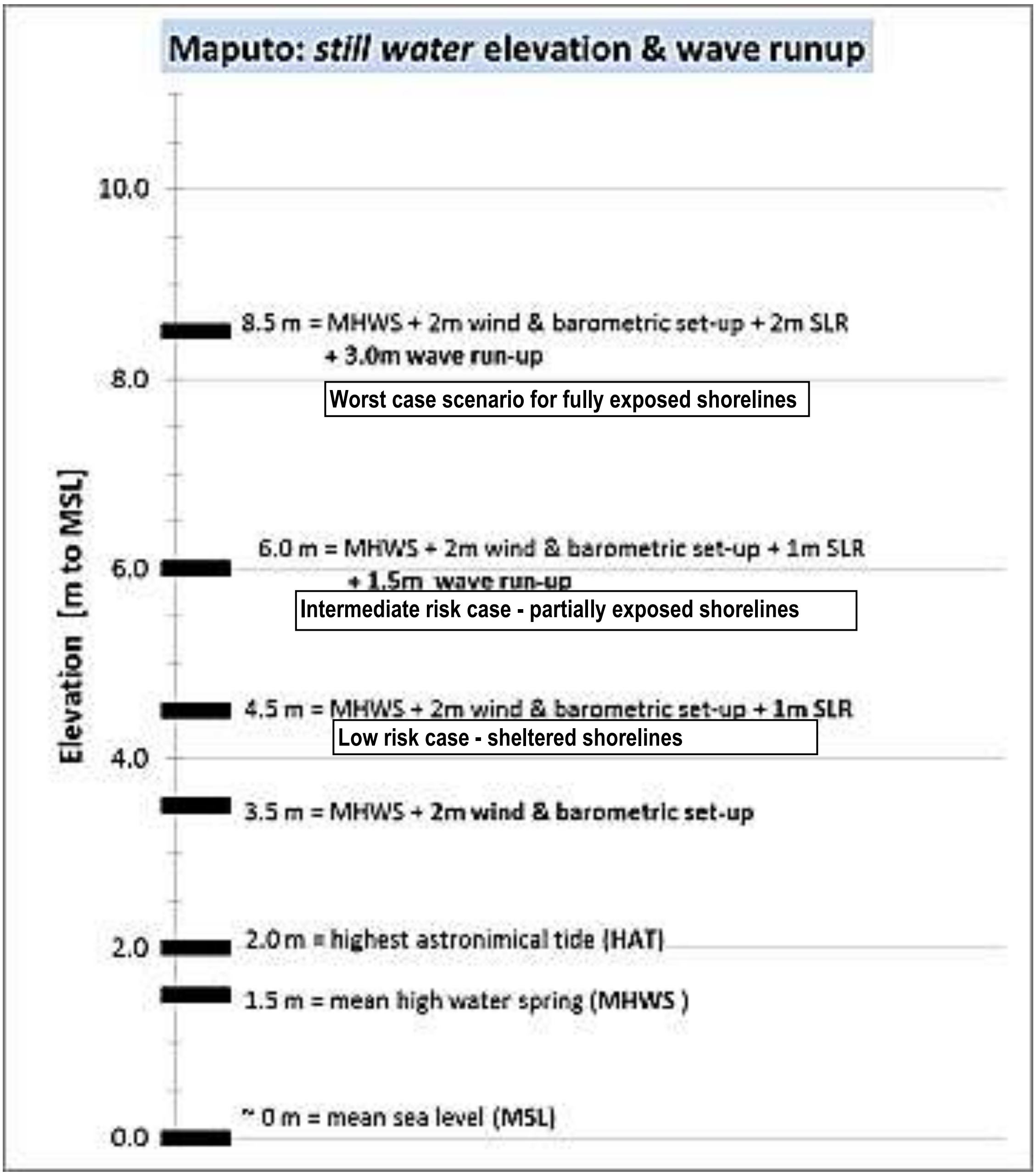


Figure 5.32: Maputo coastal flooding and wave run-up levels

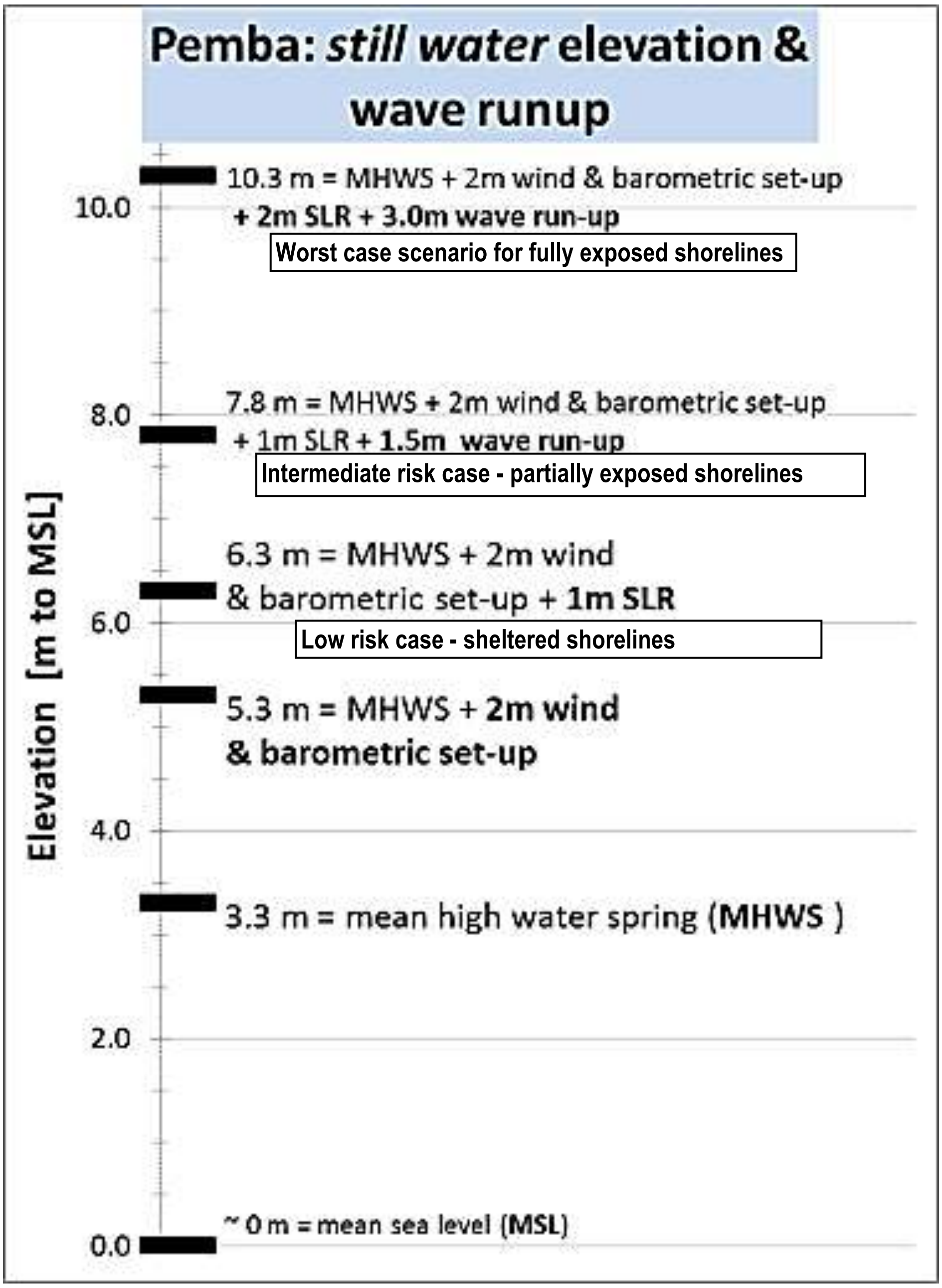


Figure 5.33: Pemba coastal flooding and wave run-up levels

The results of the calculated sea water flooding levels of all of the coastal towns are summarised and compared in Section 6.2.1 (and Figure 6.3), where the implications are also discussed.

From the discussion above it is concluded that:

1. The physical conditions (wave heights, direction and sea water level) that occur at the coast during a cyclone was determined by the setting up of a cyclone model which was calibrated using data measured at Beira during Tropical Cyclone Lizette in March 1997.

2. The storm wave conditions that are predicted to prevail offshore of Mozambique were determined for current conditions and also with expected climate change factors taken into account. An appropriate technique was used to derive the expected wave height and wave direction distribution off each of the study sites.

3. Due to the geographical location and local bathymetry at each of study sites, the tide levels are different. The influence of a rise in sea level on the high tide levels is therefore also different in different areas along the coast.

4. Using the results of the above studies and calculation of wave run-up heights, the High, Medium and Low **sea water flooding hazard levels** for three selected scenarios were determined.

The values of these parameters are incorporated into the coastal hazard assessment discussed in Chapter 6.

CHAPTER 6: COASTAL HAZARD ASSESSMENT

6.1 COASTAL HAZARD ASSESSMENT METHOD

6.1.1 Introduction

In this chapter an overview of hazard assessment along the coast, as well as possible trends reflected in the regional data is provided. A relatively coarse level of assessment, based on a comprehensive set of hazard drivers and vulnerability modification factors, is further provided for the Mozambican coastline. A more detailed level of assessment, focussing on better quantification of the primary hazards is also given for the selected coastal cities and towns.

6.1.2 Methods of assessing vulnerability of coastal areas and developments

Breetzke *et al*. (2008), although not providing a vulnerability assessment method per se, contains information and guidelines on risks and response to coastal erosion that is particularly relevant to the southern African scenario. The coastal vulnerability index (CVI) devised by the US Geological Survey and founded on six physical variables is found to be useful to assess the vulnerability of the coastline to climate change (Theiler & Hammar-Klose 2000). These six variables are: geomorphology; coastal slope; relative sea level change; shoreline erosion/accretion rate; tidal range; and wave height. Another indicator, the coastal social vulnerability index (CoSVI) developed by Boruff *et al*. (2005), is used to determine social-economic vulnerability of coastal areas to sea level rise (SLR). These indices can also be combined to give an overall vulnerability index, which appears to be a viable approach to the southern African situation. The methods of Dutrieux *et al*. (2000) are considered to be more useful for integrated coastal zone management aimed at sustainability and protection/management of the natural environment, and are particularly useful for guidance on more detailed vulnerability mapping of smaller areas (e.g. islands).

The methods recently developed and applied in Portugal and Spain have a practical approach and are well-suited to the southern African and Mozambican context. Jimenez *et al*. (2009) have developed good coastal storm vulnerability assessment methods, but the input data requirements are considered to be too onerous for wide scale application in the African context. Jimenez (2008) provides a good description of how coastal vulnerabilities can be assessed for multiple hazards.

However from the literature study it was concluded that the set of parameters included in the method developed by Coelho *et al*. (2006) would be pragmatic and most relevant for application to the study area.

6.1.3 Adaptation of suitable method for study area

The first part of the Coelho *et al*. (2006) method is to assess the degree of exposure and vulnerability to coastal processes using the following nine indicators as the basis: <u>foreshore elevation; distance (e.g. infrastructure) to shore; tidal range; offshore wave height; historical</u>

erosion / accretion rate; geology (type of rock or sediment); geomorphology (type: e.g. rocky cliff or river mouth); ground cover (e.g. forest/mangrove or urbanised/industrial); and anthropogenic actions (e.g. shoreline stabilisation intervention or sediment sources reduction). Specific limit values associated with each of the indicators are defined and the assessment is done by selecting the appropriate range of values for each indicator. A vulnerability classification of Very Low (Vulnerability Score = 1) to Very High (Score = 5) is then derived.

Three additional indicators have been identified here that are relevant to the study area, which have been added by the authors to the Coelho *et al*. (2006) assessment methodology:

- Degree of protection from prevailing wave energy (site location, coastline configuration/shape & orientation, bathymetry). Following a method proposed by Barwell (2011), scoring is done according to wave exposure as listed below and illustrated in Figure 6.1, in increasing order of exposure:
    - Leeside of large island or extensive spit on opposite side of incident waves (A);
    - Leeside of headland, rocky point or peninsula (A);
    - Partially sheltered from deep-sea wave energy (B);
    - Directly exposed to waves only slightly refracted from deep-sea (C); and
    - Directly exposed to storm wave attack, with narrow surf zone (D).

  (Wide areas of dense mangroves can also provide some wave protection, but this factor is already accounted for in the "ground cover" indicator mentioned before.) Additionally, if sites are located close to a river/estuary mouth, the vulnerability is scored more severely due to the risk of mouth meandering for example. This indicator therefore explicitly accounts for the differing vulnerability to incident storm waves due to location (and other wave modification factors), ranging from fully exposed open coast sites to well sheltered locations, for example within bays or on the leeside of headlands.

- Sea level rise erosion potential ("Bruun" factor i.t.o. inshore slope; see Section 5.5.4). Sea level rise is likely to result in flooding/inundation and coastal erosion. However, flooding/inundation vulnerability is already accounted for in the elevation and distance to shore. Thus, only the Bruun erosion potential needs to be assessed: for a specific amount of sea level rise, the erosion is directly related to inshore slope. (Alternatively, the parameter to quantify could be taken as distance to the 10, 15 or 20 m depth contour; the choice depends on the "active" nearshore profile depth);

- Relative height (ideally volume) of the protective foredune buffer (i.e. the available sand reservoir). The importance of the foredune buffer as a natural coastal defense mechanism is discussed in Barwell (2011).

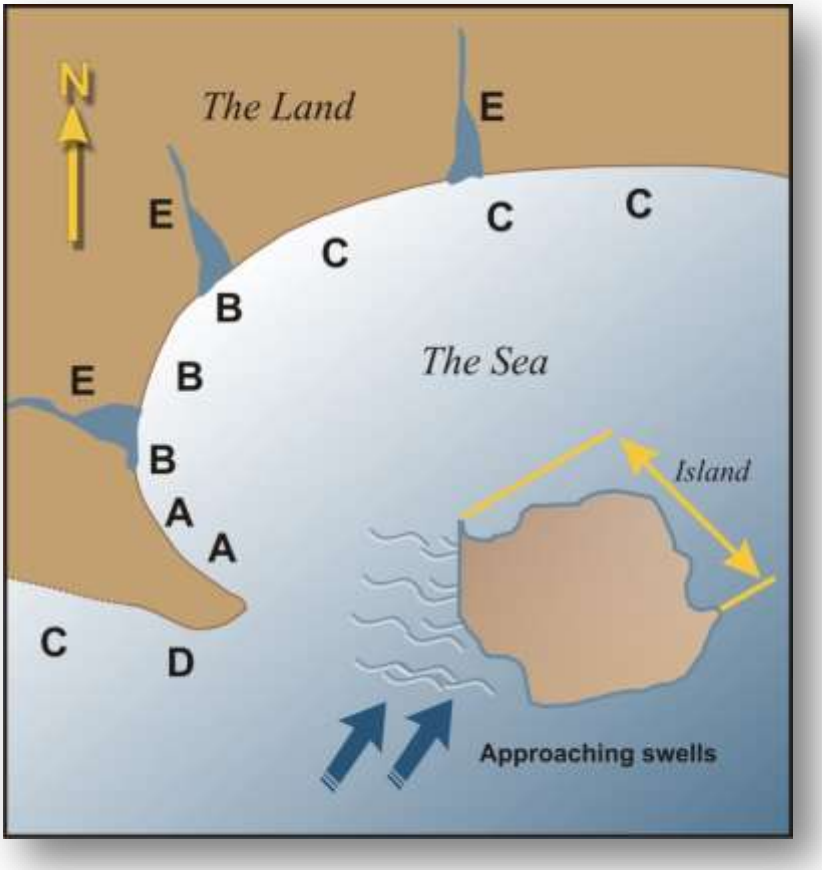


Figure 6.1: Degree of protection/exposure from prevailing wave energy (A – most protected, D – most exposed)

In the tropics (i.e. Mozambique) two important additional indicators have been included by the authors: cyclones (e.g. occurrence per annum); and protective corals/fringing reefs (alongshore extent as % of total shoreline length). (Potential additional factors that could be considered in future are: characteristics of the winds (velocities above 12 km/h, that dominate during the dry season with an onshore component more than 20% of the time); pressures from human activities (to dunes/vegetation); and existing cross-shore beach width (e.g. to accommodate storm erosion or long-term trend).)

Nevertheless, it is important to keep in mind which data are readily available to quantify a specific factor. “Double accounting” must also be avoided, e.g. distance and elevation already account for slope on land, so if distance and elevation are assessed, slope on land should not also be added as a factor. Seaward slope is, however, independent of on-land slope and is used specifically to assess vulnerability to erosion due to SLR.

Almost all of the 14 indicators included in Table 6.1 can be assessed directly, based on the available input data. Some of the indicators require further interpretation or analysis of the input data to properly assess the vulnerability.

Erosion /accretion (# 5 in Table 6.1) is one of the most difficult indicators to quantify if historic data is not available, as was the case for virtually all areas of the Mozambican coast. Assessment of erosion (or accretion) was therefore assessed from remote sensing (satellite images with semi-automated change detection). The technique of using remote sensing to assess change is described in Appendix 1. Four study areas were identified for the satellite remote sensing assessment, namely Maputo, Maxixe, Vilanculos and Beira. Three change detection methods were assessed at the Maputo (Object-Oriented Image Analysis, Change Vector Analysis and Spectral Change Analysis) site while two were used for the Maxixe, Vilanculos, and Beira sites (Change Vector Analysis and Spectral Change Analysis).

As discussed in Appendix 1, the results show that the Change Vector and Spectral Change Analyses report consistent results while the Object-Oriented Image Analysis returned inconsistent results. All three image analysis procedures were affected by tides which made differentiating between ocean, beach and shallow water very difficult. This resulted in commission and omission type errors depending on the nature of the tides and the imagery used. Spatial resolution also played a role in the quality of the results with a ±60 metre accuracy deemed too inaccurate. The study concluded that in the future high resolution satellite imagery or digital aerial photography or laser scanning (e.g. LIDAR) should be used to assess coastal stability. If suitable pre 1980's coastal aerial photography can be sourced, this could be useful to quantify historic shoreline changes over a longer period.

To complement the remote sensing technique, use was made of Google Earth images for orientation, aerial observations (during the low altitude coastal flight inspection in May 2010) and in-situ ground inspections.

At Beira, for example, the remote sensing coarse resolution images do not show significant erosion trends within the main city area. Noticeable changes are due to construction, while the other noticeable changes are observed in the naturally dynamic mangrove/sand/mud-bank areas. The Beira aerial observations and in-situ investigation found no obvious indicators of significant erosion (e.g. scarps, many trees undercut, etc.); also old (more than three decades) structures are found quite near the high-water line as well as old surviving groynes. The conclusion is thus that there is no large erosion trend at Beira. (Possible erosion since the 1950's could be in the order of 10 m in total.)

The other coastal sites were assessed in the same manner. In all instances more emphasis was placed on the application of coastal engineering experience during the flight observations and site inspections, rather than on the generally somewhat inconclusive remote sensing information.

In summary, a total of 14 vulnerability indicators have been determined as appropriate and applicable for the Mozambican coast (also in terms of the input data/information required). The 14 vulnerability indicators, the specific limit values associated with each of the indicators and the vulnerability classification ranges, are summarised in Table 6.1.

Table 6.1: Vulnerability indicators, limit values for each indicator and vulnerability classification ranges applied for Mozambican coastal vulnerability assessment.

#	Vulnerability Criteria	Vulnerability Classification & Score				
		VL	L	M	H	VH
		1	2	3	4	5
1	TE: Elevation (m)	>30	21 - 30	11 -20	6 -10	<5
2	DS: Distance to shore (m)	>1000	200 - 1000	50 -200	20 -50	<20
3	TR: Tidal range (m)	<1	1 - 2	2 – 4	4 – 6	>6
4	WH: Max wave height (m)	<3	3 - 5	5 - 6	6 – 7	>7
5	EA: Erosion / accretion rate (m/yr)	>0 (accretion)	-1 to 0	-3 to -1	-5 to -3	< -5 (erosion)
6	GL: Geology	Hard rocks (Magmatic)	"Medium" hardness rocks (Metamorphic)	Soft rocks (Sedimentary)	Non-consolidated coarse sediment	Non-consolidated fine sediments
7	GM: Geomorphology	Mountains	Rocky cliffs	Erosive cliffs, Sheltered beaches	Exposed beaches, Flats	Dunes, river mouths, estuaries
8	GC: Ground Cover	Forest/ Mangroves	Ground Vegetation, cultivated ground	Non-covered	Rural urbanised	Urbanised or industrial
9	AA: Anthropogenic Actions	Shoreline stabilisation intervention	Intervention without sediment sources reduction	Intervention with sediment sources reduction	Without intervention or sediment sources reduction	Without intervention but with sediment sources reduction
10	Degree of protection from prevailing wave energy	Leeside of large island or extensive spit on opposite side of wave incident waves	Leeside of headland, rocky point or peninsula	Partially sheltered from deep-sea wave energy	Directly exposed to waves only slightly refracted from deep-sea	Directly exposed to storm wave attack, with narrow surf zone
11	Cyclones (occurrence/a)	0	>0 <1	1-2	>2-3	>3
12	Sea-level rise Bruun erosion potential (inshore slope)	<0.1 (1/10)	0.1– 0.029	0.03 – 0.014	0.015-0.005	>0.005
13	Corals/fringing reefs (alongshore extent as % of total length)	<10	10-30	30-50	50-80	>80
14	Relative height (m) of the protective foredune buffer	>20	10-20	5-10	0.5-5	<0.5

A conceptual description of a coastal hazard/risk model (based on the foregoing), which explains the functional relationships between components of the model, is presented in Figure 6.2. The "Coastal Hazard Assessment Model" approach could basically be described as an expert analysis of functional responses (linked to process-based modelling).

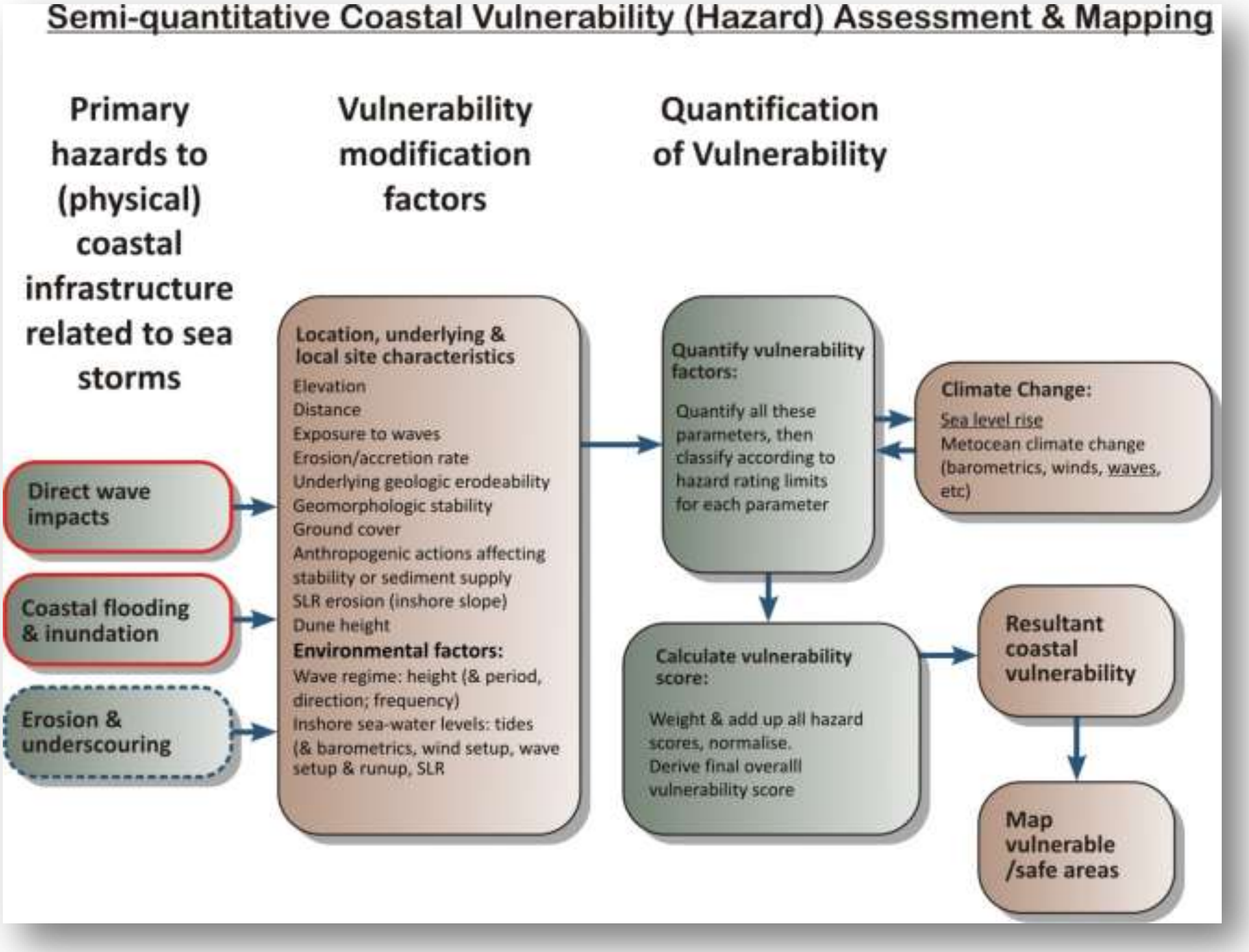


Figure 6.2: Conceptual description of the coastal hazard/risk evaluation model with functional relationships between components.

Having developed a suitable assessment method to identify hazardous coastal areas, each particular hazard can then be investigated further to quantify the risk of occurrence or to determine which locations within an area are at risk from a specific event.

6.2 DETAIL ASSESSMENT OF FLOODING HAZARD AND QUANTIFICATION OF ELEVATION VULNERABILITY

One of the most important vulnerability indicators and considerations in planning coastal developments, ICZM and determining adaptation measures is the elevation (thus also location) of coastal areas in relation to sea water flooding levels. Thus, available data related to these aspects are quantified and assessed in detail for each coastal town.

6.2.1 Sea water flooding hazard levels

Following on from the discussion in Section 5.6, three flooding scenarios were defined to establish the hazard levels at the specific sites in terms of possible flooding due to the various factors associated with 'normal' meteorological factors as described in Figure 6.3. In addition to these factors, the effects of climate change are taken into consideration. The flooding scenarios shown in Figure 6.3 are:

- LOW vulnerability areas, relatively sheltered from direct wave impact => mean high-water spring (MHWS) + wind, wave and atmospheric set up (a total of 2 m) + 1m SLR (best estimate of SLR by 2100). This low flooding level is appropriate for planning and management of infrastructure along sheltered shoreline locations, with a design life of less than 50 years.

- MEDIUM vulnerability areas, semi-exposed to direct wave impact => MHWS + wind, wave and atmospheric set up (2 m) + 1m SLR + 1.5 m run-up (moderate run-up height). This intermediate flooding level is appropriate for planning and management of infrastructure along the semi-exposed locations, with a design life of less than 50 years.

- HIGH vulnerability areas, fully exposed to direct wave impact => MHWS + wind, wave and atmospheric set up (2 m) + 2m SLR (probable maximum SLR by 2100) + 3 m run-up (estimated run-up for relatively severe storm) This high flooding level is appropriate for important infrastructure with a design life of more than 50 years (such as ports and airports) along the exposed locations. (For "greenfield" or undeveloped areas, a more conservative allowance of 2 m SLR is also preferable.)

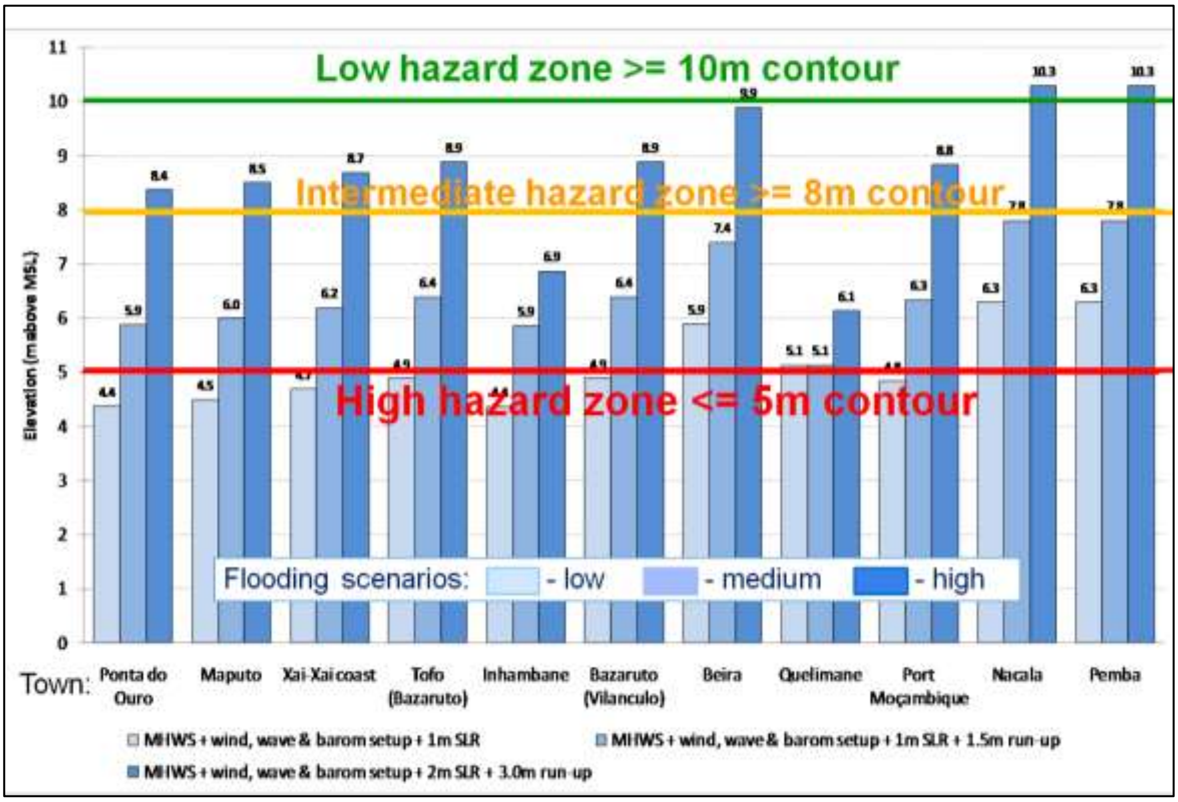


Figure 6.3: Coastal flooding levels for 11 towns/cities

These three flooding level scenarios were calculated for each of the study towns and cities as depicted in the figure (the 3 bars for each town). It can be seen that for most of the towns and cities the LOW flooding scenario (sheltered locations), ranges from 4.4 to 6.3 m MSL, on average at about the +5 m MSL level, here defined as the "high hazard level". Thus, virtually all areas (from sheltered to exposed locations) below the 5 m contour will already be at risk, even for the LOW flooding scenario. The MEDIUM flooding levels (applicable along semi-exposed locations) range from +5.9 m to +7.8 m MSL. Thus, areas located above the +8 m MSL contour, (rounded up from 7.8 m) defined as the "intermediate hazard level" (Figure 6.3), will in virtually all instances have a low risk in terms of the MEDIUM flooding scenario (applicable along semi-exposed locations).

Almost all of the HIGH flooding scenarios, being the worst case scenario for exposed locations, lie below the 10 m MSL elevation (the values range from 6.1 to 10.3 m MSL), depicted as the "low hazard level" in Figure 6.3. INGC promotes a pro-active approach ('prevention is better than cure'), implementing the 'precautionary principle' when locating and designing national key point infrastructure (e.g. national roads, railways, petroleum / oil pipelines and storage, ports and airport infrastructure, etc.). It is for this reason that it is recommended that such highly important and costly infrastructure *generally* be designed to be located at or above the +10 m MSL level (Low hazard) *along exposed shorelines*. 'Normal' municipal and other infrastructure should *generally* be located above the +9 m MSL level *along exposed locations*. Along *semi-exposed shorelines* it is recommended that the critical infrastructure *generally* be designed to be located at or above the +8.5 m MSL level, while 'normal' infrastructure should *generally* be located above the +7.5 m MSL level *along semi-exposed shorelines*. *Note, that the actual wave exposure/shelter* *of each shoreline location is duly considered in the detail recommended adaptation options (including "design" levels/elevations) for each site (Chapter 8).* It is to facilitate easy assessment and comparison of vulnerable areas, that just three *contour lines* (5, 8 and 10 m MSL) derived from satellite imagery and *roughly associated with three generalised flooding scenarios* are indicated for each city/town, as discussed in the following section.

6.2.2 Elevation hazard

Using satellite imagery (SRTMv4.1 (90m resolution) and ASTER (30m resolution), but mostly the SRTM because, for example, it has better algorithms to detect the land and sea interface), and (limited) local available topographical data, the positions of the contour lines roughly associated with the three sea water flooding hazard levels were estimated and superimposed onto Google Earth images at each coastal town and city. This allowed for a 1st level identification of the vulnerability of the coastline of Mozambique (Vulnerability parameter # 1 in Table 6.1) and assessment of specifically the current development and infrastructure at each study area (Example for Maputo shown in Figures 6.4a, b and c).

It is reiterated that such results are dependent on the accuracy of the input data, which again underscores the need for good topographic and bathymetric input data if more detailed or accurate results are required. (In other words, the contours are not based on accurate topographical data, and therefore can only give a rough indication of where the accurate contour location is in reality.) It should also be noted, that although the above generalised LOW/MEDIUM/HIGH scenarios are derived from the correct theoretical flooding levels for the different combinations of events, the actual landward extent of the flooded areas would not reach all the way to the +8 m or + 10 m contours in many locations, as "on-land" factors such as the roughness (due to buildings, trees, etc.) will reduce the actual landward extent of the flooded area. (This is not accounted for in most run-up models, including the Nielsen & Hanslow model applied in this project.) In lieu of detailed three-dimensional wave run-up and landward flooding modelling the estimated contour locations give a good but somewhat conservative (i.e. of lower risk) indication of the potential extent of flooded areas. These comments are applicable to all of the study areas.

In Figure 6.4a it can be seen that much of the existing port and adjacent developed areas are located below the estimated + 5 m contour position. Along the sheltered and semi-exposed Maputo shoreline depicted in Figure 6.4a, the safe level for important national infrastructure that is expected to be in operation up to and after the year 2100 is considered to be +8.5 m MSL.

The Costa de Sol and Matola areas are depicted in Figures 6.4 b and c. Note that by their nature ports are located as close to the water as possible and therefore often in lowlying areas. By recommending that ports, as national key infrastructure facilities and with design lifespans extending from 50 to 100 years, be located above the +8.5 m MSL level in Maputo and +10.0 m MSL in Beira, means that, for example the design of the foundation structure and layout should allow for the future heightening of the quays, warfs and adjacent infrastructure.

Figure 6.4a: Estimated contours for <u>Maputo</u>

Figure 6.4b: Estimated contours for <u>Maputo – Costa de Sol</u>

Much of the area near Costa de Sol (formerly wetland and some mangroves) is very low lying and already at considerable risk from coastal flooding (should for example a cyclone approach this area), as it is also exposed to wave run-up effects.

Figure 6.4c: Estimated contours for Maputo / Matola

In Figure 6.4c it can be seen that the main access roads and toll road structures (and some developed areas) are located below the + 5 m contour, while +7 m MSL is considered as the low risk level for important national infrastructure (and a main evacuation/"escape" routes in this instance) in this relatively sheltered area under the scenario of 1m SLR by 2100.

Elevation hazard at the rest of the study sites

Figure 6.5 shows a Google Earth$_{TM}$ image of Beira with the satellite derived estimated positions of the + 5 m,+ 8 m and +10 m contours (to MSL) overlain thereon. From the above points, it can be seen that all areas below the + 5 m contour are already vulnerable to flooding alone resulting from a cyclone coinciding with mean high water spring tides (4.9 m to MSL) as depicted in Figure 6.3. This excludes the additional elevation that could be reached due to wave run-up along the semi-exposed and exposed shoreline locations.

The minimum future elevation to plan for would be about 8 m above MSL (excluding any adaptation measures), which would allow for a combination of a cyclone coinciding with mean high water spring tides (4.9 m MSL), plus 1 m SLR, plus wave runup of 1.5 m. This is applicable to almost the whole Beira shoreline, as most locations are either fully exposed (all "south" facing shorelines), or semi-exposed (western shoreline during cyclone waves approaching obliquely from the south-south-west)

Ideally, for critical infrastructure, the future elevation to plan for, would be 10 m above MSL (excluding any adaptation measures), which would allow for 2 m SLR and a wave runup of 3 m along the exposed SW, S and SE shorelines.

By implication, the map shows that most of Beira is already at extreme flooding risk and that only the high area a few km inland (to the North) would really be at a low riskin future. (Note, this is flooding due to high seawater levels, and not related to river floods resulting from extreme rainfall events.) Where possible, new developments should be located above the 8 m level and ideally, for critical infrastructure, above the 10 m level, again, in the absence of any adaptation measures.

Figure 6.5: Estimated contours for Beira

Figures 6.6 to 6.16 show the results for the rest of the study sites.

Figure 6.6: Estimated contours for Ponto Do Ouro

Ponto Do Ouro is fully exposed to ocean waves, but high tides are lower than most of the Mozambican coast. The intermediate flooding level is +5.9 m MSL, while the extreme flooding scenario is +8.4 m MSL.

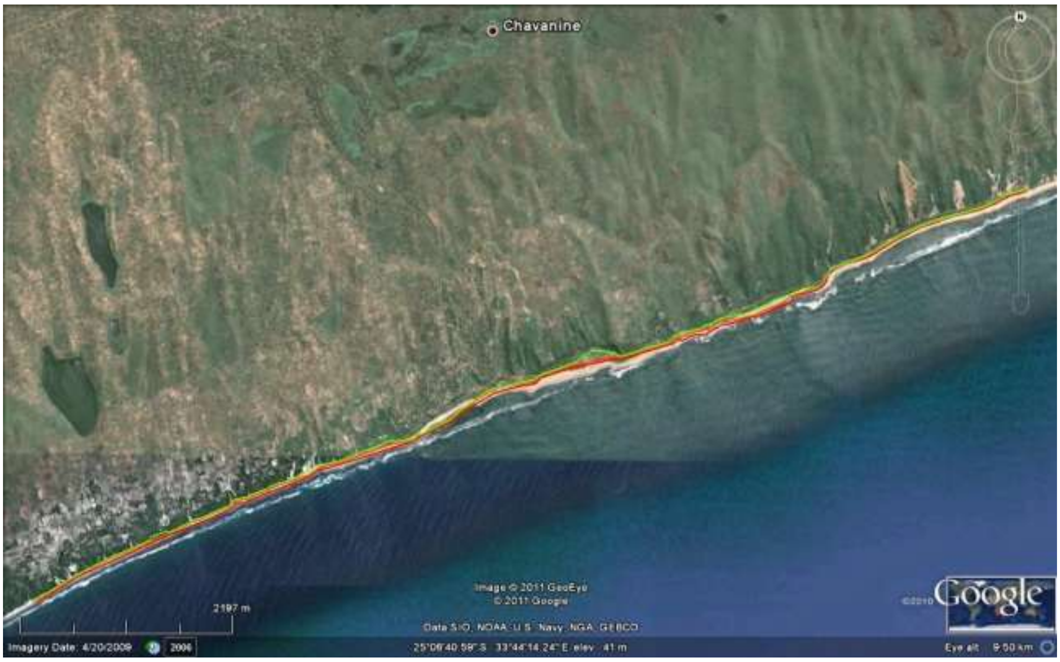


Figure 6.7: Estimated contours for Xai-Xai Beach

Xai-Xai Beach is also fully exposed with relatively lower tides, giving rise to flooding levels of +5.9 m MSL and +8.4 m MSL for the intermediate and extreme flooding scenarios respectively. (The Xai-Xai town centre is located about 10 km inland from the shore, in a north-westerly direction from the coastal area shown in Figure 6.7. Therefore the town itself is not vulnerable to hazards from the sea, other than cyclone winds and possibly flooding from rainfall.)

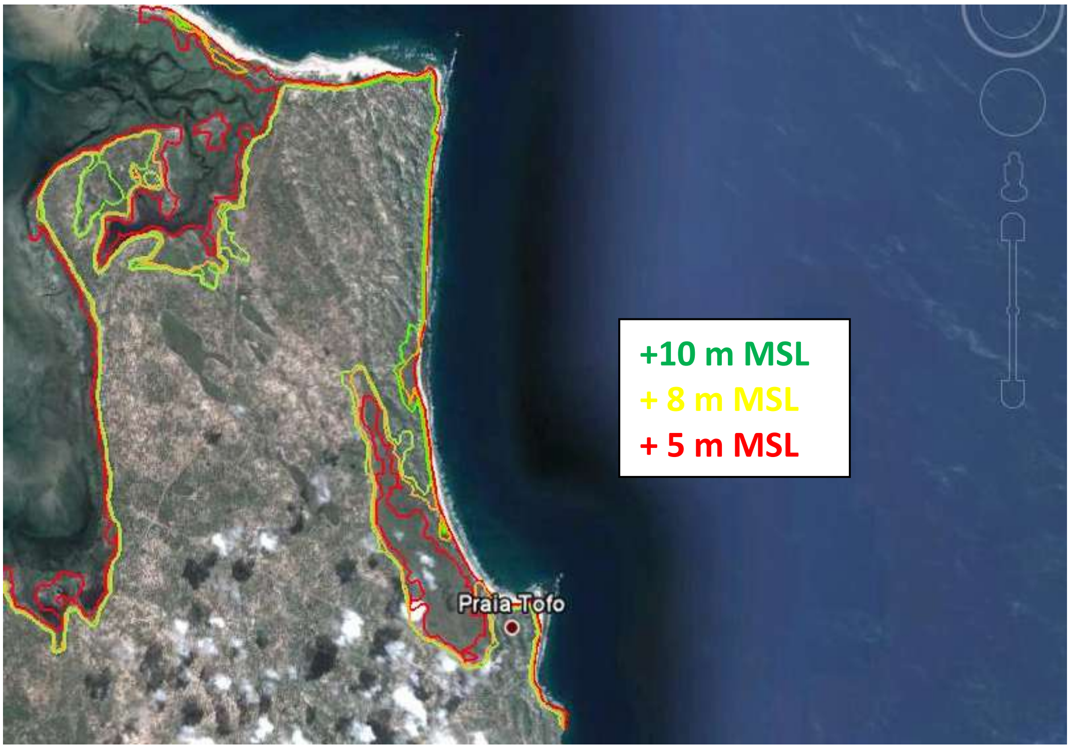


Figure 6.8: Estimated contours for Tofo / Barra (overlain on Google Earth image)

Most of the Tofo area is fully exposed (Figure 6.8). The northern shore at Barra is generally less exposed to wave action, but this area is directly exposed to cyclone waves approaching from the NE. Thus, flooding levels of +6.4 m MSL and +8.9 m MSL are applicable for the intermediate and extreme flooding scenarios respectively. The coastal topography is relatively steep with high ground relatively close to the sea, expect for two extensive low-lying wetland areas which are susceptible to flooding from the sea.

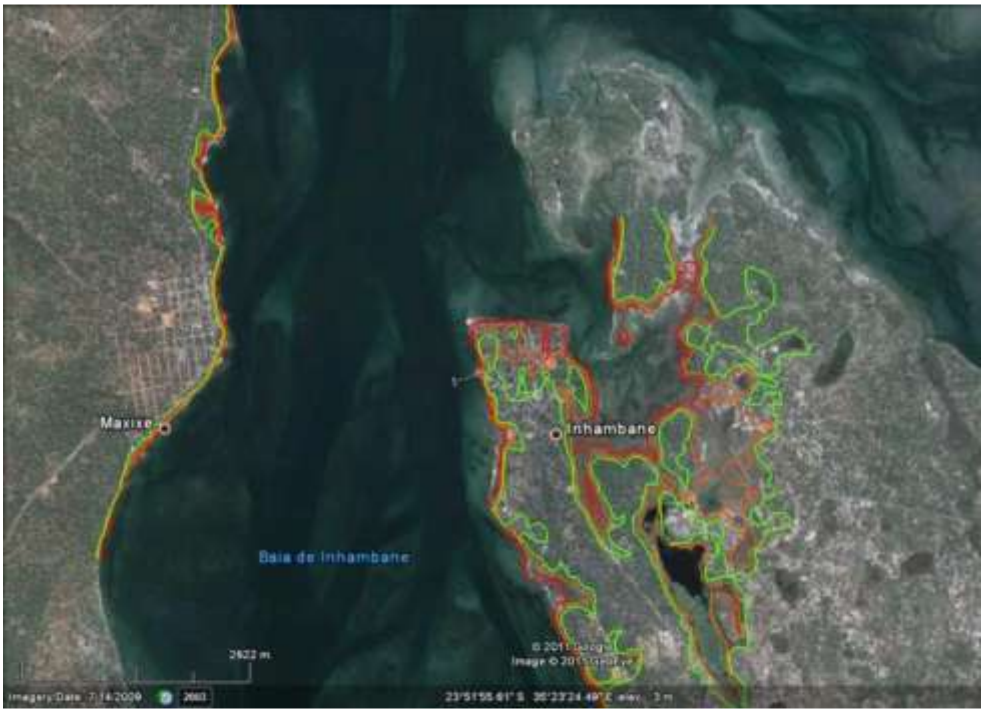


Figure 6.9: Estimated contours for Maxixe; Inhambane

The Maxixe and Inhambane shorelines are only semi-exposed to cyclone waves (approaching from the NE). Thus, wave run-up is not expected to exceed about 1.5 m. The intermediate flooding hazard level of +5.9 m MSL is mostly applicable. Critical infrastructure (100 year planning horizon) should only allow for an additional 1 m of SLR (i.e. 2 m SLR in total) by 2100, thus giving a “design” level of +6.9 m MSL.

Figure 6.10: Estimated contours for Vilankulos

Despite some shallow sandbanks and a small island to the east, Vilankulos is relatively exposed (to cyclones from the east), with flooding levels of 6.4 m and 8.9 m MSL for intermediate and extreme flooding scenarios respectively.

Figure 6.11: Estimated contours for Quelimane

Quelimane is located inland and is not exposed to wave effects. From a coastal/marine flooding perspective alone (i.e. not considering river floods), the intermediate flooding level is the same as the low flooding level at +5.1 m MSL. Only critical infrastructure need consider the extreme scenario of 2 m SLR by 2100, thus giving a flooding level of +6.1 m MSL.

Figure 6.12: Estimated contours for Ilha De Mozambique

While Ilha De Mozambique is semi protected by some islands, it is exposed to specific cyclone wave approach directions. This island is very narrow, and flood wash-over from the seaward side is possible in the low lying areas during extreme events. Thus, flooding levels of 6.3 m and 8.8 m MSL for intermediate and extreme flooding scenarios are respectively applicable to the whole island.

Figure 6.13: Estimated contours for Nacala port area

Figure 6.14: Estimated contours for Nacala bay area

Most of the Nacala and Minguri shoreline is relatively well sheltered from the open sea (Figure 6.14). Only very limited ocean wave penetration into the bay is possible from the north, while only moderate local wave generation inside the bay is possible due to the limited fetch (e.g. resulting from cyclone winds over the bay). The "sea water flooding hazard" levels for the bay shorelines of Nacala and Minguri (Figure 6.14) show that for a 1m sea level rise (by 2100) plus spring high tides and limited local raising of water levels (through barometrics and wind), that areas below the +6.3 m contour will be in danger of being flooded. The intermediate flooding level of +6.5 m MSL (rounded up from +6.3 m MSL) is appropriate for planning and management of infrastructure along the bay shoreline with a design life of less than 50 years. Taking a conservative and precautionary approach, the extreme scenario of 2 m SLR by 2100 should be considered for critical infrastructure. Thus, the safe hazard level for important infrastructure inside the bay such as the port (Figure 6.13) and airport with a design life of more than 50 years is +7.5 m MSL. As for Maputo and Beira ports, this recommendation should not be interpreted as meaning that the port should be relocated to landward of the +7.5 m MSL contour lines, which would render it inoperable. The recommendation is for the Nacala port infrastructure to be upgraded to deal with CC risks in its present location, including raising the infrastructure in stages, eventually to above the level of +7.5 m MSL in this case.

Only the shoreline outside of the bay (to the north of Fernao Veloso, Figure 6.14) is relatively exposed to cyclone waves approaching from the north-east or north. Here, the intermediate flooding level of +8 m MSL is appropriate for planning and management of infrastructure with a design life of less than 50 years (allowing for the scenario of a +1 m sea level rise along with a 1.5 m storm run-up level during cyclones).

Figure 6.15: Estimated contours for Pemba

Figure 6.16: Estimated contours for Pemba port area

The eastern and northern shores of Pemba outside of the bay (Figure 6.15) are exposed to cyclone waves approaching from the north-east or north. Along these more exposed shores outside of Pemba Bay, the intermediate safety hazard level of +9 m MSL is appropriate for planning and management of infrastructure with a design life of less than 50 years (allowing for the scenario of a +1 m sea level rise along with a 3 m storm run-up level during cyclones.)

On first impression it may seem that the Bay shoreline is well sheltered from wave action. However, of importance is that, due to the large expanse of water in Pemba Bay (i.e. relatively large wind fetch), the Pemba peninsula provides only partial protection from cyclonic forces (waves and sea water flooding) when a cyclone moves inland across Pemba. This has implications for the design of coastal protection around the port and the shoreline around the whole bay in that significant local water level set-ups and local wave run-up can occur. The informal settlements in the Porto Amelia area (Figure 6.16) are very low-lying, much of it located between the normal high tide line and less than 5 m above MSL. This area is particularly vulnerable to flooding from the sea. The “sea water flooding hazard” levels for locations inside Pemba Bay (Figure 6.15) show that for a 1m sea level rise (by 2100) plus a run-up of +1.5 m during cyclonic events, that areas below the +8 m contour will be in danger of being flooded. This intermediate flooding level of +8 m MSL is appropriate for planning and management of infrastructure along the bay shoreline with a design life of less than 50 years. However, taking a conservative and precautionary approach, the extreme scenario of 2 m SLR by 2100 should be considered. Thus, the safe hazard level for important infrastructure inside the bay with a design life of more than 50 years such as the port is +9 m MSL (Figure 6.16).

Conclusion on the elevation hazard

The **overall conclusion** is that the Mozambican coastal zone has much low-lying infrastructure. This poses a major risk because of expected climate change impacts. The question may be raised whether the risk of damage to key coastal areas suddenly increases above a certain sea level? Based on the assessment of the drivers, hazards and impacts (Chapter 5), it is expected that there will be a progressive increase in risk, but no specific tipping point. However, the consequences of the impacts are expected to increase exponentially. The situation is serious, but not impossible to correct if action is taken timeously (the sooner the better), as discussed in Chapters 7 and 8.

It is reiterated that the results in terms of the maps indicating potential flooded areas, are dependent on the accuracy of the input data, which underscores the need for good topographic input data if more detailed or accurate results are required. It should also be noted, that although the flooding scenarios are derived from the correct theoretical flooding levels for the different combinations of events, the actual landward extent of the flooded areas would not reach all the way to the derived levels in many locations, as “on-land” factors such as the roughness (due to buildings, trees, etc.) will reduce the actual landward extent of the flooded area. In lieu of detailed three-dimensional wave run-up and landward flooding modelling the estimated contour locations give a good but somewhat conservative (i.e. of lower risk) indication of the potential extent of flooded areas.

6.3 COARSE VULNERABILITY ASSESSMENT FOR WHOLE MOZAMBICAN COAST

A relatively coarse level of assessment, based on a sub-set of hazard drivers and vulnerability modification factors, is provided for the entire Mozambican coastline. Nine of the 14 hazard drivers and vulnerability modification factors were selected from the ideal set of 14 indicators identified in Section 6.1.2, due to the fact that data could only be obtained on a country wide basis for the the particular nine parameters. Despite this shortcoming, the coarse hazard assessment is still useful in comparing vulnerability on a more regional level, and does give a coarse indication of how some important hazards are spatially distributed. (The full set of 14 parameters/indicators was used in the detail assessments described in Section 6.4.)

Spatial data were collated and incorporated in the following nine GIS layers:

- Topographic elevation
- Distance to urban infrastructure
- Geology
- Geomorphology
- Land cover
- Tidal range
- Maximum offshore wave height (NCEP)
- Erosion – accretion
- Cyclone (occurrence inversely weighted by distance from shore)

Examples of the coarse spatial input data and derived hazard/vulnerability classification mapping for most of these parameters are given below.

An overview of the baseline typology mapping of Mozambican geology (http://139.191.1.96/projects/soter/index.htm (Souirji, 1997) is presented in Figure 6.17.

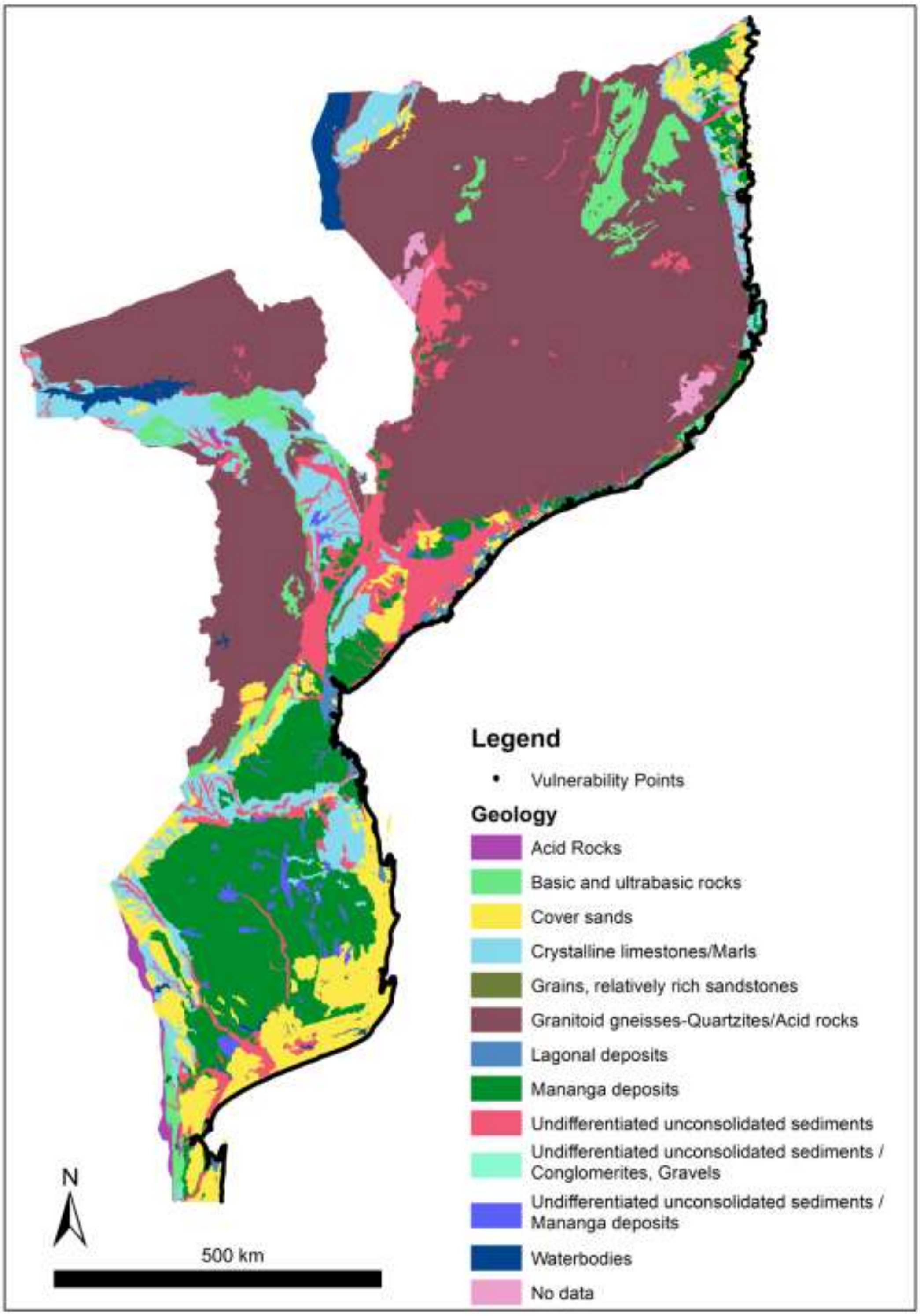


Figure 6.17: Baseline typology mapping of Mozambican geology

The type of geology of the coastal areas (i.t.o. rock hardness or sediment coarseness), gives a good indication of underlying resistance to coastal erosion or "erodability". A map of the resultant geologic vulnerability classification from 1 (very low vulnerability) to 5 (very high vulnerability) is indicated in Figure 6.18.

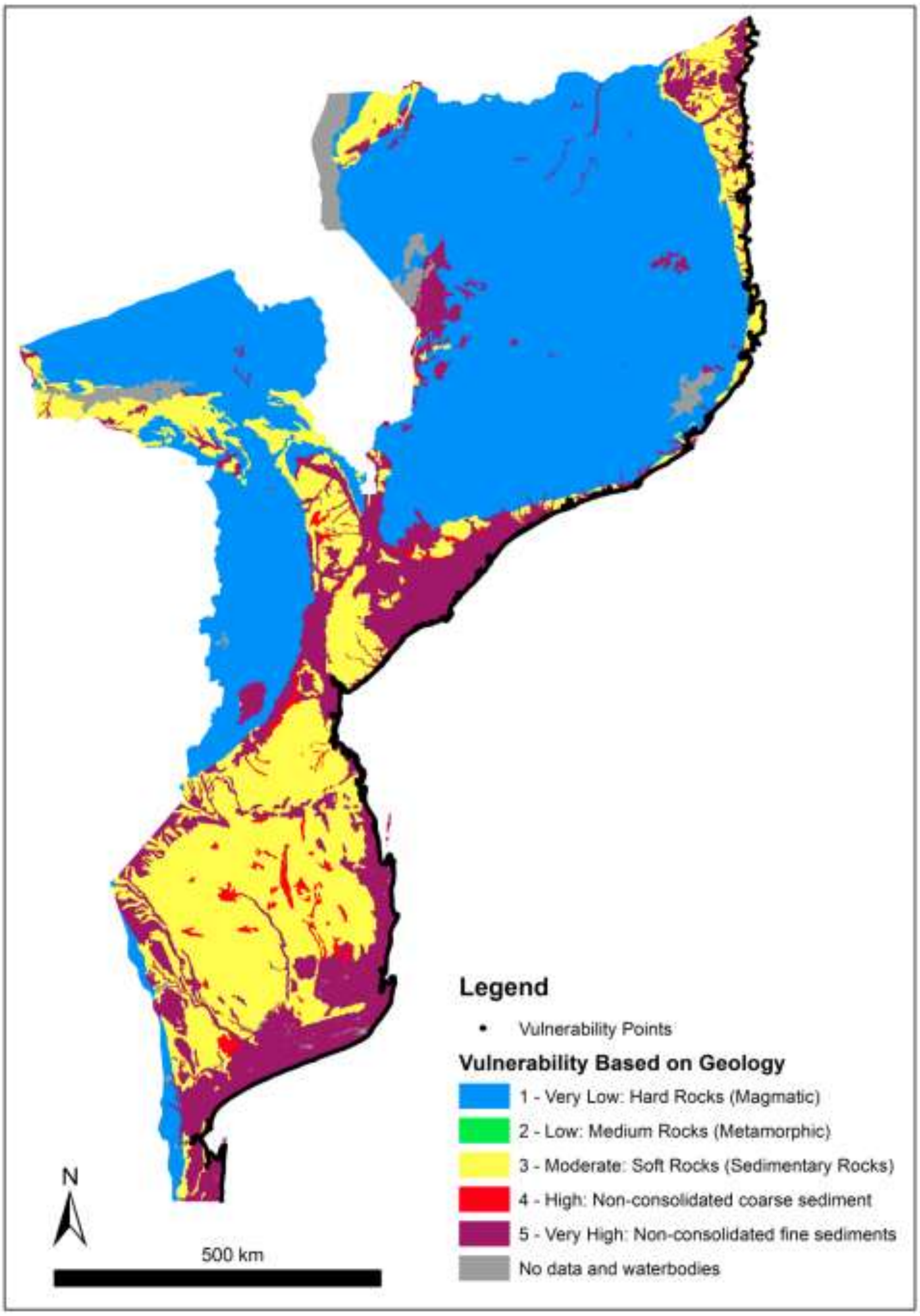


Figure 6.18: Vulnerability mapping based on geologic classification

An overview of the baseline typology mapping of Mozambican geomorphology is presented in Figure 6.19.

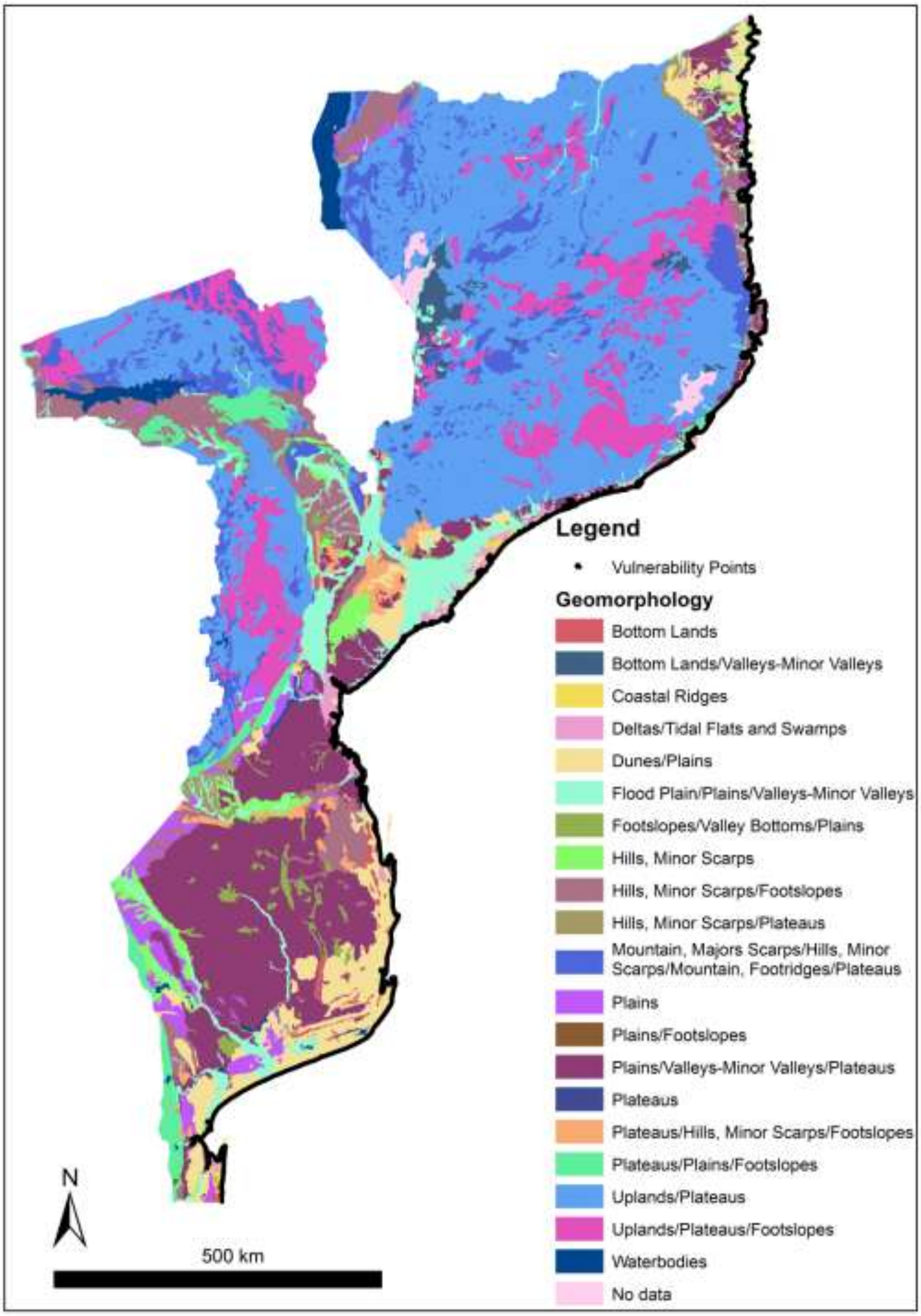


Figure 6.19: Baseline typology mapping of Mozambican geomorphology

The geomorphologic characteristics of the coastal areas (e.g. rocky cliffs or exposed beaches), similarly give a good indication of underlying resistance to coastal erosion or "erodability". A map of the resultant geomorphologic vulnerability classification from 1 (very low vulnerability) to 5 (very high vulnerability) is indicated in Figure 6.20.

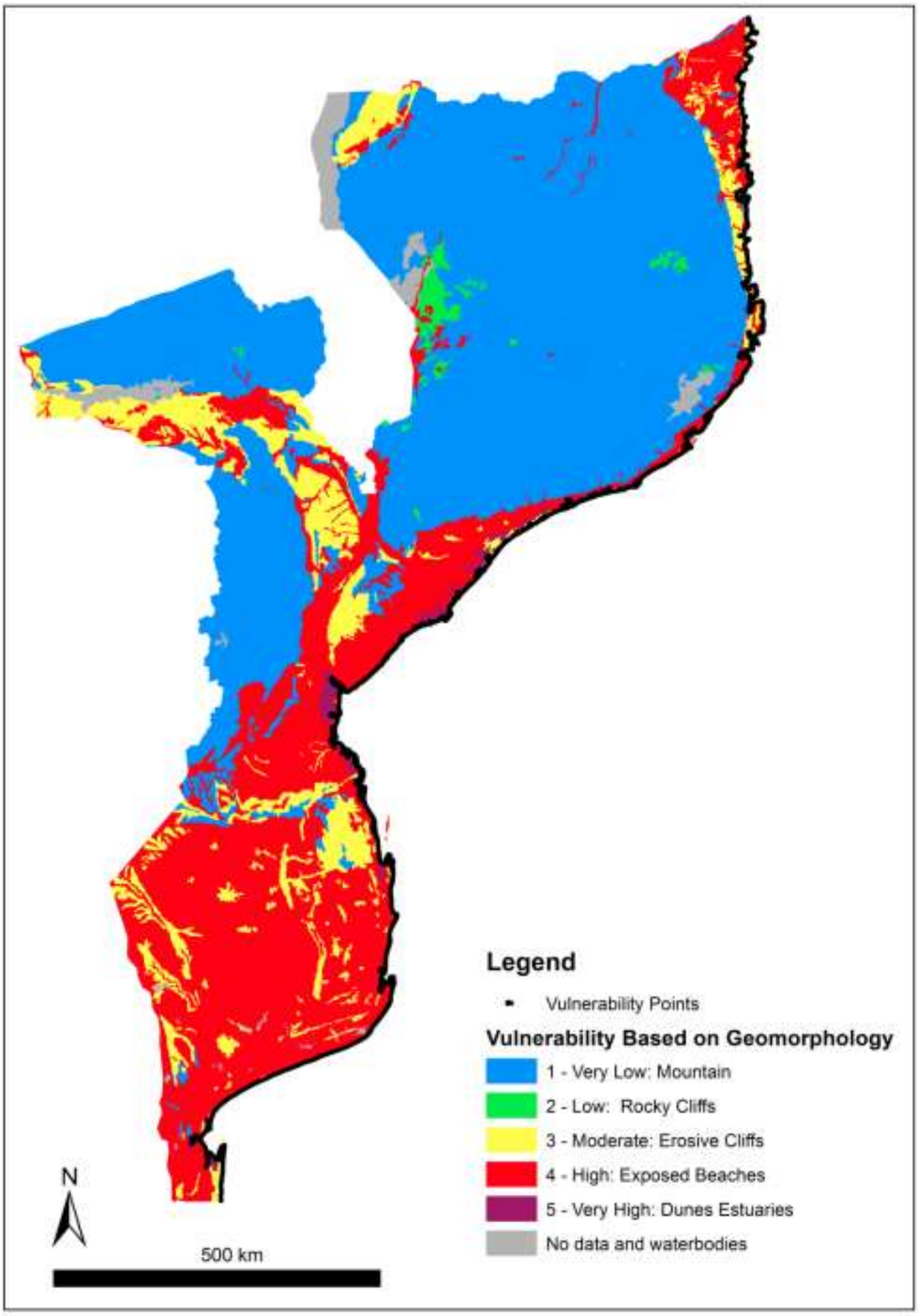


Figure 6.20: Vulnerability mapping based on geomorphologic classification

A coarse overview of hazards and vulnerability of Mozambican coast is summarised in Figure 6.21, in terms of tidal range, offshore wave height, cyclone threat (i.t.o. occurrence, category and inversely weighted by distance from shore), and elevation vulnerability.

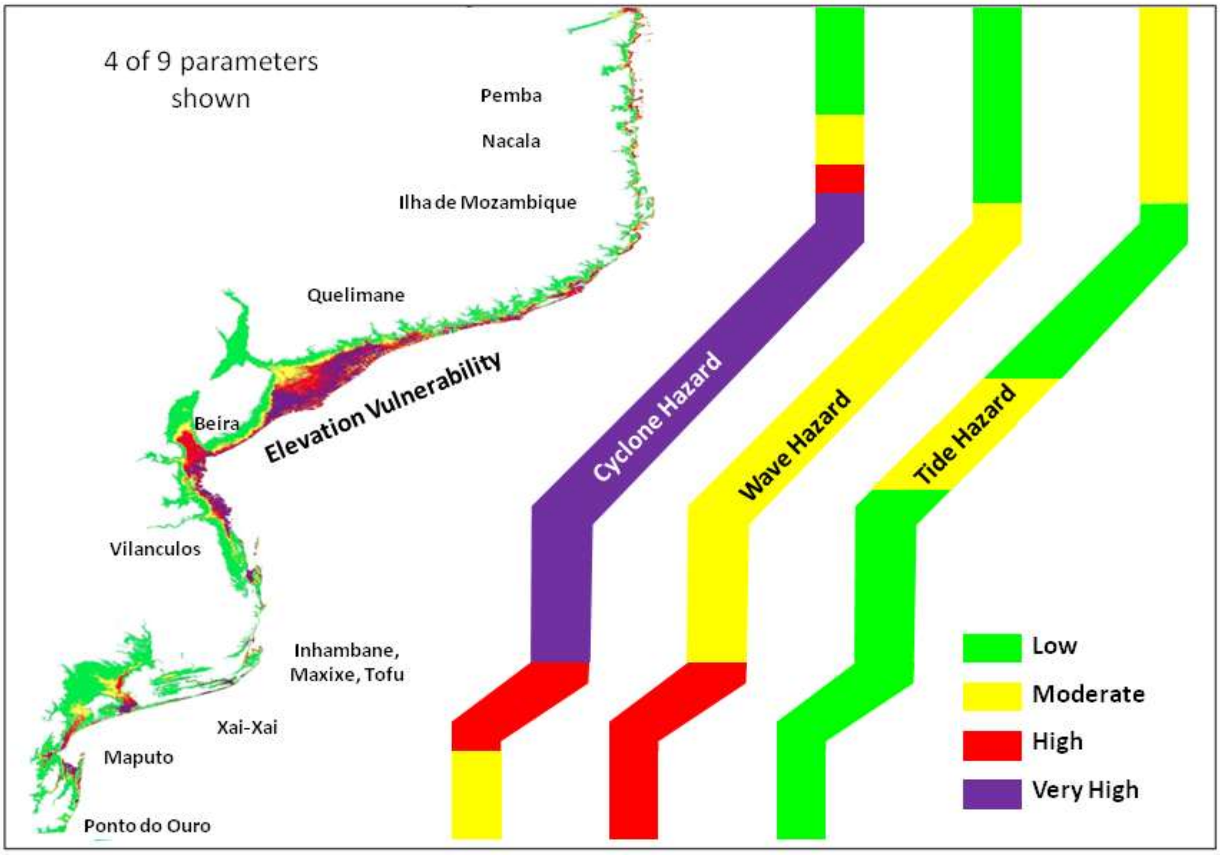


Figure 6.21: Coarse overview of hazards and vulnerability of Mozambican coast

Conclusion on the hazard and vulnerability of the whole coastline

Broadly speaking, the low lying central delta coast areas (e.g. Beira) are very vulnerable in terms of elevation. The highest occurrence of cyclones (very high hazard) is found along the central parts of Mozambique, tapering off to the south (from roughly Tofo) and also sharply to the north (from about Ilha de Mocambique). In terms of wave height, based on the NCEP data and excluding cyclones, the hazard increases slightly from north to south, with most of the coast subject to moderate offshore wave attack. Due to the particular bathymetry off Mozambique and (amongst others) the location of tidal nodes, the northern coast (e.g. Nacala and Pemba) as well as parts of the central coast (e.g. Beira) face the highest tidal hazard (note that the hazard here is still rated as moderate relative to coastlines in some other parts of the world where tidal extremes are much higher).

Although the coarse hazard assessment is useful in comparing vulnerability on a more regional level, and does give a coarse indication of how some important hazards are spatially distributed, a much more detailed assessment is required to identify appropriate adaptation measures at the local level, as described in Section 6.4.

6.4 DETAIL VULNERABILITY ASSESSMENT FOR SELECTED COASTAL TOWNS AND CITIES

6.4.1 Application of the Coastal Hazard Assessment Method

A relatively coarse level of assessment for the Mozambican coastline, is provided in the previous section. A more detailed level of assessment, based on a comprehensive set of hazard drivers and vulnerability modification factors, and focussing on better quantification of the primary hazards is also given for selected areas. The focus is on the abiotic physical coastal aspects which include factors linked to climate change.

Coastal points were defined along the whole Mozambican coast at 1 km intervals as indicated in the Maputo example area in Figure 6.22 below. The results of all the coastal risk assessments were determined at each of about 10 points (i.e. 10 km) at each of the study sites.

Figure 6.22: Maputo example - Location of Coastal Points (1 km intervals)

Based on the coastal hazard/risk evaluation method as described in Section 6.1, a coastal vulnerability assessment was conducted for each of the study sites. Data were obtained or derived for each of the 14 parameters at each of the coastal points. Important inputs were gleaned from low elevation aerial reconnaissance of the entire Mozambican coast (May 2010) and complemented by a site investigation of 10 sites.

These observations and inspections were conducted to assess local coastal processes, site characteristics, coastal vulnerability, existing protection/adaptation methods and were used to derive appropriate response options. Other inputs were collated from remote sensing data and GIS layers and information made available through the Mozambican colleagues on the project team.

The input data values were then scored according to the vulnerability classification for each parameter as defined in Table 6.1. An example of the scoring for the Ponto Do Ouro study area for Scenario A1, for example, is show in Table 6.2.The individual scores were then added and normalised to calculate the overall vulnerability score or rating for each coastal point.

Table 6.2 : Example of vulnerability scoring (1 to 5 - very high) for Ponto Do Ouro

Indicator	Location: Ponto Do Ouro & Shoreline location reference number								
	4237	4236	4235	4234	4233	4232	4231	4230	4229
#1: TE: Elevation	3	3	4	5	4	4	4	4	4
#2: DS: Distance (e.g. infrastructure) to shore	1	2	3	4	3	3	3	3	1
#3: TR: Tidal range	3	3	3	3	3	3	3	3	3
#4: WH: Max wave height	5	5	5	5	5	5	5	5	5
#5: EA: Erosion / accretion rate	2	2	2	2	2	2	2	2	2
#6: GL: Geology	5	5	5	5	5	5	5	5	5
#7: GM: Geomorphology	5	5	4	4	4	4	4	4	4
#8: GC: Ground Cover	1	1	5	5	4	1	1	1	1
#9 AA: Anthropogenic Actions	4	4	4	5	4	4	4	4	4
#10 Degree of protection from prevailing wave energy.	5	5	3	4	5	5	5	5	3
#11 Cyclones	2	2	2	2	2	2	2	2	2
#12 Sea-level rise Bruun erosion potential	3	3	3	4	4	3	3	3	4
#13 Corals/fringing reefs	1	1	1	1	1	1	1	3	5
#14 Relative height of the protective foredune buffer (i.e. the available sand reservoir).	1	1	3	4	3	3	2	2	2

Note, the above scoring example is for a specific scenario, namely "Scenario A1". The different scenarios are discussed in the following section.

6.4.2 Scenarios assessed for coastal vulnerability

Detail vulnerability assessments for 12 coastal towns were conducted for 16 different hazard scenarios. Based on the SLR projections (Section 5.3) and hazard assessment and analyses, four levels of SLR were considered, namely 0 m, 0.5 m, 1 m and 2 m. As cyclones are such a major hazard along the Mozambique coast, the assessments were conducted both with and without taking cyclones into account. Other than SLR, the effects of climate change were also assessed by both including and excluding increases in "storminess" (i.e. wave height increase leading to increased wave attack). The total number of scenario combinations thus assessed comes to 16, as summarised in Table 6.3.

Table 6.3: Summary of scenarios assessed for coastal vulnerability

#			Excluding cyclones		Including cyclones	
			Present wave climate	Increased storminess	Present wave climate	Increased storminess
			1	2	3	4
No Climate Change:		**A**	Present wave climate	Present wave climate	Present wave climate	Present wave climate
Climate change included	SLR = 0.5 m	**B**	Present wave climate	Increased storminess	Present wave climate	**Increased storminess**
	SLR = 1.0 m	**C**	Present wave climate	Increased storminess	Present wave climate	**Increased storminess**
	SLR = 2.0 m	**D**	Present wave climate	Increased storminess	Present wave climate	**Increased storminess**
Note:	*1 Scenario A1 is the same as A2, therefore no A2 Scenario is included in the scoring* *2 Scenario A3 is the same as A4, therefore no A4 Scenario is included in the scoring*					

The potential effect of each scenario combination (e.g. D4: SLR = 2 m; increased storminess; including cyclone hazard) was assessed on each of the 14 vulnerability indicators at each shoreline location (assessment) point. To account for each different scenario, the scoring for each vulnerability indicator was changed (e.g. vulnerability score increases by 1 for a particular scenario) or the weighting for that indicator changed (increased). Thus, appropriate weightings were also applied to the scoring to account for those parameters which have a (progressively) greater influence on the vulnerability as the scenarios change. The scores or weightings for specifically Vulnerability Indicators # 1, 2, 4, 5, 10 and 13 (Table 6.1) were therefore consistently adapted to properly account for each different scenario.

For example, as the sea level rises, both elevation and distance from the sea (Indicators #1 and #2 in Table 6.1) decrease relatively. Thus, the vulnerability in terms of these 2 indicators increases with each higher SLR scenario. (Specifically, for all C Scenarios, i.e. SLR = 1 m, the scores for Indicators #1 and #2 are double weighted; while for all D Scenarios, i.e. SLR = 2 m, the scores for Indicators #1 and #2 are triple weighted.) Increased storminess has a direct effect on vulnerability to waves (Indicator #4 in Table 6.1). (Therefore, specifically, for Scenarios B2, C2, D2, B4, C4 and D4, i.e. increased storminess, the individual location scores for Indicator #4 are increased by one vulnerability class (= 1 point)).

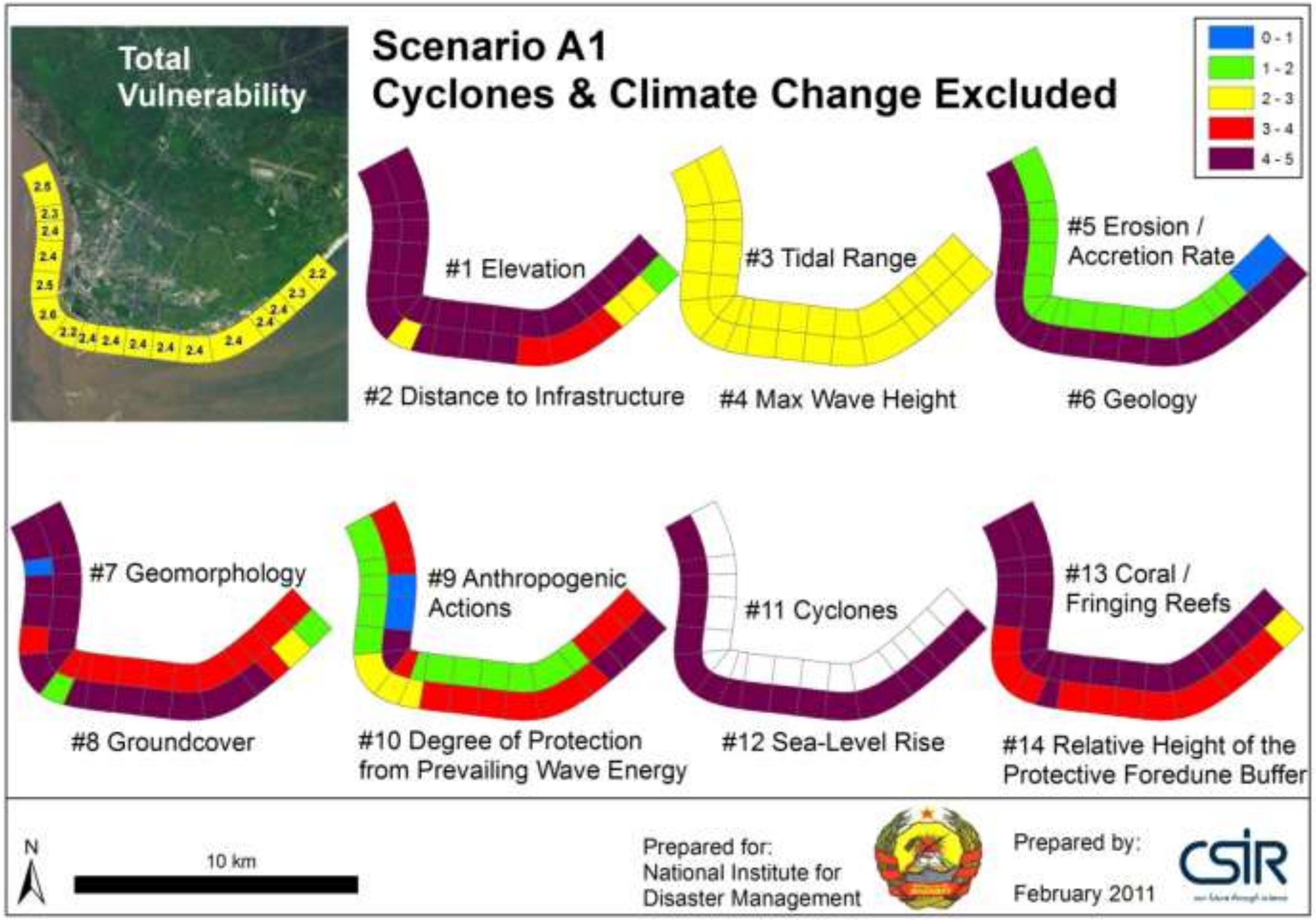
Cyclones mostly approach from some easterly direction, within a very wide range of approach directions. In addition, due to their “circular” wind fields, the largest incident waves can approach the shoreline from a very wide range of directions. Thus, while a specific location may be relatively sheltered from say long period ocean swells approaching from the south-east, waves generated by a cyclone could approach from, e.g. the north-east, to which this particular location might have much less shelter due to the specific shoreline configuration in this area. The occurrence of cyclones therefore reduces the degree of protection (Indicator #10 in Table 6.1) of many particular coastal locations. (For example, under all Scenarios 1 and 2, a particular coastal location may be partially sheltered from the usual deep sea swell approaching from the south-east and according to the evaluation criteria awarded a vulnerability score of 3 for Indicator #10. Under all Scenarios 3 and 4, i.e. including cyclones, this particular coastal location may be fully exposed to cyclone generated waves approaching from the north-east and now awarded a vulnerability score of 5 for Indicator #10.)

These examples are given to illustrate how each of the 14 vulnerability indicators was assessed in terms of potential effects of the 16 different scenario combinations. In general, the vulnerability of coastal locations increase as the scenarios "increase" from A to D and # 1 to # 4 in Table 6.3, resulting in Scenario D4 being the "worst case" scenario. The effects of the different scenarios on the vulnerability ratings at each location can be seen in the vulnerability maps discussed in the following section.

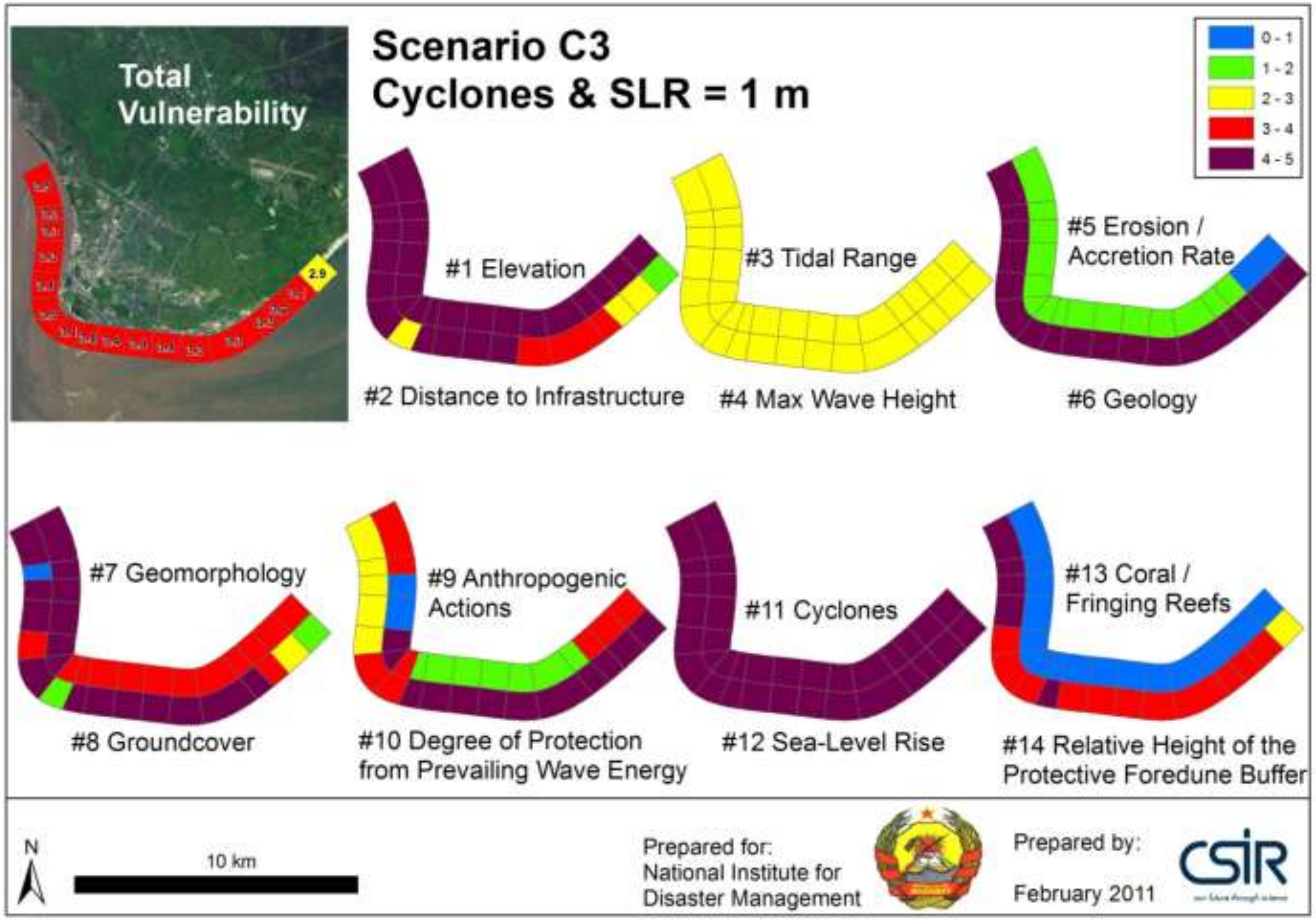
6.4.3 Mapping of detail vulnerability assessment outputs

The vulnerability scores for each parameter at each coastal point (representative of a 1 km section) along the Beira study area, for example, is summarised in the map depicted in Figure 6.23. The vulnerability at each point is indicated by the colour code, ranging from blue "very low" (score in 0 to 1 band), to purple "very high" (score in 4 to 5 band), as indicated by the legend. The examples are shown for 3 of the 16 scenarios assessed.

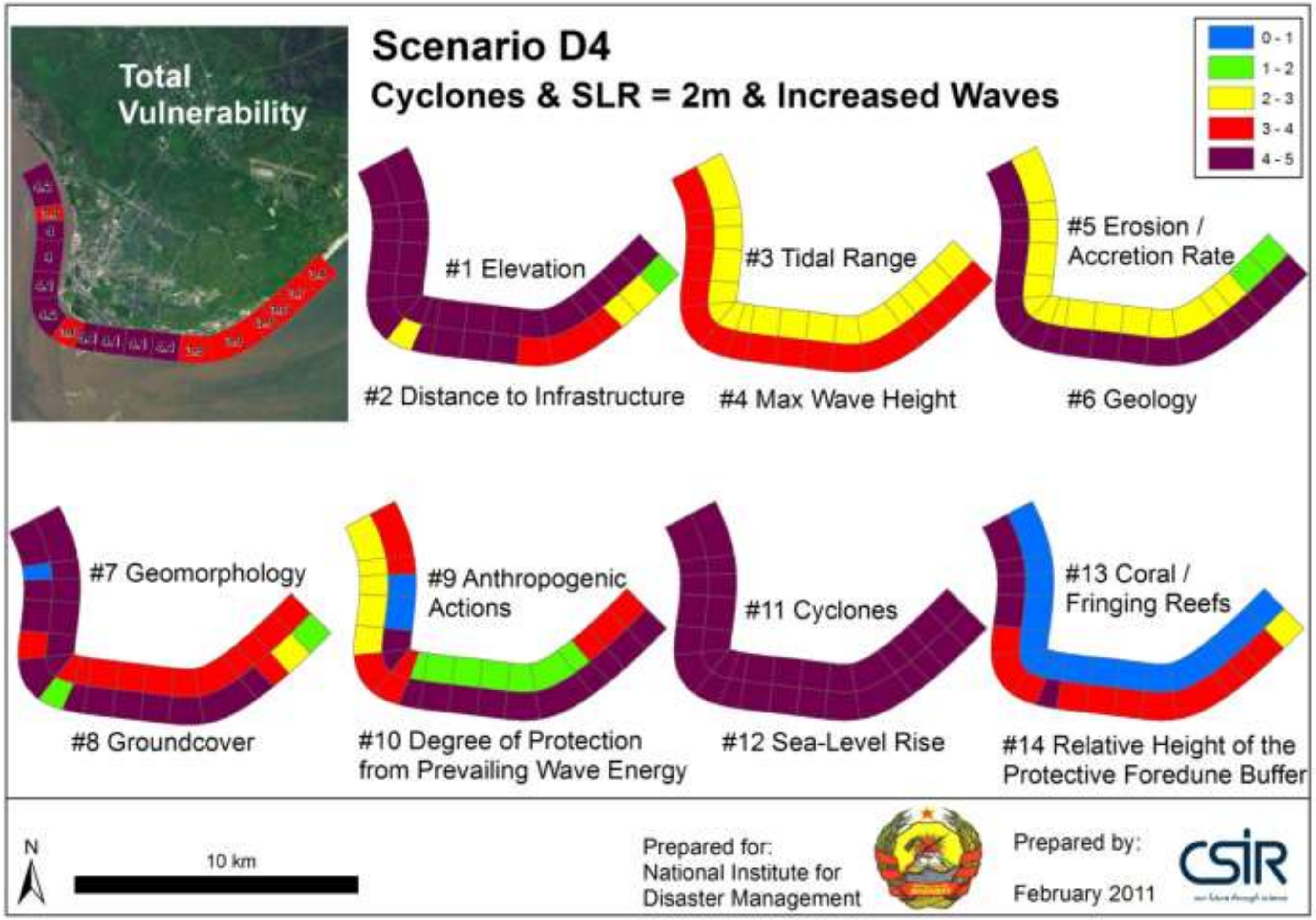
The total or overall vulnerability scores (all parameters combined) at each point (representative of a 1 km coastal section) along the study area, for each of the 16 scenarios, is summarised in the maps depicted in Figure 6.24. The vulnerability at each point is again indicated by the colour code, ranging from blue "very low" (score in 0 to 1 band), to purple "very high" (score in 4 to 5 band), as indicated by the legend. Besides the differences in vulnerability due to the different scenarios, it is concerning to note that almost all of the points are rated as having between medium (for Scenarios A1 to B4) to some very high vulnerability (for Scenarios D3 and D4).


Total Vulnerability
2.5
2.3
2.4
2.4
2.5
2.6
2.2
2.4
2.4
2.4
2.4
2.4
2.4
2.4
2.4
2.3
2.2
Scenario A1
Cyclones & Climate Change Excluded
0 - 1
1 - 2
2 - 3
3 - 4
4 - 5
#1 Elevation
#2 Distance to Infrastructure
#3 Tidal Range
#4 Max Wave Height
#5 Erosion / Accretion Rate
#6 Geology
#7 Geomorphology
#8 Groundcover
#9 Anthropogenic Actions
#10 Degree of Protection from Prevailing Wave Energy
#11 Cyclones
#12 Sea-Level Rise
#13 Coral / Fringing Reefs
#14 Relative Height of the Protective Foredune Buffer
N
10 km
Prepared for:
National Institute for
Disaster Management
Prepared by:
February 2011
CSIR

(a)


Total Vulnerability
2.9
Scenario C3
Cyclones & SLR = 1 m
0 - 1
1 - 2
2 - 3
3 - 4
4 - 5
#1 Elevation
#2 Distance to Infrastructure
#3 Tidal Range
#4 Max Wave Height
#5 Erosion / Accretion Rate
#6 Geology
#7 Geomorphology
#8 Groundcover
#9 Anthropogenic Actions
#10 Degree of Protection from Prevailing Wave Energy
#11 Cyclones
#12 Sea-Level Rise
#13 Coral / Fringing Reefs
#14 Relative Height of the Protective Foredune Buffer
N
10 km
Prepared for:
National Institute for
Disaster Management
Prepared by:
February 2011
CSIR

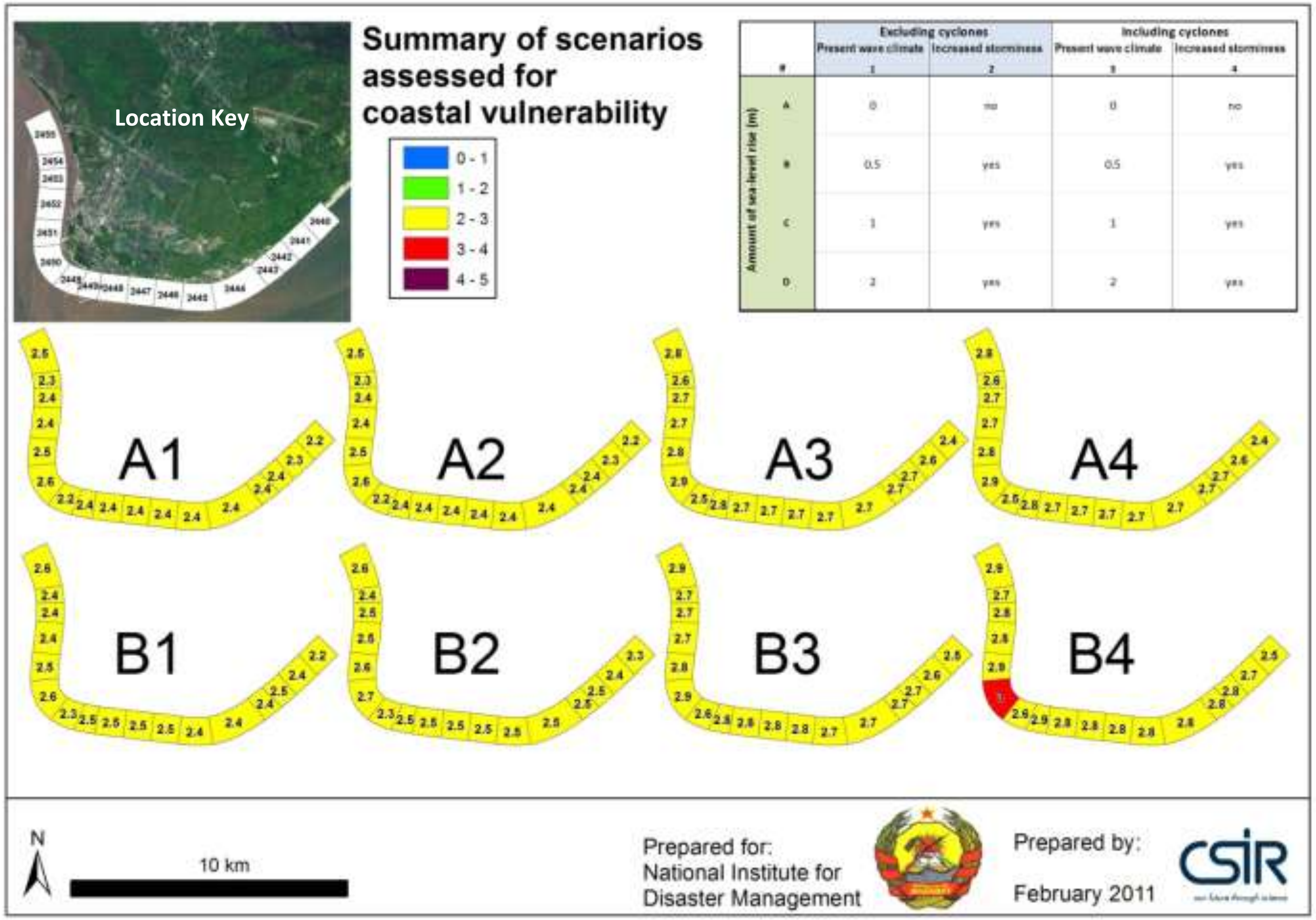
(b)



(c)

Figure 6.23 a to c: Beira vulnerability mapping showing all 14 parameters for 3 of the 16 scenarios.

(Vulnerability is measured on a scale of 1- 5 with 1= lowest vulnerability and 5 = highest vulnerability as depicted in Table 6.1))



	#	Excluding cyclones Present wave climate 1	 Increased storminess 2	Including cyclones Present wave climate 3	 Increased storminess 4
Amount of sea-level rise (m)	A	0	no	0	no
	B	0.5	yes	0.5	yes
	C	1	yes	1	yes
	D	2	yes	2	yes

Figure 6.24a: Beira detail vulnerability mapping: Scenarios A & B
(showing overall vulnerability rating when the 14 parameters in Table 6.1 are combined).

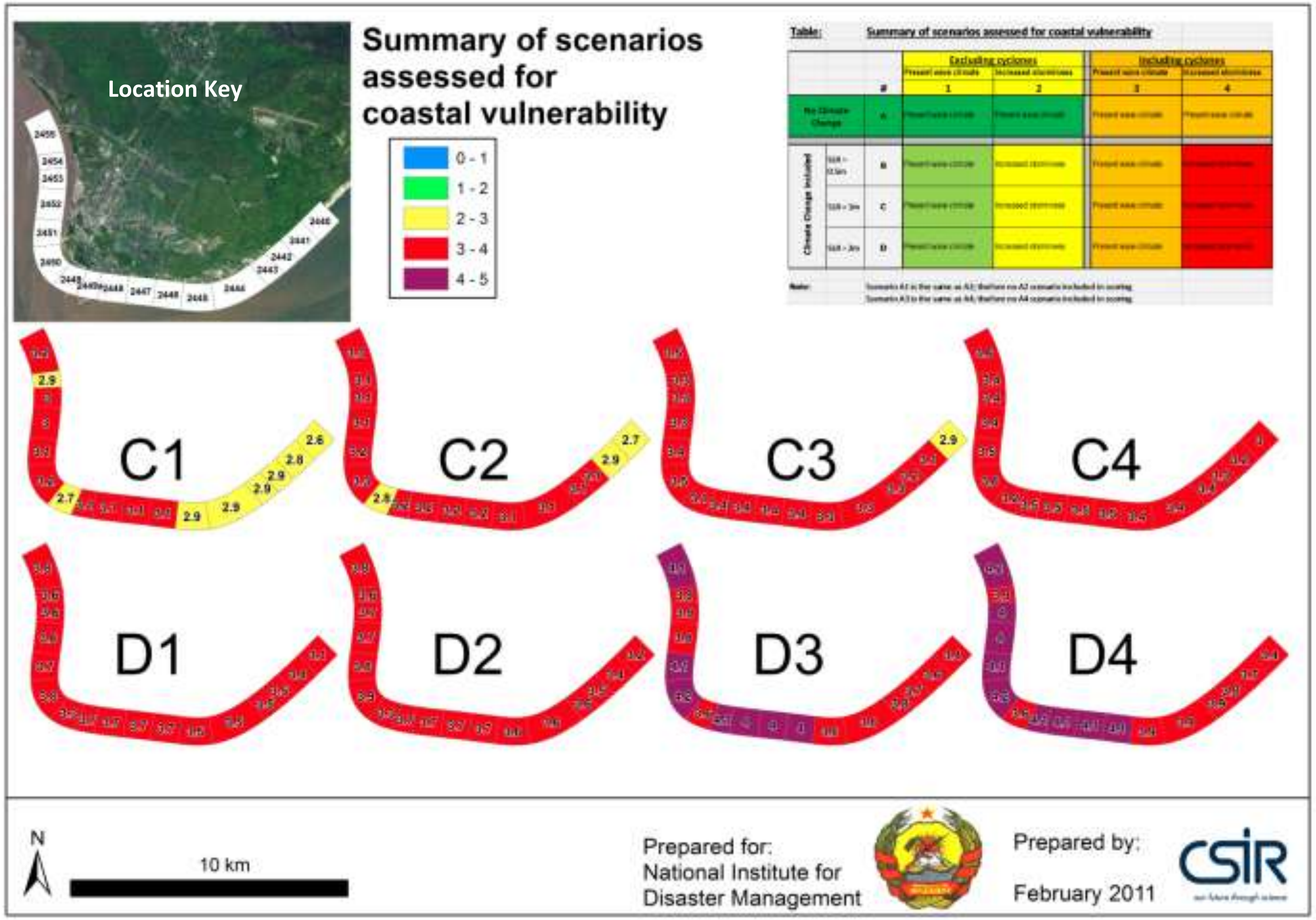


Figure 6.24b: Beira detail vulnerability mapping: Scenarios C & D
(showing overall vulnerability rating when the 14 parameters in Table 6.1 are combined).

Similar total vulnerability maps for each of the other study sites, for the 8 scenarios that include cyclones (i.e. C1 to D4), are summarised in the maps depicted below in Figures 6.25 to 6.34.

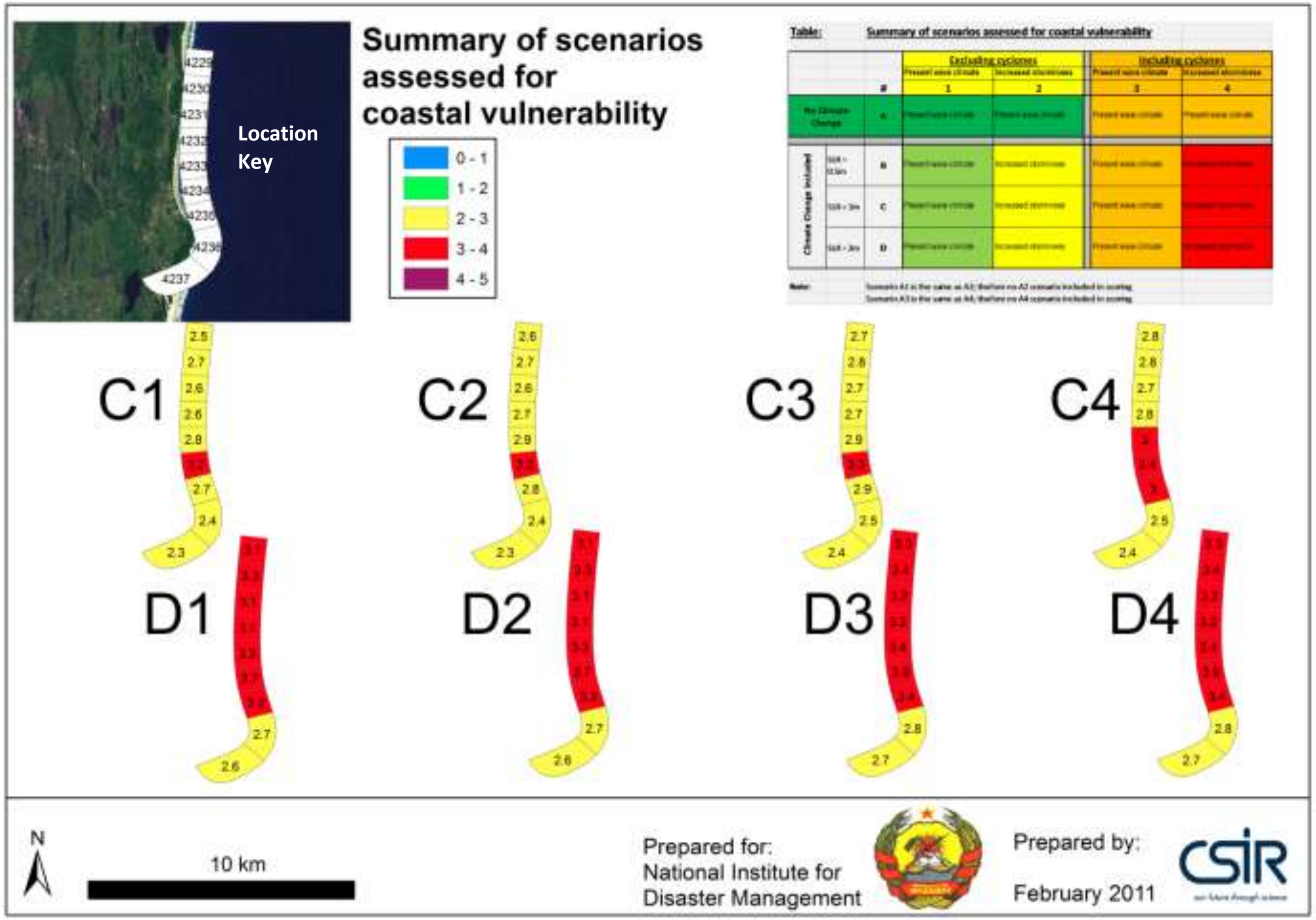


Figure 6.25: Ponto Do Ouro detail vulnerability mapping: Scenarios C & D

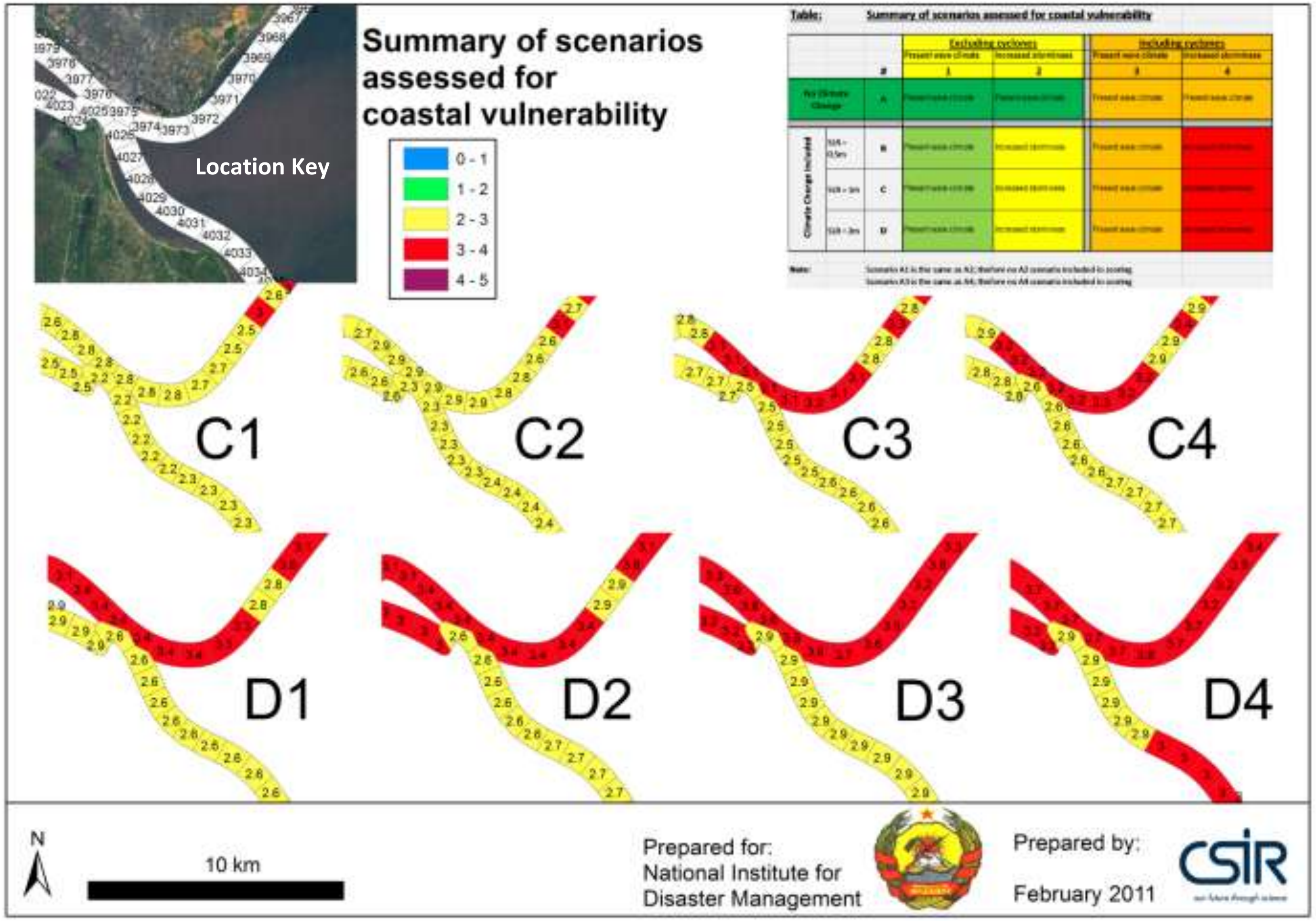


Table: Summary of scenarios assessed for coastal vulnerability

			Excluding cyclones		Including cyclones	
			Present wave climate	Increased storminess	Present wave climate	Increased storminess
		#	1	2	3	4
No Climate Change		A	Present wave climate	Present wave climate	Present wave climate	Present wave climate
Climate Change Included	SLR = 0.5m	B	Present wave climate	Increased storminess	Present wave climate	Increased storminess
	SLR = 1m	C	Present wave climate	Increased storminess	Present wave climate	Increased storminess
	SLR = 2m	D	Present wave climate	Increased storminess	Present wave climate	Increased storminess

Note: Scenario A1 is the same as A2; therefore no A2 scenario included in scoring
Scenario A3 is the same as A4; therefore no A4 scenario included in scoring

Figure 6.26: Maputo (and Matola) detail vulnerability mapping: Scenarios C & D

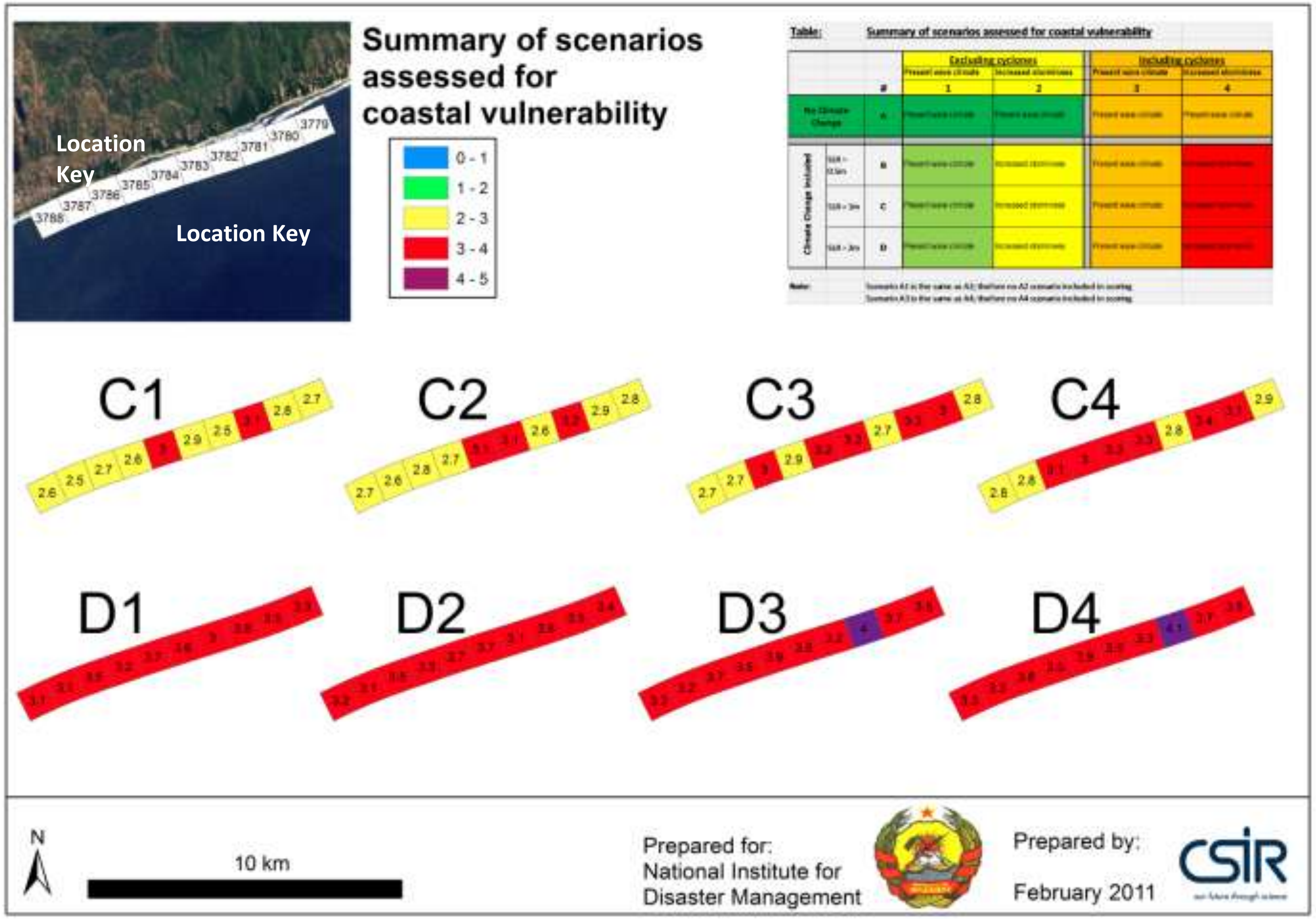


Figure 6.27: Xai-Xai Beach detail vulnerability mapping: Scenarios C & D

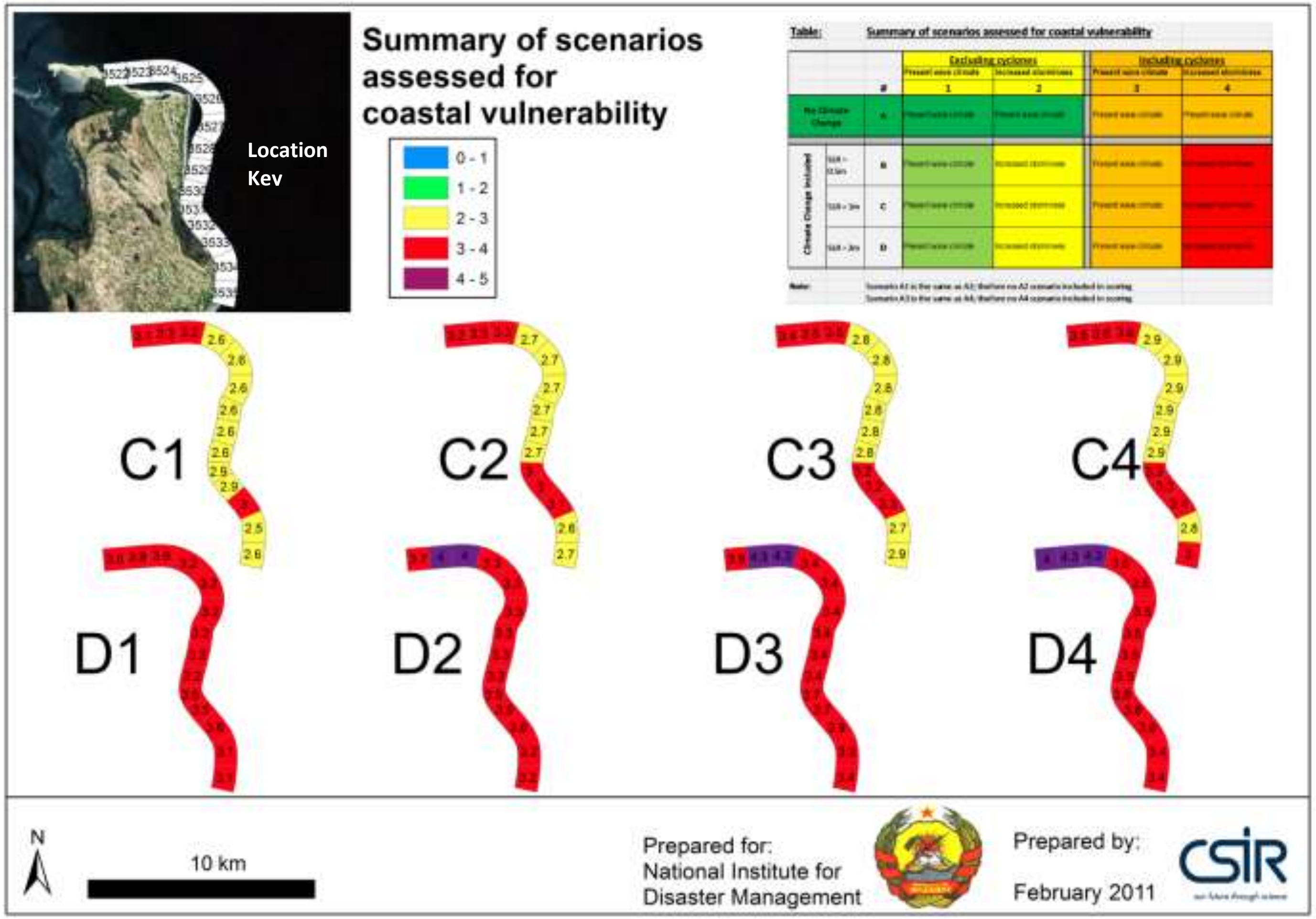


Figure 6.28: Tofo and Bara detail vulnerability mapping: Scenarios C & D

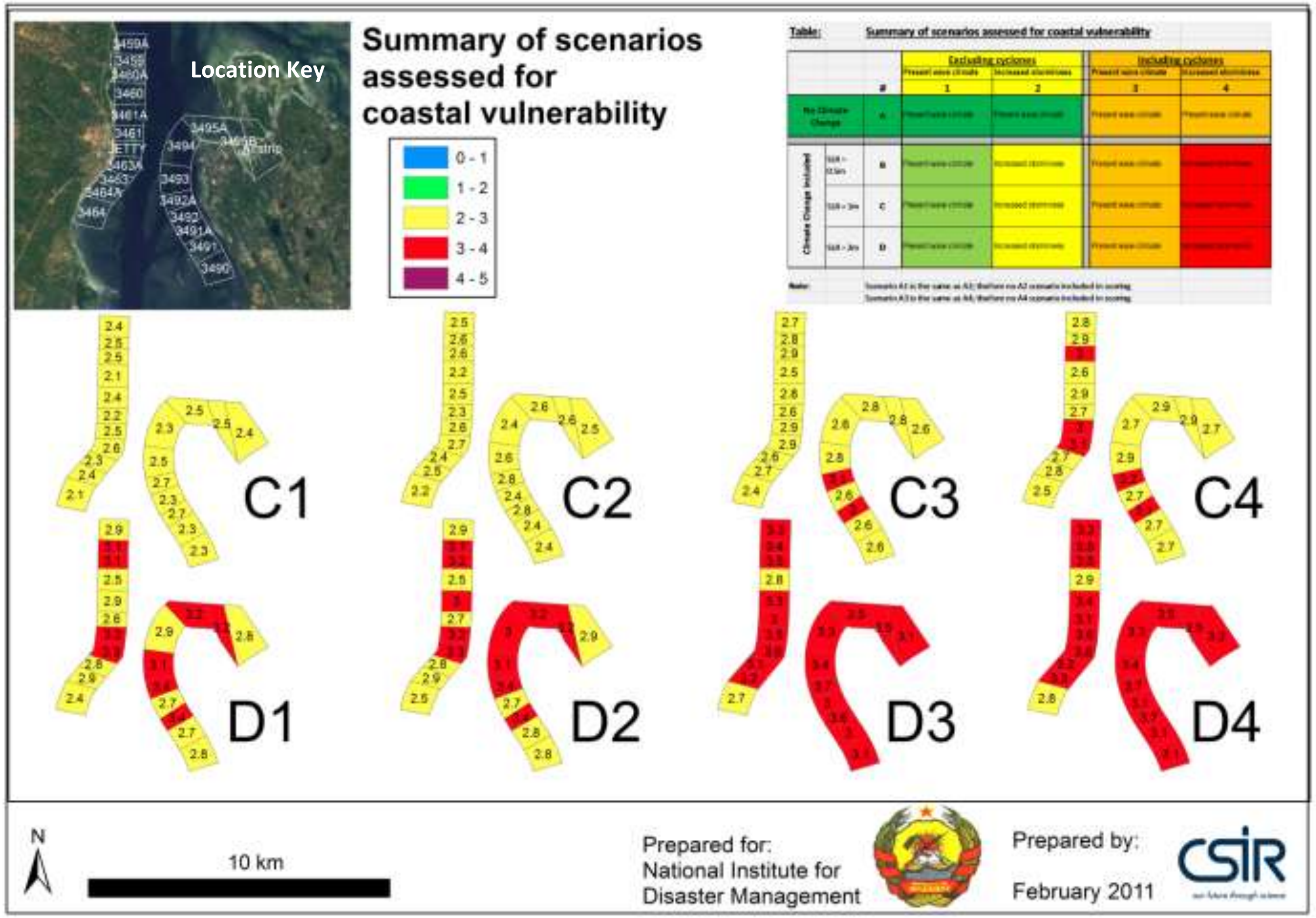


Figure 6.29: Imhambane and Maxixe detail vulnerability mapping: Scenarios C & D

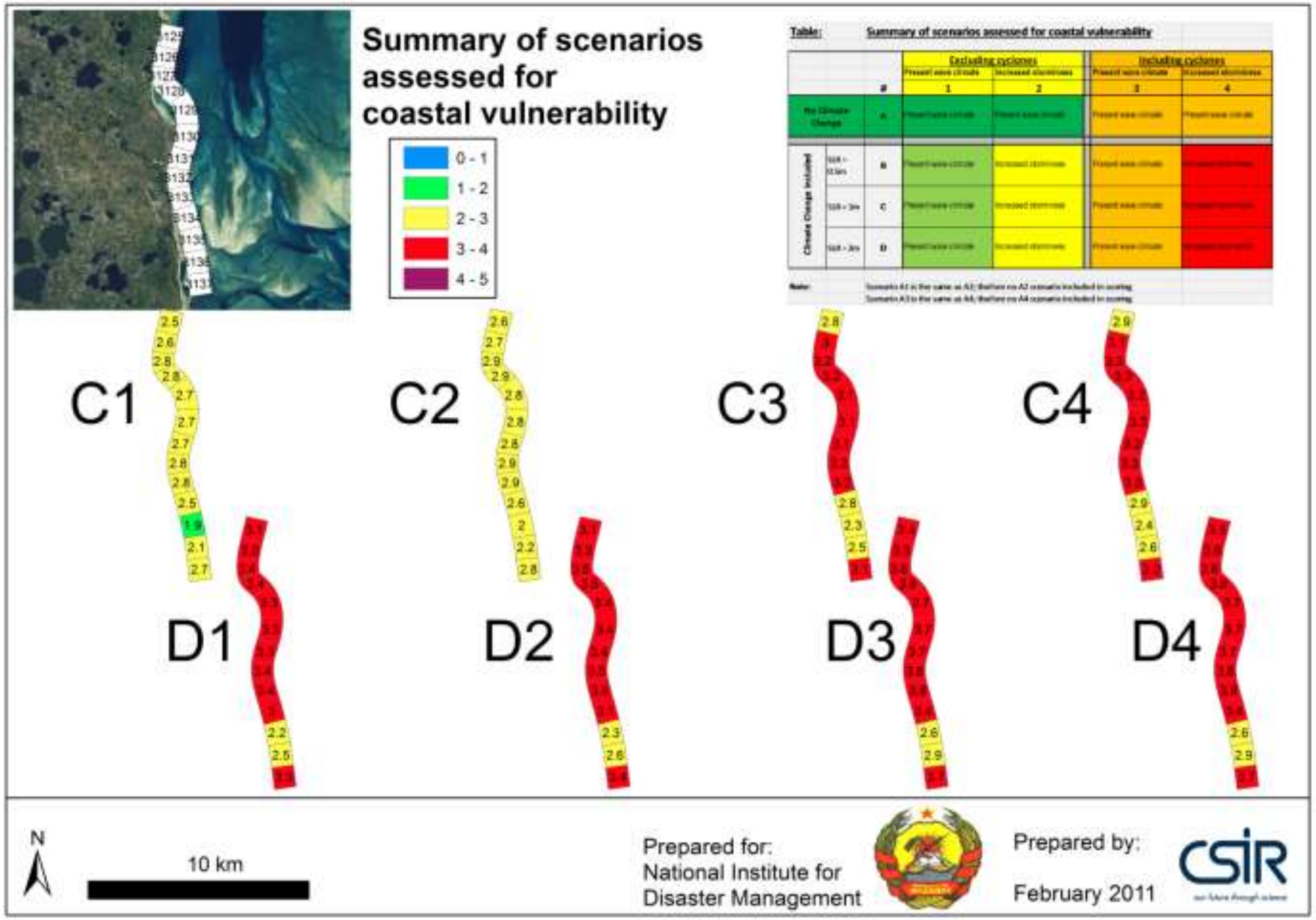


Figure 6.30: Villancoulos detail vulnerability mapping: Scenarios C & D

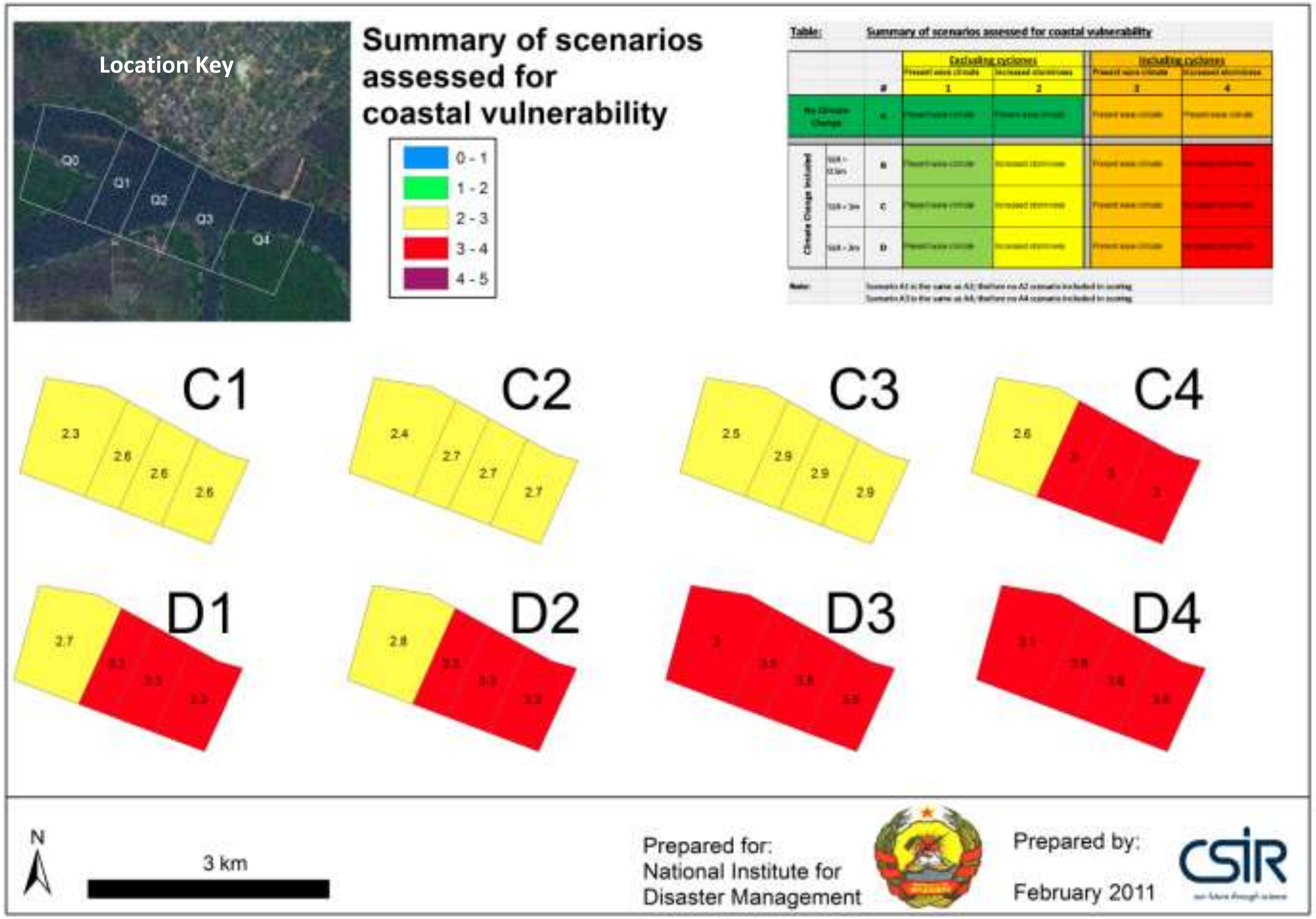


Figure 6.31: Quelimane detail vulnerability mapping: Scenarios C & D

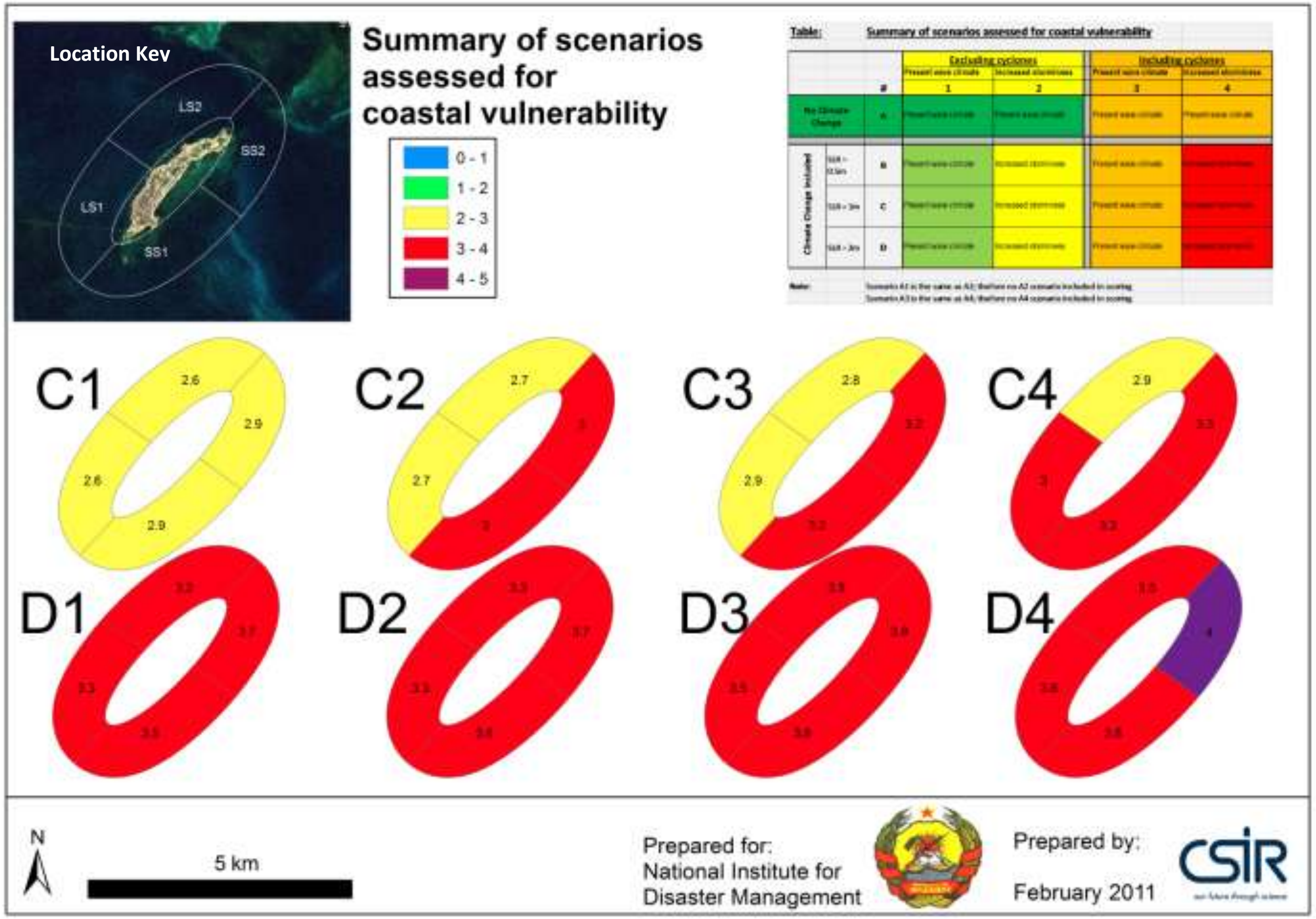


Figure 6.32: Ilha de Mozambique detail vulnerability mapping: Scenarios C & D

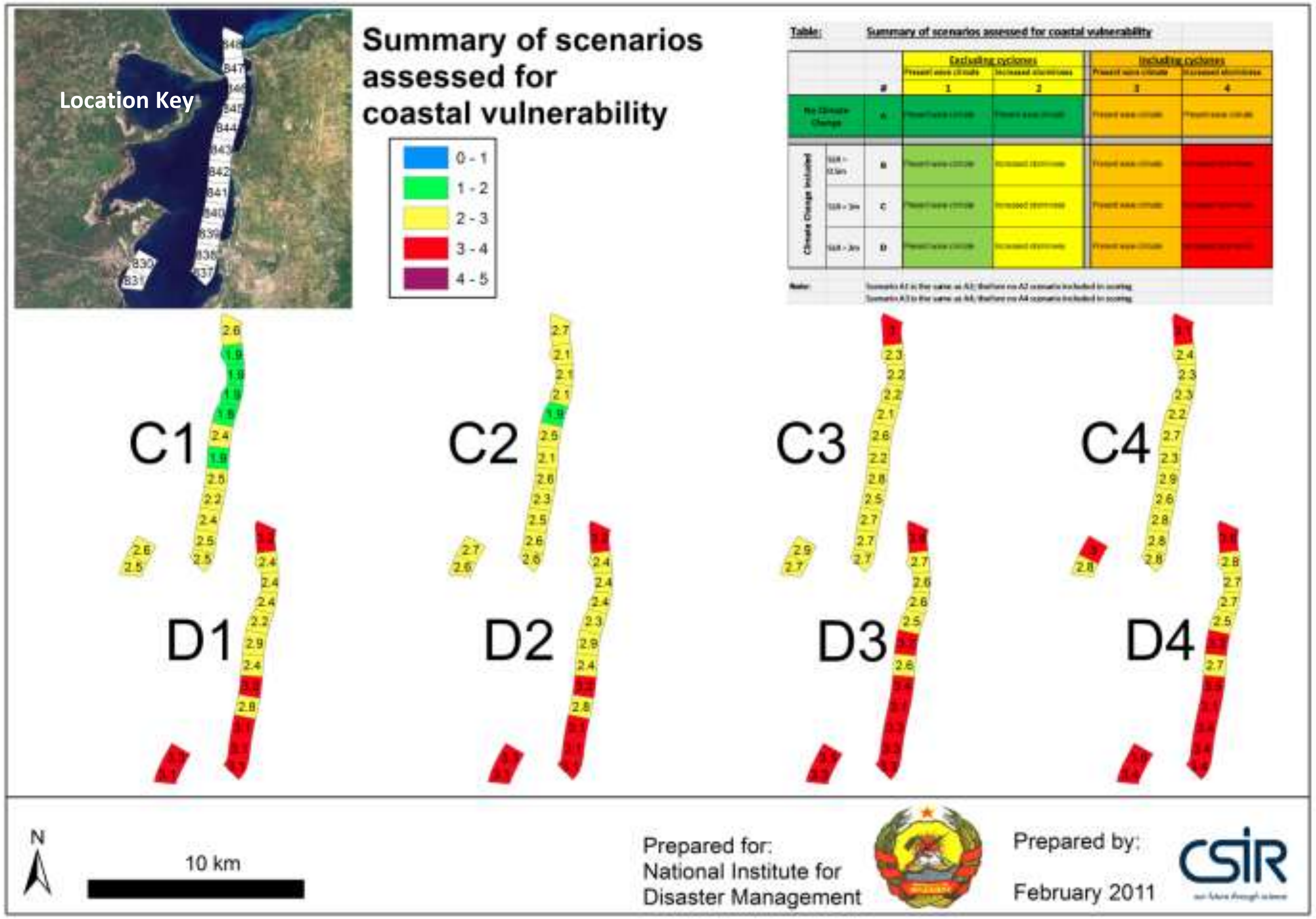


Figure 6.33: Nacala detail vulnerability mapping: Scenarios C & D

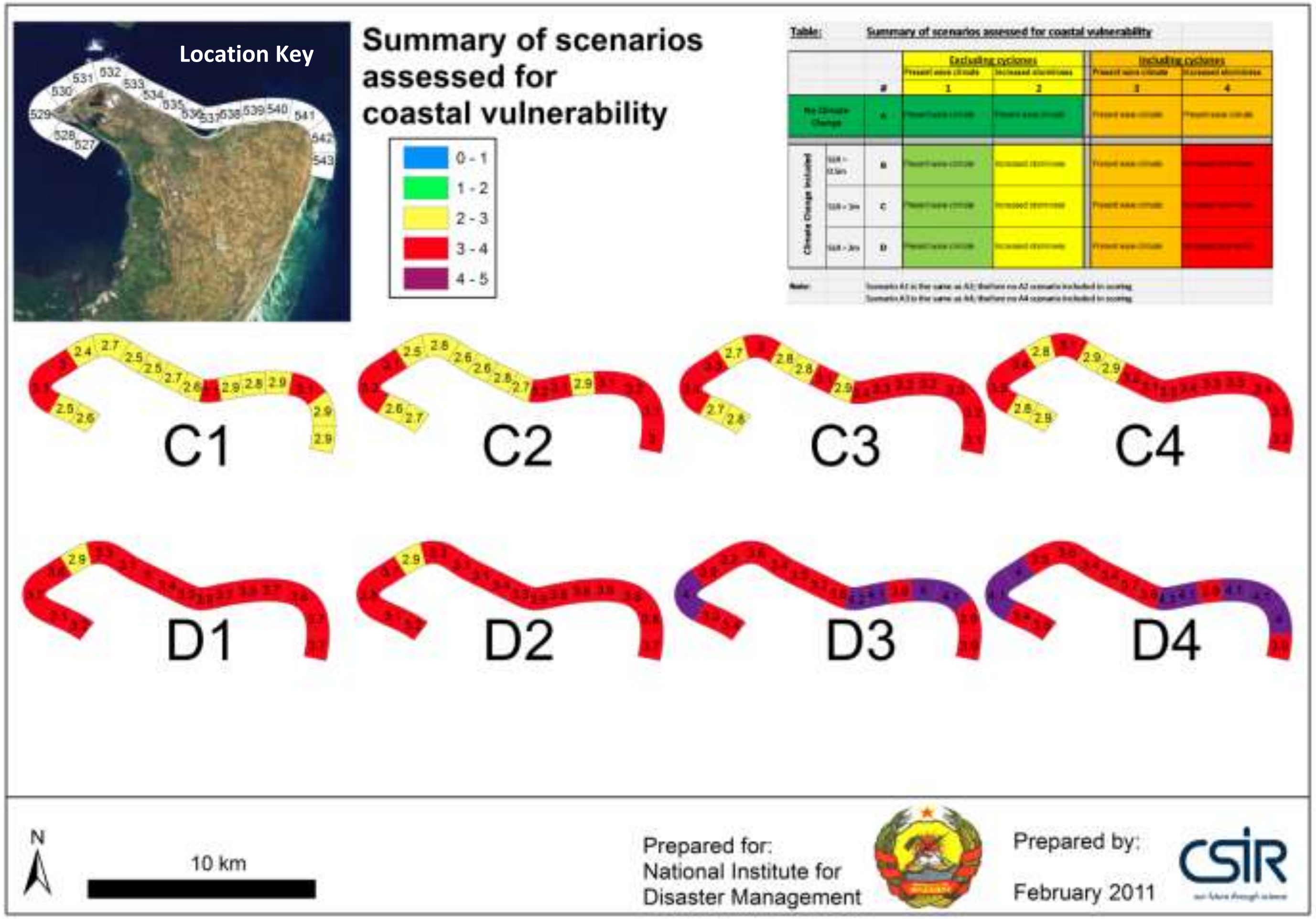


Figure 6.34: Pemba detail vulnerability mapping: Scenarios C & D

6.4.4 Comparison of detail coastal vulnerability of 12 Mozambican areas

A comparison of the vulnerabilities of each of the 12 towns and cities for the *A3 scenario with existing wave climate including cyclones (i.e. present day, no climate change effects)* is presented in Figure 6.35.

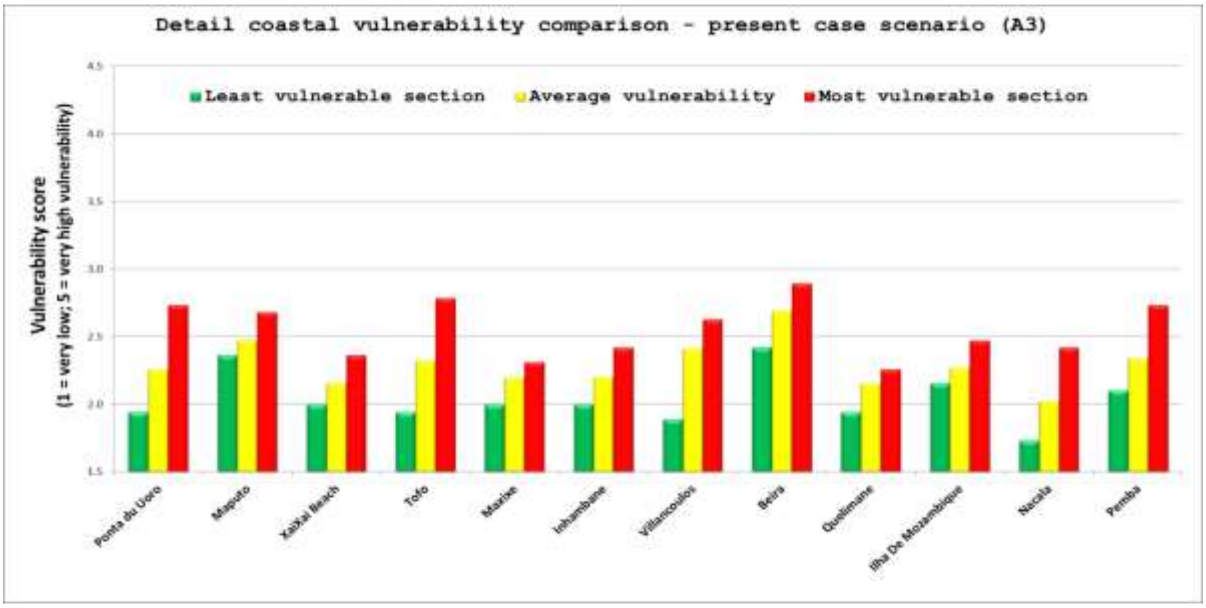


Figure 6.35: A comparison of the vulnerabilities of each of the 12 towns and cities (from south to north) for the present case scenario (A3)

In this study the vulnerability was typically assessed over an area of about 10 km total for each town/city. The vulnerability was then assessed in detail per alongshore section of coast, typically per 1 km alongshore sections, although in some areas the sections were shorter. The green bars in Figure 6.35 indicate the lowest vulnerability score per section within the total length of shoreline assessed for a particular town. The yellow bars indicate the average vulnerability score over the total length of shoreline assessed for a particular town. The red bars indicate the highest individual vulnerability score within the total length of shoreline assessed for a particular town. In general for the present day scenario (A3), the most vulnerable towns are Ponta du Uoro, Maputo, Tofo, Villancoulos, Beira and Pemba.

The least vulnerable towns for the present day scenario (A3), are generally XaiXai Beach, Maxixe, Quelimane and Nacala. As indicated by the yellow bars, all of the towns assessed have medium vulnerability on average to the impacts of climate change. At present (Scenario A3) Beira is the most vulnerable city in terms of all three categories (least vulnerable, average and most vulnerable section). (Note, other socio-economic factors such as population density are not accounted for in this relative comparison of abiotic physical vulnerability to coastal/marine & CC threats.)

A comparison of the vulnerabilities of each of the 12 towns and cities for the *most likely future case scenario (C4)* is presented in Figure 6.36 (The most likely future case scenario, C4, includes SLR of 1 m by 2100, vulnerability to cyclones and an increase in storminess.)

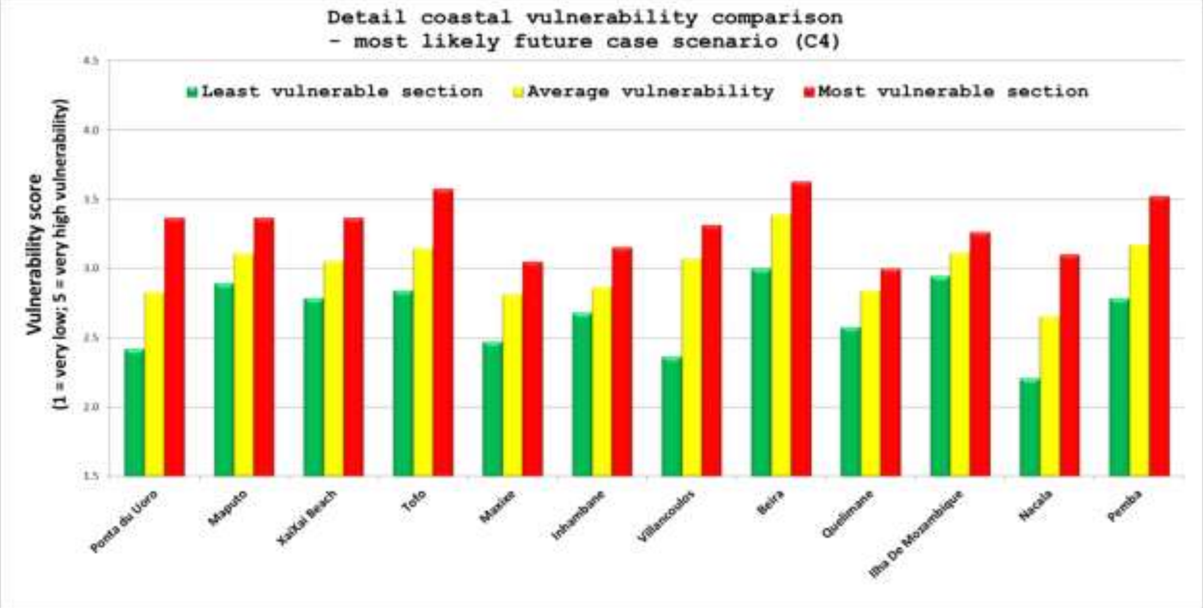


Figure 6.36: A comparison of the vulnerabilities of each of the 12 towns and cities for the most likely future case scenario (C4)

In general for the most likely future case scenario (C4), the most vulnerable towns are again Ponta du Uoro, Maputo, Tofo, Villancoulos, Beira and Pemba, but now also joined by XaiXai Beach. The least vulnerable towns for the most likely future case scenario (C4), are generally Maxixe, Quelimane and Nacala. As indicated by the yellow bars, some of the towns assessed now have high vulnerability (score 3 to 4) on average to the impacts of climate change, while, as indicated by the red bar, every town assessed has at least some location that is highly vulnerable to the impacts of climate change. In the most likely future (Scenario C4), Beira is again the most vulnerable city.

A comparison of the vulnerabilities of each of the 12 towns and cities for the worst case scenario (D4) is presented in Figure 6.37 (The worst case scenario, D4, includes SLR of 2 m by 2100, vulnerability to cyclones and an increase in storminess.)

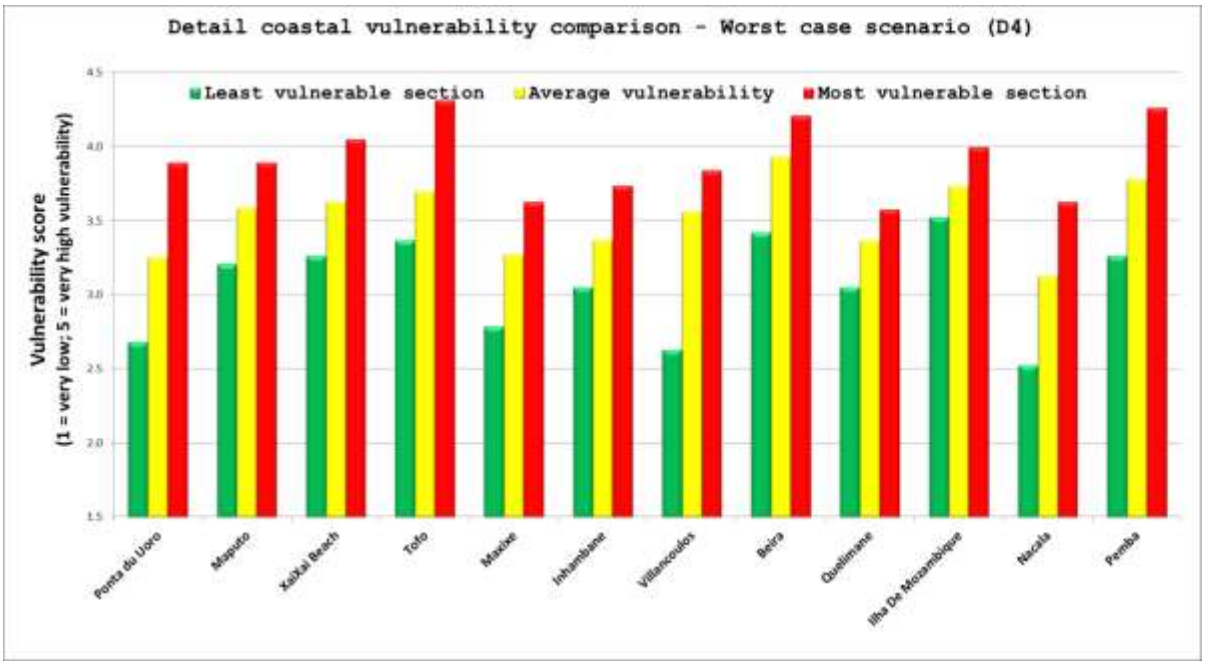


Figure 6.37: A comparison of the vulnerabilities of each of the 12 towns and cities for the worst case scenario (D4)

In general for the worst future case scenario (D4), the most vulnerable towns are now XaiXai Beach, Tofo, Beira, Ilha De Mozambique and Pemba. The least vulnerable towns for the worst future case scenario (D4), generally remain Maxixe, Quelimane and Nacala. As indicated by the red bar, under this scenario, every town assessed has at least some location that is either highly or very highly vulnerable to the impacts of climate change. In the worst case future (Scenario D4), Beira remains the most vulnerable city, in terms of average vulnerability.

In the above three figures (6.35 to 6.37), for Scenarios A3, C4 and D4 (present, most likely future and worsts case future respectively), the y-axis has purposefully been kept at the same start and end points, so that the three figures can be directly compared. The big increases in vulnerability to climate change, from present to most likely future to worst case future scenarios respectively, are thus clearly observed. For example, the most vulnerable locations in XaiXai Beach, Tofo, Beira and Pemba all increase from medium vulnerability under present conditions (A3) to very high vulnerability for the worst future case scenario (D4).

The results of the vulnerability assessment were used to determine suitable adaptation options and also to prioritise the recommended actions. These aspects are discussed in the next chapter.

CHAPTER 7: ADAPTATION OPTIONS

The results of a comprehensive literature survey as well as in-house coastal management and engineering experience are discussed and summarised in this Chapter.

7.1 STRATEGIC PRINCIPLES AND BEST PRACTICE GUIDELINES

As discussed in Chapter 5, in Southern Africa, including Mozambique, the most important drivers of risk to coastal infrastructure from erosion and flooding, are waves, tides and sea level rise in future. It is the combination of extreme events (sea storms occurring during high tides in conjunction with sea level rise) that will have by far the greatest impacts and will be the events that increasingly overwhelm existing infrastructure in the future (Theron *et al.* 2010). Several authors (e.g. Theron, 2007 and others) have summarised the basic options for responding or adapting to these predicted coastal climate change impacts as follows:

- Do nothing;
- Defend the existing position of the shoreline;
- Advance the existing position of the shoreline;
- Retreat.

Each of these options has a different impact on the risk. Besides these basic “climate change response options”, there are other actions that can be taken to reduce risk resulting from physical coastal/marine hazards (including CC), such as for example reducing human pressure on the natural defences, as is described in more detail further in this Chapter. In the foregoing chapters, the main scenarios that were considered for changing risk in the future relate to climate change, in particular sea level rise and increased storminess (due to changed/increased oceanic wind fields). These two drivers of change were therefore incorporated directly into the modelling and results discussed in the previous chapters. Man (and especially relating to the Mozambican abiotic coastal domain) has virtually no regulatory control or significant influence over these drivers. Only in the long-term and with strong unified global intervention could these drivers eventually be significantly influenced. Thus, in terms of global change or other scenarios of change, we need to identify local mitigation/adaptation options by which resilience of the coastal area can be increased.

Anthropogenic actions /interventions in the Mozambican coastal zone that could potentially be affected and that would affect vulnerability are:

- Coastal constructions which result in a significantly steeper profile (e.g. gabion revetments or seawalls) or reduce the roughness of the profile (e.g. smooth concrete or block surface), result in relatively higher wave run-up elevations for the same input wave conditions. Such constructions also often lead to erosion hot-spots in adjacent beach areas.
- Degradation of dune vegetation or destabilisation of dunes and especially actions which lead to reduction of dune volume (and height) lead to increased risk of coastal erosion. The dune sand (volume) forms the natural buffer against erosion during sea storms, preventing

excessive landward migration of the shoreline and allowing for recuperation of the beach between storms, provided that the natural processes are not impacted by human activities.
- Increased human development within the hazard zone (i.e. usually too low or too close to the sea) directly leads to increased risk.
- Any human activities which reduce the amount of sand within the coastal zone (e.g. dams on rivers or sand mining) or which reduce the rate at which sand is replenished into the area (e.g. causing a deficit in the coastal sediment budget) almost invariably eventually leads to progressive coastal erosion (thus necessitating increased erosion setback distances for coastal developments).

Considering the above interventions, it is obvious that they all relate to actions which would exacerbate the problems or increase the risks within the coastal zone. Key mitigations/adaptations or opportunities for increasing resilience thus lie in preventing or reducing such actions or impacts (in line with Integrated Coastal Zone Management actions).

For the purpose of this document it is important to note that in coastal management programmes it is desirable, beneficial and good practise to develop a *coastal protection corridor* with various zones, including:

- the Coastal Reserves as a no development zone,
- a coastal buffer strip as a limited development zone, and
- conservation corridors that include inland areas that require additional protection.

Proper planning can often eliminate the need for protection measures that might be required for future developments. The following points, adapted from various coastal management guidelines, (including Breetzke *et al.* 2008) serve as a guide:

(1) *Avoid the hazard*
Locate the development in such a way that the hazard cannot affect it. This requires determination of setback lines and buffer zones (Theron, 2000). This will always be of long-term financial and ecological benefit.

(2) *Prevent the loss*
Accept that extreme natural events will occur. Therefore take measures to minimize damage to or loss of property against the impact of extreme natural events.

(3) *Do nothing if appropriate,* rather than ill conceived plans/actions, especially those that ignore full (“triple bottom line”) long-term costs/consequences. (If, for example, the main hazard in an area is deemed to be erosion, it may in a particular case be argued that the erosion is cyclic and that the sand will be replenished naturally over time. In such particular instance it may then be appropriate not to take any action.)

The *key questions* that should be considered in planning developments near the shoreline are:

- Will disaster risk increase for the population living in/near the area of intervention? If yes,
- Is the development “location dependent”, i.e. is it really necessary for it to be located on or immediately adjacent to the shoreline?

- If development must take place within the sensitive dynamic area, what mitigating and maintenance measures will be implemented?
- Can sediment movement and therefore erosion be altered by the proposed development?
- Will the existing protection e.g. foredune ridge, mangroves etc be affected in any way?
- Will the groundwater regime be affected in any way? And potable water supply for population centres nearby?
- Will the proposed development or activity affect the coast in terms of its tourism/entertainment value .e.g. aesthetic-, swimming- surfing- or sunbathing values?
- Will the proposed development or activity affect the coast in terms of its nature conservation value, or detrimentally affect the ecology e.g. breeding of birds or other organisms?
- Has an accountable body or organisation been identified to determine the mitigating measures and ensure that such measures are properly implemented?

Strategy to plan & "live" with coastal erosion:
Following the coastal erosion events of 2006 and 2007 the KwaZulu-Natal Department of Agriculture and Environmental Affairs has compiled a *Best Practical Guide for Living with coastal erosion (*Breetzke *et al.* 2008*)*. The following are adapted from the document to ensure relevance to this study:

"Living with coastal erosion" requires that the following principles are acknowledged:

- Continued global warming is likely to cause sea level rise and increased intensity and frequency of coastal storms;
- Increased coastal erosion will lead to higher and continued risk to human life and the natural and built environments;
- Best International Practice in the face of sea level rise and changing coastal dynamics is a phased retreat away from the shoreline;
- It is not inconceivable that areas along the coast will lose more sand as a result of natural processes;
- The severity of this loss will be dependent on coinciding phenomena such as storm events [winds & waves], occurring at equinox (highest annual) and spring high-tides and cyclones;
- Any construction too close to the sea/beach interferes with natural sand movement and may impede beach and foredune recovery after a serious storm event;
- Removing sand from beaches increases the severity of erosion;
- Badly planned and inappropriate sea defences may cause further loss of sand resulting in beach degradation on site and to beaches and properties further along the coast; and
- Removing vegetation from dunes destabilises these protective sand barriers and reduces its function as natural sea defences.

The following are best practice guidelines to manage the human response to coastal erosion:

Accept and live with erosion

- Plan any coastal construction so that it is a safe distance away from the high-water mark and reinstate natural defence mechanisms with the necessary environmental authorisations.

A collective response is required

- Holistic planning and implementation by authorities in response to coastal erosion is critical. Coastal Management Programmes, incorporating Shoreline Management Plans, are required to reduce the direct and associated effects of erosion.
- Neighbours need to institute similar mitigation measures for the same reason. This collaboration will increase defence effectiveness and reduce costs.

Establish a coastal setback

- A development setback line is designed to protect both the natural environment from encroachment from buildings as well as protecting beachfront developments from the effects of storms and accelerated coastal erosion..
- Development seaward of this setback is considered to be at high risk from coastal erosion.

Work with natural processes in responding to erosion (and flooding)

- Soft coasts mostly require soft solutions.
- The preferred protection measures should make use of soft engineering solutions – e.g.:
    - A geofabric sand container or other suitable sand bags (which could be covered with dunes & vegetation),
    - Managed dune systems, which should be vegetated with appropriate dune species as per the original natural zones and maintained; maintain, or even better, increase the sand reservoir (volume) stored in the dune system.
    - Protection, restoration and maintenance of natural systems like mangroves and coral reefs.

Replace lost sand with sand (i.e. beach nourishment)

- It is important that the sand used must be of a similar nature to that found on the beach.
- Accessing beach sand from other sources should only be considered following input from appropriate experts (e.g. it might be necessary to find an offshore sand source – this is usually very expensive).

Consider hard engineering solutions in exceptional cases only

- Resort to hard engineering solutions only in exceptional cases and only after detailed environmental impact assessment and authorisation is obtained.

Be prepared, monitor and react: Employ appropriate "early warning" systems; Appropriately reconstruct coastal infrastructure and amenity

- Early warning systems (or appropriate long-term monitoring) allow plans to be made to "handle" extreme events (e.g. sea storms) and reduce the associated risks.

- Infrastructure that is damaged as a result of coastal erosion should not just be replaced. Its appropriateness should be assessed and necessary improvements made, and in the medium- to long-term, plans prepared and implemented for a managed retreat of such infrastructure.

Avoid and reduce the risk

- This includes risk factors emanating from "non-marine/coastal processes", e.g. stormwater runoff from streets, parking areas or drains:
- Coastal property owners are responsible for the maintenance of stormwater discharge and may be liable for any erosion or negative impact such discharge may have on the frontal dune or beach.
- Where stormwater has to be discharged onto a dune or beach, such discharge should be away from the dune face and toe. Discharge should preferably be onto a hardened area such as a rocky headland.

Most of the response options described in this section (7.1) are purposefully what can be termed "soft" options or "working with nature". This is in line with strategic principles and best practise guidelines in terms of coastal management and responding to climate change. The following section (7.2) has a more site specific focus and includes all appropriate adaptation measures and coastal protection options, "soft" and "hard".

7.2 POTENTIAL ADAPTATION MEASURES/COASTAL PROTECTION OPTIONS

7.2.1 Range of potential solutions

Many useful publications that address potential implications and adaptation/coastal protection measures can be found in the literature, e.g. UNCTAD (2008) – Table 7.1. Other examples include: NCCOE (2004), Stive *et al.* (1991), Breetzke *et al.* (2008), FEMA (2000), USACER (2004), SNH (2000), Van Rijn (2011), and others.

However, due to various factors, southern African states actually have very little adaptive capacity and their ability to halt coastal impacts on a large scale are virtually non-existent (Theron 2011). According to Tol (2004), adaptation would reduce impacts by factor of 10 to 100, and the adaptation costs would be minor compared to the damage avoided.

This is a clear imperative to set and implement adaptation measures sooner rather than later. To mitigate detrimental impacts resulting from climate change, an understanding of the adaptation options available to developing African nations needs to be reached and that these are considerably different from some traditional approaches used in the developed countries. Mozambique is also not a wealthy country and has less money available for coastal constructions; more affordable response options are required.

Table 7.1: Examples of potential implications and possible adaptation measures (adapted from UNCTAD, 2008)

CLIMATE CHANGE FACTOR	POTENTIAL IMPLICATIONS	ADAPTATION MEASURES
Rising sea levels • Flooding and inundation • Erosion of coastal areas	• Damage to infrastructure, equipment and cargo (coastal infrastructure, port-related structures, hinterland connections) • Increased construction and maintenance costs, erosion and sedimentation • Relocation and migration of people and business, labour shortage and shipyard closure • Variation in demand for and supply of shipping and port services (e.g. relocating) • Changes in water levels in harbours	• Relocation, redesign and construction of coastal protection schemes (e.g. levees, seawalls, dikes, infrastructure elevation) • Insurance • Raising of existing breakwater-structure to counter additional overtopping • Raising of existing quay and wharf levels
Extreme weather conditions • Tropical cyclones • Storms • Floods • Wind	• Damage to infrastructure, equipment and cargo (coastal infrastructure, port-related structures, hinterland connections) • Increased damage to ships as a result of wave current interaction • Erosion and sedimentation, subsidence and landslide • Relocation and migration of people and business • Reduced safety and sailing conditions, challenge to service reliability • Modal shift, variation in demand for and supply of shipping and port services • Change in trade structure and direction • Change in wave climate (swell and long period waves) in harbours	• Set up barriers and protection structures • Relocate infrastructure, ensure the functioning of alternative routes • Raising of existing breakwater-structure to counter additional overtopping • Increase monitoring of infrastructure Conditions (e.g. CSIR breakwater monitoring programme) • Restrict development and settlement in low-lying areas • Strengthen foundations, raising dock and wharf levels • Smart technologies for abnormal events detection • New design for sturdier ship • Designing new ports • Revising dredging maintenance programmes, amended beach nourishment programmes • Revision in ship mooring operations and equipment in ports • Alterations to ports to compensate for additional wave action (swell induced or long period waves)

7.2.2 Listing and description of potential solutions

By considering the coastal processes and characteristics of the study area, and factors governing suitability for coastal development, various potential responses can be formulated. A significant number of management options and “soft” and “hard” coastal engineering methods are available to protect the shoreline. The options described here do not include all possible coastal protection measures/options; however, the listed options include the potentially more appropriate measures:

A “Management options”

A1 **“Accept and retreat.”** This involves repositioning infrastructure at risk so that it is no longer in danger of being affected by erosion or flooding. This requires zoning (through set-back lines) and retreat of communities and infrastructure to landward of the setback plus possibly an additional buffer zone. Ultimately this means better planning and management of both the built environment and natural resources, including specifically to increase the climate resilience of current development plans, in this case coastal infrastructure & development. Government must be directly involved in resettlement of populations to lower risk areas (this is also a good option for low cost housing projects). However, much can additionally be achieved by encouraging, incentivizing & enabling “private” migration to lower risk areas. Large costs are associated with the relocation of utility infrastructure (power, roads, water reticulation, water treatment, storm-water runoff and telecommunications), but these can be offset to some extent, e.g. through enhanced tourism & investment opportunities, or foreign aid.

This option, the “accept & retreat” option, will allow for the continued erosion of the coast by the sea. Where the coastline has not yet been significantly developed (low existing infrastructure value), as in the case of large parts of the Mozambican coast, and the cause and effect of the erosion problem is of a large scale, this is often a wise choice in the long-term (e.g. Theiler, *et al.* 2000). It is also very much in line with the strategic principles and best practice guidelines discussed before. This option implies abandoning and removing existing infrastructure located near the sea. All infrastructure and development would have to be located landward of at least the 50 year coastal development setback line, while major developments and those with a longer design lifespan should be located landward of the 100 year setback line. However, this option does not provide protection for existing strategic or high value developments/infrastructure that are likely to be considered areas that must be defended.

A2 **“Abstention”** involves the ‘do nothing’ option. This option can be feasible if the risk of loss of property or human life is considered to be minimal. With this option, the current status quo will prevail, i.e. the actual/potential shoreline erosion and/or flooding continues with the associated consequence to the area.

A3 **“Alternative” coastal developments**. Provide good access to and develop alternative coastal areas (including providing services such as storm-water drainage and ideally sewerage systems), which are not prone to impacts such as flooding or erosion.

It is recommended that while interventions within existing developed areas are instigated, development of these alternative areas should progress in parallel.

A4 **"Accommodation"**. The intent here is not the direct defence or protection against the rising sea or storm waves, but to increases resilience or to better accommodate the associated impacts on infrastructure. Such measures include "climate or flood proofing", such as raising property, more robust buildings, and improved early warning of climatic hazards such as extreme storms. The relevant action is to plan to build infrastructure to higher design standards to withstand higher frequency of storm wave impacts, flooding/inundation and under-scouring. Some of these measures can be employed by property owners and private developers (Figure 7.1). At ports the foundation should be strengthened to allow for a future raising of the levels of the wharfs and quays as SLR occurs.

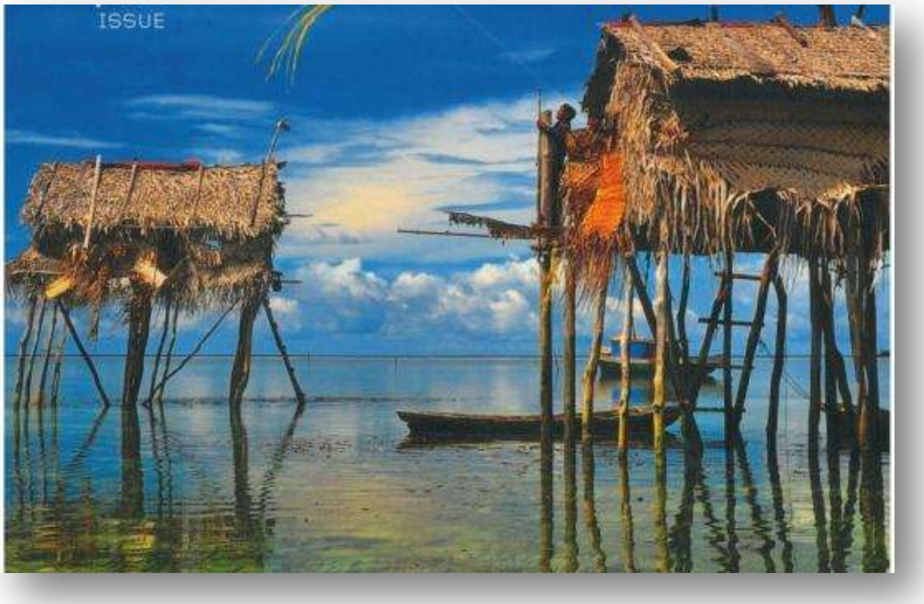


Figure 7.1: Example of local accommodation measure
(Photo: Holland Herald, KLM, September 2011)

B "Soft engineering" or Restoration ("semi-natural" interventions in the littoral zone)

B1 **Sand nourishment:** discrete localized nourishment projects or ongoing/regular nourishment projects; to mitigate existing and/or expected future coastal erosion problems, or even to build up a wider than present beach area, which will also reduce possible wave impacts and flooding potential. Stive *et al.* (1991), argue that shore nourishment is an effective mechanism to prevent shore retreat owing to long-term sea level rise because of the uncertainties and the flexibility that shore nourishment provides. Provided that sufficient sources of suitable sand are available, this is a good "soft" adaptive strategy, often better than "hard" (e.g. structural) approaches in the long-term. However, sand nourishment is expensive (like "hard" solutions) and the need for eventual re-nourishment, although foreseen and planned for, is sometimes perceived as "failure" by the Public.

Beach area can often be created or expanded by artificially feeding sand to an area (beach nourishment). To maximize benefit to cost ratios, the time between required re-nourishment events (maintenance intervals) is typically found to range from 6 to 12 years. However, a lack of a sufficient sand source could rule this out as a viable option in such areas. Usually a discrete localised beach nourishment project is quite feasible in areas where the background erosion rates are up to 0.9 m per year; are marginally feasible in areas where the background erosion rates are 0.9 m to 1.5 m per year; and are generally not economically viable if the rates are greater than 1.5 m per year (USA values - Dean, Davis and Erickson 2006). However, USA back-shore property values are very high, while most Mozambican values would be much lower. The implication is that the acceptable background erosion rate for developed areas of the Mozambican coast area is probably lower than 0.9 m/yr.

At a cost of perhaps \$ 10/m^3 a project of 2 million m^3 would cost in the order of \$ 20 million. If costs are compared on a unit cost per metre basis, this option is actually very competitive. To supply a mean volume of say 300 000 m^3/yr, could cost in the order of \$ 3 million per year, or perhaps \$ 500/m of shoreline. If options for cost sharing with existing port dredging operations are not available, foreign aid could be employed to fund such projects.

Figure 7.2: Beach nourishment by means of direct "rainbowing" of sand from the dredger to shore (only practical in certain areas).

Figure 7.3: Beach nourishment by means of pumping sand onto the beach through a pipe system

B2 **Managed (vegetated and/or reinforced) dune**. Construct/reinstate and/or manage vegetated dune buffer areas. Where appropriate, it can be crucial to maintain an affordable and effective soft-engineering coastal defence mechanism that preserves the ecosystem services that protect natural backdune areas and man-made development against the forces of the sea.

Rock protection or gabions can be placed underneath a (normally vegetated) dune. During a storm the dune will be eroded, but the rock/gabion will prevent excessive erosion. After the storm the dune could recover naturally, but in some instances may require active restoration and management.

Dunes are usually the soft coast's natural protective buffer against storm seas and high spring tides. Sand trapped in a dune system is stored and can be returned to the beach, thus preventing beach erosion. Vegetated dunes protect houses, roads and recreational facilities against corrosive sea spray, sand blasting and inundation by sand blown inland from the beach, as the vegetated dune functions as a natural sand trap. The dunes should have a crest height of approximately +6 m to +10 m to MSL (depending on local circumstances), while the base width should ideally be at least 60 m. In terms of the cross section, the seaward slope of the dune should be approximately 1:6. The estimated total cost of a dune, including reinforcement, is in the order of $ 240 000 per 100 m alongshore. The dune would be aligned approximately parallel to the shoreline.

The estimated cost of constructing a non-reinforced dune is in the order of $ 1400 /m. The following items should be allowed for in costing: site establishment, bulk earthworks, shaping and trimming, irrigation system, fertilizers, mulching, harvesting of pioneer species, planting of dune vegetation, fencing, footpaths, signage and limited consultation. Estimated cost of placed rock reinforcement is about $ 100/m^3, with additional costs relating to the reinforcement, estimated at about 75 % of the cost of the rock. Such reinforcement would only be required if there were very important reasons to reduce the shoreline variability in a specific location. The use of local labour in labour intensive projects could reduce the cost of building or maintaining dune systems.

Figure 7.4: Example of a vegetated dune at Beira with sufficient volume and height to protect landwards areas from storm erosion or coastal flooding.

Vegetation (e.g. grass planting), thatching and fencing can be installed to hold or trap beach sand. In some instances, vegetation can reduce erosion by holding the sand. Casuarina trees have been planted in some coastal locations in Mozambique (e.g. Tofo, Maputo). However, these Casuarina trees have not been effective in preventing local soil erosion. The use of proper dune vegetation and appropriate grasses can be more effective. Suitable dune vegetation and grasses typically have a fine root system that goes over 2 meters deep, is tolerant to salt and cannot be easily uprooted. The vegetation is typically capable of tolerating sand-blasting and traps windblown sand, thereby contributing to dune development. By planting this vegetation strategically and fixing large volumes of sand in calm periods, a buffer can be created over a number of years that can erode in the stormy periods, thereby reducing erosion of the backshore areas.

The use of non-invasive dune vegetation above other alternatives can be advantageous because it is cheaper and can have a higher aesthetic value. Further, it does not have negative effects on the adjacent coast, as many engineering structures do. It can therefore be used if there are limited financial resources available and could be undertaken by the owners of the property along the beach. Thus, it is a relatively "cheap" low environmental impact quasi-natural intervention to promote natural dune volume growth.

On the other hand, it is difficult to be certain that the degree of protection is adequate for more than low erosion rates, particularly cyclones that can recur frequently result in relatively high erosion rates. It does not provide immediate protection and requires some maintenance to establish. Thus, it often has small potential for making a big difference, especially if used in isolation and not in conjunction with other management actions/interventions or protective measures. In general it can be concluded that grass planting, thatching and fencing are relatively "cheap" low environmental impact quasi-natural intervention to promote natural dune volume growth, but sometimes have small potential for making a big difference.

B3 Mangroves, corals and wetlands

Mangroves are not only ecologically important (especially for fisheries), but if they occur in sufficiently dense stands of sufficient cross-shore extent, they also structurally behave like a semi-permeable barrier (mostly due to their root system, much of which is above ground level). Energy is dissipated and sediments can even accumulate under suitable circumstances, thus reducing the flooding/erosion potential of waves/cyclones and proving some shore protection to landward areas. Wetlands can have a similar dampening effect and if of sufficient extent can help to dissipate flood waters and wave impacts on landward areas. Properly planned restoration of damaged mangrove areas are practical and can be used as a local job creation initiative, often in collaboration with private enterprise.

Storm waves approaching the coast (e.g. resulting from cyclones) are affected by bottom topography, and shallow coral reefs that cause wave breaking dissipate much of the incident wave energy. However, as the sea level rises, existing topographic features including coral reefs will be located in deeper water and will have a reduced effect on waves approaching the coast. Areas landward of the reef breaker zone will experience an amplified wave climate compared to the present. At low rates of eustatic sea level rise, healthy corals can grow to match the rate of SLR, thereby retaining their protective effect. Deeper water features including coral reefs may deepen to the degree that their effect on the wave energy impacting on the shoreline is negligible.

However, the coral reef areas of Mozambique are very vulnerable to CC impacts, through coral bleaching (e.g. Obura 2005), in terms of direct effect on the biota as well as on the important linked socio-economic sectors (e.g. tourism). As mentioned, the coral reefs serve other important functions, such as sheltering the coast from wave action and by providing beach building materials. Thus, loss of coral due to CC will also negatively impact these functions with detrimental impacts on the coast (e.g. erosion).

Similarly, fringing reefs are found along some areas in Mozambique. These reefs comprise tough, algal-clad intertidal bars composed largely of coral rubble, and provide protection from wave attack to the inshore areas and beach sands that are susceptible to erosion (Arthurton 2003). If the coast is subjected to the predicted sea-level rise, the protective role of the reef bars will be diminished if their upward growth fails to keep pace (Theron and Rossouw, 2008).

Mangroves, corals & wetlands therefore all have some "coastal protection" potential and can mitigate coastal climate change impacts to some degree. The opportunities therefore lie in protecting and managing these natural defences, or indeed in enhancing/expanding their positive effects by increasing such areas where practical or reintroducing such natural systems where they have been lost or impacted.

<u>C “Hard engineering” & armouring</u> (construct shore protection measures)

C1 **Seawalls** (mostly vertical or curved concrete structures) **and revetments** (including rock and concrete sloping revetments), involve the construction of ‘hard’ protective structures that are placed along the shoreline so as to act as a distinctive barrier between the land and the water, thereby directly preventing erosion and/or flooding of the back shore. Ground level (natural or raised) on the landward side of the structure is usually at the same elevation or higher than that of the crest of the structure.

There are many types of revetments and retaining walls. The material of which they consist (rock, wood or concrete) and characteristics (e.g. permeability) result in differences in costs, longelivety, effectiveness & environmental impacts. Without detailed topographic surveys of the local project sites and possible underground foundation rock, it is very difficult to estimate quantities and thus construction costs. Design and construction supervision costs could be about an additional 10% of the total cost. The estimated costs provided further on in this Chapter and Chapter 8 are mainly for comparative purposes and more exact costs can only be determined once detailed designs have been completed. The availability of suitable rock, access roads and a quarry site all have big impacts on the total project cost. The extent of work can also be tailored to suit the available budget, although the greater the number of phases, the greater the overall project cost, i.e. due to longer construction supervision required and additional costs for re-establishment of a contractor on site.

Figure 7.5: Examples of a revetment (left) and a seawall (right) in Mozambique

Figure 7.6: Example of a rock revetment protecting houses (South Africa)

C2 **Dikes,** similarly to C1, act as a distinctive alongshore barrier between the land and the water, but are often massive sloped (even landscaped and vegetated) loose standing sand or earthen mound constructions. They can be armoured (e.g. by a revetment) on the seaward side, or left unarmoured, but might then require significant maintenance or restoration after large storms. Their massive nature and large space requirements also make this an expensive option and difficult to apply in congested or very built up areas. However, they can be an option where absolutely necessary to protect current, immobile, vital infrastructure (e.g., potentially appropriate areas associated with the ports and cities of Beira and Maputo provided that sufficient space can be made available), but the development of new infrastructure directly adjacent to the dike should generally be avoided. To be effective against flooding, they have to be continuous or linked to other defences. It is essential to also plan for dispersing of floodwaters trapped inside the dike resulting from rainfall runoff or river flooding.

Figure 7.7: Examples of vegetated dikes (Germany)

C3 **Perched beach or sill structures,** which aim to artificially keep the upper part of the beach profile in place seaward of where it naturally would be. Wave energy is dissipated on the beach, which reduces the wave run-up.

The available beach area can be expanded significantly by constructing a “perched” beach. This is simply a structure that allows a beach to be formed at an elevated level on the upper beach and prevents significant wave erosion. The structure consists of some form of partially submerged retaining wall, bulkhead or revetment, and is usually aligned roughly parallel to the shoreline. Hard rock substrate is required to provide good founding conditions, as the structure will have to withstand significant wave action.

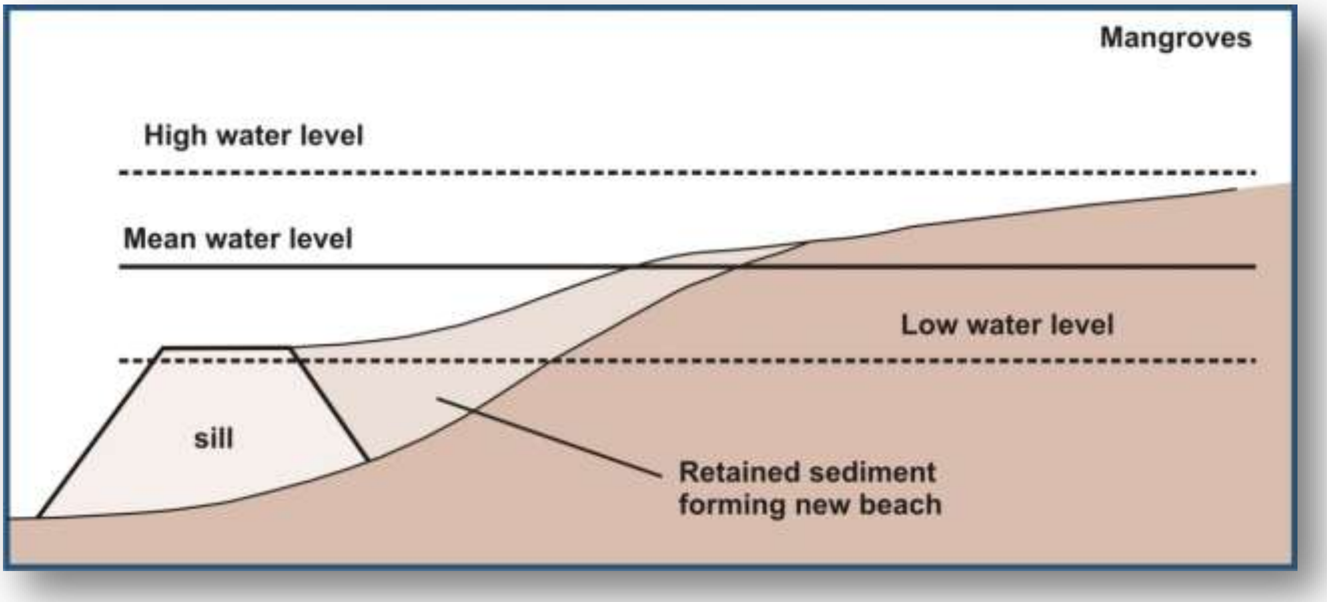


Figure 7.8: Perched beach with partially submerged retaining structure

A lack of good rock foundation conditions would make this an even more expensive construction. Some structures are designed to support the near-coast profile seaward of where it would otherwise be. Successful prototypes of such low structures, when designed to retain an artificial "perched" beach, are rare. The two main disadvantages are perhaps that the perched beach can easily lead to dangerous bathing conditions (due to e.g. the presence of a hard structure in the surf zone, the sudden drop-off and potential generation up rip currents), and a local intervention (i.e. small project area) would not address possible existing much wider background coastal erosion problems.

C4 **Shore-parallel structures** (e.g. artificial surf zone reefs, detached breakwaters, rock berms, etc.). These structures are normally built parallel to the shoreline and some are not connected to the shoreline. The structures are mainly designed to induce wave breaking and can either be submerged or above the water. (This could also include tidal pools, with or without beaches, as multi-functional structures.) These types of structures are usually expensive to place, require heavy plant and access roads and might need to transport both construction plant and rock material over long distances if it is not locally available (as in some parts of Mozambique), all of which can make this an expensive option.

Figure 7.9 Example of erosion mitigation through shore-parallel structures (Anglin, et al. 2001)

Figure 7.10: Example of beach accretion through submerged artificial reefs

An offshore beach retention structure is a non-shore-connected feature that acts to retain a beach larger than would exist in its absence. Most of these structures perform this function by affecting waves such that a reduction in wave energy in their lee or a changed alignment of waves in their lee results, sustaining a protrusion of the shoreline. These structures are categorized as surface piercing or submerged offshore (or detached) breakwaters and artificial reefs. Each has advantages in retaining a beach. Conversely, there are disadvantages linked with each of them, including in some instances that the beach remains depleted and erosion continues, adverse erosion impacts on adjacent beaches, and failure of the structure. The most successful offshore structures have been those that are high, surface piercing, impermeable, “two-dimensional” breakwaters. Complexity in the functional design process increases as the height of the structure is reduced. In addition to diffraction effects, wave energy that passes through or over low or submerged, “two-dimensional” breakwaters must be considered.

Thus, the concept of an artificial reef is to cause the waves that at present prevent a beach from building up, to break on this reef. By dissipating sufficient energy, a beach will form along the shore in the lee of the structure. The crest elevation and width of this reef have to be sufficient to cause such wave breaking and energy dissipation. This is similar to what occurs naturally in many areas where Tombolas are found in the lee of natural reefs. If the crest is too high, the reef will be more visually obtrusive. On the other hand, if the crest is too low, the reef will not be effective in reducing wave energy with the associated build-up of sand in the lee area. The crest of the beach-reef will probably have to be at at least +2 m to +4 m to MSL or higher (depending on which area of the Mozambican coast is considered). The crest should probably be 4 m wide or more (also for practical construction purposes). The reef should be constructed of rock armour with sufficient weight to be stable under the expected wave conditions. The reef should be founded on existing bedrock if at all possible and the side slopes should probably be one in two (that is one vertical to two horizontal). The reef would be aligned approximately parallel to the shoreline and would have a unit length of at least 150 m. A disadvantage is perhaps that the localised artificial reef would not address possible existing wider background coastal erosion problems. In addition, potentially dangerous rip currents could be generated near the extremities of the reef especially during high tides.

Similar to the artificial beach-reef, the concept of an artificial surf zone reef or alongshore breakwater is also to initiate wave breaking to allow a beach to form in the lee of the structure. The difference is that the surf zone reef is not located on the existing beach, but significantly further seawards in the surf zone (or beyond). This means that the surf zone reef is less obtrusive than the beach-reef and also presents less of a barrier between the beach and the inner surf zone area. On the other hand, the surf zone reef will obviously be much more expensive, due to the larger rock volume (larger sectional area and reef length) and the larger rocks sizes required to remain stable under the incident wave conditions in the deeper water. The surf zone reef would have a unit length of about 200 m or more, including required gaps in the reef. As the sea level rises in time, the effectiveness will be reduced and reconstruction/addition may be required. This reconstruction/addition needs to be incorporated into the design.

C5 Groynes (straight, curved, T, L etc.). Groynes constructed perpendicularly or at an angle to the shoreline, can trap sediment and provide protection.

Groynes can trap sand and aid the formation of a beach at the foot of the groyne. In general, a larger beach will tend to accrete on the updrift side of the groyne, with a smaller beach directly on the downdrift side in the lee of the groyne. A localised erosion area usually forms slightly further downdrift of the groyne. Lengthening of the groyne up to the outer surf zone will increase the beach area, but at a much greater cost. Groynes create very complex current and wave patterns. The orientation, length, height, permeability, and spacing of the groynes determine, under given natural conditions, the actual effects on breaking wave conditions, local currents, sand transport and changes in the bottom configuration. Problems sometimes arise with groynes due to cross-shore sand losses during storms or the formation of strong rip currents parallel to the structure.

Figure 7.11: Existing groynes along Maputo shoreline

Figure 7.12: Groynes protecting Richards Bay entrance channel shoreline, South Africa (Photograph S Pillay)

C6 A **spending beach** of very coarse sand, gravel or cobbles can be used to dissipate wave energy and reduce erosion. Storm erosion of such a beach would be much less than for the natural finer grained beach material. A large source of such material is required relatively near the application site to make this option economically viable. (No obvious large deposits of such materials were observed during the Mozambique site reconnaissance.)

C7 The installation of a **beach (and dune) dewatering mechanism**. Sediment "stability" can be increased by reducing the pore water pressure.

Geotechnical assessments of Kwazulu-Natal coastal areas (Theron, 2008) indicated that the phreatic surface and the emergence of seepage water along the shoreline influence slope stability. It seems that this is the only geological parameter that could potentially be manipulated in limited local areas. The basic concept here is to decrease the pore water pressure of the beach sand/dune to such an extent that the beach sand is not fluidized by waves and/or the groundwater within the dune is drawn down to enhance the dune slope stability. The system consists of a pipe network (with relatively closely spaced water extraction points), which is placed some distance below the normal sand level (say 1 m) and to which suction is applied.

Although not a new technology, this concept found favour in coastal engineering applications in the late 1980s and early 1990s (e.g. Jenkins and Bailard, 1989, Parks, 1991, Ogden and Wiesman, 1991, and Wiesman *et al*, 1995) with patents being granted to Vesterby in 1987 and Parks in 1991 (Parks, 1992). In theory, this is a promising concept, but in practice it has met with limited success in coastal engineering applications. More recent publications (e.g. Turner and Leatherman, 1997, Bruun, 1989, and Bruno, 1999) are somewhat critical of earlier claims that this is a successful technology. The problems include the practical side of the application (sometimes aggravated by conditions in the harsh and dynamic coastal zone). The difficulties range from maintenance of the electrical supply, motors and pumps which extract water from the system to the robustness and durability of the pipe network. The initial position of the pipes and the flow rate through the system are also critical design parameters, but due to the dynamic nature of the coastal zone it is very difficult to ensure success under all conditions. For example, if the pipes are placed too deep or the flow rate is too low, the sand will not be effectively de-fluidised. On the other hand, if the pipes are placed in too shallow a position, the pipes may be scoured open resulting in damage. There is also a considerable risk that the system could be scoured open and damaged by wave action, especially if the shoreline is experiencing an erosion phase (or longer term trend), or localised erosion "hot-spot.

Due to the many technical and practical problems associated with this option, the high maintenance costs, as well as the largely unproven track record, this option is not recommended.

C8 **Coastal flood control gates** in "enclosed" areas (e.g. river mouths, small bays).

Well known examples include components of the Delta works in the Netherlands and the Thames flood barrier in the UK. These flood defence works tend to be very large and expensive schemes (as in the two examples mentioned), linked into wider dike defence systems. Suitable foundation conditions are ideally required, which is a major constraint in river mouth and delta areas with deep mud/silt deposits. For these reasons, this option is considered to be largely unsuitable for practical application in Mozambique.

In low to moderate wave energy environments:

C9 **Closely spaced piles or wave fences** to dissipate wave energy.

Such structures can be successful in dissipating wave energy in low to moderate wave energy environments. However, they have no effect on rising sea levels, and coastal areas will still be subject to increased risk from flooding due to SLR. Thus, this is generally considered to be an unsuitable adaptation measure for the purposes of this investigation.

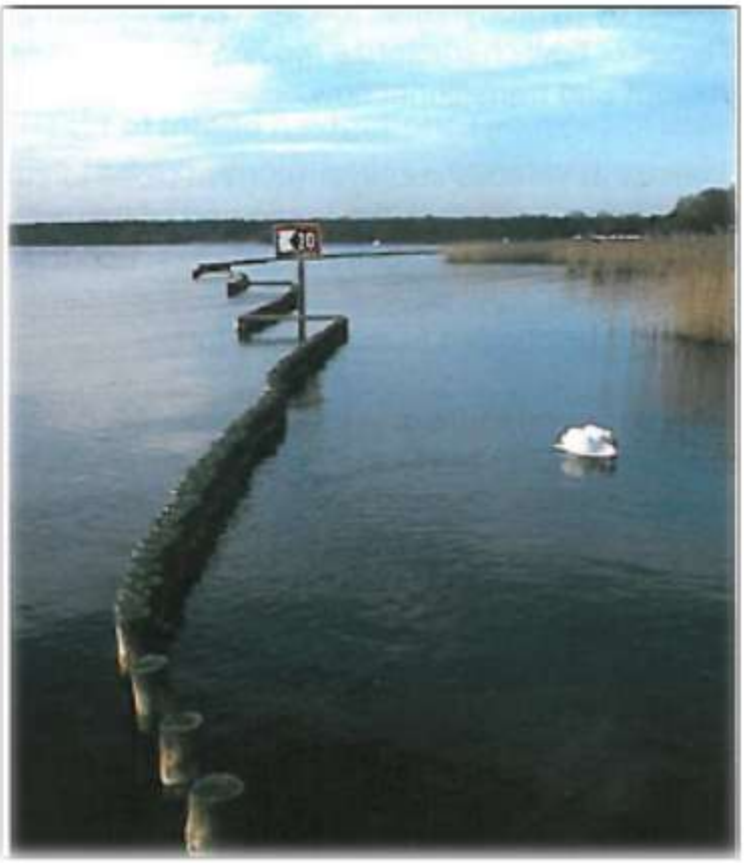


Figure 7.13: Piles driven to form a wave fence (about 50 % reflective - PIANC, 2008)

C10 **Floating moored "breakwater" type structures**.

Figure 7.14: Patented floating breakwater (www.whisprwave.com)

Such structures can be successful in dissipating wave energy in low to moderate wave energy environments. However, they have no effect on rising sea levels, and coastal areas will still be subject to increased risk from flooding due to SLR. These types of structures also require considerable maintenance, with significant cost implications. Thus, this is generally considered to be an unsuitable adaptation measure for the purposes of this investigation.

C11 **"Geotextile" shore protection**, usually sand filled geotextile containers.

Traditional forms of shore protection, such as detached breakwaters, groynes, revetments have become expensive to build and maintain (especially if not well designed or constructed in the first place). This has prompted novel designs of low-cost shore protection. These protection measures may need replacement at relatively short intervals but might still be more affordable and economic in the long term than conventional methods. Low-cost shore protection methods are especially suitable when emergency beach erosion measures are urgently required.

The CSIR has conducted comprehensive literature reviews in order to learn from international experience. Promising measures were identified and new low-cost shore protection measures were developed (Theron *et al.* 1994). These concepts were then tested initially in the laboratory and eventually in prototype (in South Africa at Strandfontein, Hermanus, False Bay and at Oranjemund in Namibia). These prototype tests enabled this new technology to be applied successfully and cost effectively to projects (Theron *et al.* 1999).

Possible applications of the low-cost shore protection include the following:

- Protection of the shoreline against erosion.

- Sleeping defence underneath a dune to safeguard against extreme beach erosion.
- Preventing scour near coastal/marine structures.
- Limiting the cost of breakwaters or groynes.

While modern geotextiles are durable, they should be regarded as temporary measures as their lifespan for longer than a decade has not been proven. Successive storms may breach the protection if it is not maintained. Maintenance will be necessary after every major storm to replace sandbags that have been moved or damaged. If they are used as “sleeping defence” structures against extreme events and covered by sufficient sand (dunes), routine maintenance costs can be much reduced. The cost of durable geotextile material is high. The work has to be done under supervision of an experienced contractor. For construction of a groyne of sandbags a typical price is \$ 200/bag for 0.75m^3 bags, including placement. A sandbag revetment would have a volume of at least 11 m^3 per meter shoreline length. Thus, for a 100 meter revetment the total price will be about \$ 300 000. Present low-cost shore protection measures may not to be appropriate for *permanent* solutions to the more severe erosion problems possibly encountered in some areas or expected in future. They are also generally not suitable for use as “breakwater type” structures in deeper water.

Figure 7.15: Examples of geotextile (sand bag) revetments (Kwazulu-Natal, South Africa)

C12 **Gabions and/or rock filled wire basket & mattress structures**.

An example of a Gabion retaining wall structure is depicted in Figure 7.14

Figure 7.16: Example of a Gabion retaining wall structure (to protect the back-beach area)

Evaluations of Gabion structures from literature and practical experience:

- "At sites where there was significant wave action, abrasion, and impact forces, the gabion baskets tended to be broken quickly. Corrosion was a significant problem at most sites, even though PVC-coated baskets were used... The hazard posed by the baskets once deterioration begins would restrict their use only to site where there is little public use." (Combe *et al.* 1989, page 61-62).
- A UK report (Welsby and Motyka, 1984) reviewed the performance of Gabion structures around the coast of the UK: "Opinion as to the lifespan of metal gabions on the foreshore is divided but the general consensus is that in areas subject to severe wave activity, gabions will succumb to rapid abrasion and as a result their lifespan can be as short as 2 or 3 years. On flat sand beaches subject to moderate or low wave activity the lifespan can be a decade or more. On the backshore, where gabion structures are not subjected to regular wave activity, they can be expected to have a considerably longer life." The report also notes that the performance of the Gabion under wave action often depends on how well they're packed (Powell, pers com. 2011).
- If there is any debris in the water or cobble on the beach, the baskets are prone to failure (Tanski, 2011 pers com.).
- In all of these types, construction practice is critical, especially regarding stone gradation and packing to resist self-destruction (McGehee, 2011 pers com.).

Gabions can also be used as "sleeping defence" structures against extreme events and covered by sufficient sand (ideally vegetated dunes), which will reduce routine maintenance costs. **While Gabion structures may be durable and relatively low-cost, they should probably be regarded as temporary measures based on the above review. Rock filled wire basket & mattress structures employed as shore protection measures may not to be appropriate for *permanent* solutions to the more severe erosion problems possibly encountered in some areas or expected in more areas in the future.**

D Combined options

Many combinations of the above options are possible. For example, to reduce the high sand loss rate from a discrete localised beach nourishment project, groynes (probably L or T shaped) could be added on either side (and within) the nourishment area. However, the disadvantages associated with groynes will still be applicable.

In areas where the beach is artificially widened a constructed vegetated buffer dune may be required to manage wind-blown sand and thereby also maintain the sand within the beach-dune system.

7.2.3 Summary list of potential solutions

The following potential options to respond and adapt to the impacts of climate change have been identified for the study areas.

A “Management options”

A1 “Accept and retreat”: repositioning infrastructure at risk; zoning, set-back lines, resettlement, etc.
A2 “Abstention” involves the ‘do nothing’ option. (If the risk of loss of property or human life is very minimal.)
A3 “Alternative” coastal developments: develop “safe” alternative coastal areas including services.
A4 “Accommodation”: increase resilience and accommodate impacts on infrastructure e.g. raising property.

B “Soft engineering” or Restoration (“semi-natural” interventions in the littoral zone)

B1 Sand nourishment: pump extra sand onto the beach to build it up and reduce wave impacts & flooding.
B2 Managed (vegetated and/or reinforced) dune. Construct/reinstate and/or manage vegetated dune areas.
B3 Mangroves, corals and wetlands. Expand/reinstate and manage/protect such natural defences.

C “Hard engineering” & armouring (construct shore protection measures)

C1 Seawalls & revetments: sloping, vertical or curved concrete/rock structures.
C2 Dikes: massive sloped (landscaped and vegetated) loose standing sand/ earthen mound.
C3 Perched beach structures: artificially keep the upper part of the beach profile in place
C4 Shore-parallel structures (e.g. artificial surf zone reefs, detached breakwaters, rock berms, etc.).
C5 Groynes (straight, curved, T, L etc.) placed perpendicular or at angle to shoreline, can trap sediment
C6 Spending beach of very coarse sand, gravel or cobbles: dissipates wave energy & erosion.
C7 Beach (and dune) dewatering mechanism. Sediment “stability” can be increased
C8 Coastal flood control gates in “enclosed” areas (e.g. river mouths, small bays).

In low to moderate wave energy environments:

C9 Closely spaced piles or wave fences to dissipate wave energy.
C10 Floating moored “breakwater” type structures.
C11 “Geotextile” shore protection, usually sand filled geotextile containers.
C12 Gabions and/or rock filled wire basket & mattress structures.

D Combined options

A combination of two or more of the identified solution options may be required.

7.3 EVALUATION CONSIDERATIONS AND CRITERIA

The considerations or criteria used to evaluate the different options focus mainly on the practical and technical aspects. The main technical consideration is whether the solution will adequately address the project aims. Another critical aspect is the expected cost. Further practical aspects include issues such as that the recommended solution should ideally address possible existing background coastal erosion problems. The solutions should also be as environmentally friendly as possible. However, ecological considerations (that is, impacts on the fauna and flora) must be taken into account; similarly social issues must be properly accounted for. Also, aesthetic impacts should be considered. Thus, the main considerations in choosing between the options are effectiveness in adapting to expected climate change impacts (e.g. increasing beach width), environmental aspects, costs, and possibly whether the option has a dual purpose in also addressing possible existing background coastal erosion problems. Impaired beach (and possible inter-tidal rocky area) usage and aesthetic impacts should also be assessed.

Useful guidelines have been published (SNH, 2000) that aid the decision making process regarding the approach to follow, as summarized in Table 7.2 below:

Table 7.2: Selection of shoreline management options based on assets at risk (adapted from the literature)

Asset	Recommended approaches:
Replaceable (e.g. caravans, golf tees/green, car parks, amenity buildings, etc)	• Move or rebuild assets inland (adaptive management), plus minor temporary works to delay the onset of the move (i.e. fencing, planting, beach re-cycling, sand bag or gabion revetments). Total costs typically range from very low to \$ 90 000 per 100 m alongshore.
Moderate economic value or medium residual life (5-25 years*) (Low density housing, roads, large caravan sites, military installations, etc)	• Series of nearshore breakwaters • Rock groynes (on mixed sediment beaches where littoral drift is active and downdrift erosion is not an issue) • Beach nourishment (with future top-ups, and possibly buried rock revetment) • Rock revetment • Total costs typically range from \$ 150 000 to \$ 750 000 per 100 m alongshore. • However, it is emphasised that if the erosion is long-term, backshore assets should not be enhanced or replaced, thereby allowing for ultimate abandonment.

**Note: These useful guidelines have been adapted from the literature, which includes a suite of responses including short lifespan options, although the main planning period considered in this report is generally 50 to 100 years.*

A critical consideration in evaluating the different options is the expected cost. Some costs have been estimated as summarized in the table below. (These estimates are mainly adapted from South African experience, but are supplemented by some experience in other African countries and limited international inputs.)

Table 7.3: Summary of some adaptation option cost estimates

DESCRIPTION	Approximate Minimum Costs (excl tax) for 1km	Approximate Maximum Costs (excl tax) for 1km	Approximate Minimum Costs (excl tax) for 10km	Approximate Maximum Costs (excl tax) for 10km
Sand feeding (beach nourishment) new @ rate of 300 000 m^3/a for 10 yrs)	$4 000 000	$60 000 000	$40 000 000	$600 000 000
Sand feeding (beach nourishment) maintenance	$400 000?	$7 780 000?		
Revetments & walls (permeable)	$2 300 000	$24 000 000	$23 000 000	$240 000 000
Vegetated dune	$750 000	$7 200 000	$7 500 000	$72 000 000
Geotextile sand containers, Geobags (semi-sheltered location)	$1 100 000	$23 000 000	$11 000 000	$230 000 000
Gabions (semi-sheltered location)	$600 000	$7 000 000	$6 000 000	$70 000 000
Rock groynes	$1 000 000	$29 200 000	$10 000 000	$292 000 000
Wave Fence (semi-sheltered location)	$2 300 000	$40 000 000	$23 000 000	$400 000 000
Floating pontoons (semi-sheltered location)	$2 250 000	$31 600 000	$22 500 000	$316 000 000
Rubble-mound breakwater structure land based	$1 500 000	$15 100 000	$15 000 000	$151 000 000
Rubble-mound breakwater: marine based	$2 900 000	$42 800 000	$29 000 000	$428 000 000
Sheet piling seawall (shore parallel)	$2 700 000	$36 000 000	$27 000 000	$360 000 000

A significant proportion of the costs for most coast protection materials is in the transport and placement. Work on dune systems can impose additional costs due to concerns over destruction of landforms and habitats, and the problems of working in locations lacking access. Delivery from the sea of bulk materials (rock or beach sediment) is often preferred as backshore damage is minimised, although land access will still have to be provided for plant, labour and additional materials. Parts of the Mozambican coast are very exposed or have very shallow in-shore areas; thus sea access is also very difficult (expensive and risky). Haul roads will have to be built across the dunes unless access can be provided from an existing route. (Rock supply, plant availability and access are big cost factors especially relevant to parts of Mozambique.) Thus, there are many local factors and other details such as local supplier pricing, which will have a big impact on project costs. (This is why the band between minimum and maximum cost estimates in Table 7.3 is so wide, to ensure as far as can be foreseen that the actual costs should be between these limits.) These can only be assessed properly at the detail design stage of specific projects. Besides direct capital costs it is critical to consider maintenance costs and life expectancy of the option. *Solutions MUST be sustainable*, which means the recommended options must also be durable and affordable to the Municipality and/or State (or responsible authority).

In choosing adaptation options it is also very important to consider the impacts to habitat, landform, landscape, coastal processes, etc. Consideration should be given to the full life environmental impacts of proposed management intervention/operations. The manager/responsible authority must consider not only the local short-term impact of a scheme, but also the following aspects (adapted from literature):

- the impact on the source area for materials (offshore dredging areas, rock quarry, etc)
- the impact of transport to the site (road congestion and surface damage, noise levels, risk of accidents at sea or on roads, access through dunes, etc)

- the impact of damaged or life expired materials on the shoreline (synthetic fencing materials, geotextile sand bags, gabion baskets and rock fill, timber, concrete, rock, etc).
- the long term evolution of the beach and dunes and the effectiveness of structures over their full life.

Management plans should allow for these environmental impacts during the decision process, particularly where costs are being passed on to future generations. Mitigation measures and good working practices to minimise impacts should be built into designs, agreed with contractors and monitored rigorously during initial and ongoing operations.

A pertinent comparison and assessment of most of the options has been reported in the literature, as summarised in Table 7.4, below.

Table 7.4: Relative costs, life expectancy and potential environmental impacts associated with shoreline management options (adapted from SNH, 2000)

(= low, ***** = high)*

Option	Impacts (1)				Costs (5)		
	Habitat	Landform	Landscape	Processes	Capital	Maintenance (2)	Life Expectancy (3)
Adaptive management	**	**	**	*	Dependant on assets	*	*****
Grass planting, Thatching, Dune fencing	*	*	*	*	*	***	*
Sandbag structures	**	**	**	**	**	*	**
Beach drainage	*	*	*	**	***	**	*
Beach nourishment	**	*	*	*	***	***	**
Gabion revetments (4)	***	***	***	***	***	**	***
Artificial headlands	**	**	***	***	***	*	***
Artificial reefs	**	**	***	***	***	*	***
Nearshore breakwaters	***	**	****	***	***	*	***
Groynes	***	***	***	***	***	*	***
Rock revetments (4)	****	****	*****	****	****	*	*****
Timber revetments (4)	***	***	****	***	****	*	***
Impermeable revetments/seawalls	****	*****	*****	****	*****	*	****

1. *Impacts over full life-cycle of option*
2. *Maintenance cost relative to capital cost (to retain design benefits)*
3. *Life expectancy of benefits without maintenance*
4. *If buried into the dune face the impacts associated with these approaches are lowered and the life expectancy increased; capital costs may be higher but maintenance costs lower.*
5. *These cost indications are more applicable to Europe and possibly less so for Mozambique*

Note, Table 7.4, as taken from the literature, does not include all the options considered for Mozambique. A further assessment by the authors (based on southern African experience) of some of the options is summarized in Table 7.5 below.

Table 7.5: Comparative functionality/suitability of some potential adaptation measures

Suitability Criteria / **Adaptation Alternative**	**Shoreline stability**	**Wave attenuation potential**	**Inundation due to SLR mitigation potential**	**Environmental & social impact**	**Relative cost**	**Relative design life**	**Maintenance Cost**	**Maintenance Frequency**
~~**Do nothing**~~	~~Low~~	~~Nil~~	~~Nil~~	~~Nil to high~~	~~Nil~~	~~-~~	~~-~~	~~-~~
Shoreline Nourishment	Medium to high	Low to high	Low to high	Low	Medium to high	Short to medium	Medium	Medium
Revetment	High	High	High	High	High	Long	High	Low
Detached Breakwater	Limited	Limited	Nil	Medium	Medium to high	Long	High	Low
Sill	Medium to High	Medium	Low	Medium	Medium	Long	Medium	Low
Submerged breakwater	Limited	Limited	Nil	Low to medium	Medium to high	Long	Medium	Low
Wave fence – fully reflective	Medium to high	~~High~~	~~Nil~~	Medium to high	Low to medium	~~Medium~~	~~Low~~	~~High~~
Wave fence – ~~partially~~ reflective	~~Medium~~	~~High~~	~~Nil~~	~~Medium~~	Low to medium	~~Medium~~	~~Low~~	~~Medium~~
Floating ~~breakwater~~	Medium	Medium	Nil	Low to ~~medium~~	Medium	Medium	Medium	High

Note: Effectiveness, impacts and costs can vary significantly due to local site characteristics, availability of materials, access and transport costs

In Table 7.5 the functionality and suitability of some coastal climate change (CC) adaptation measures are assessment and compared:

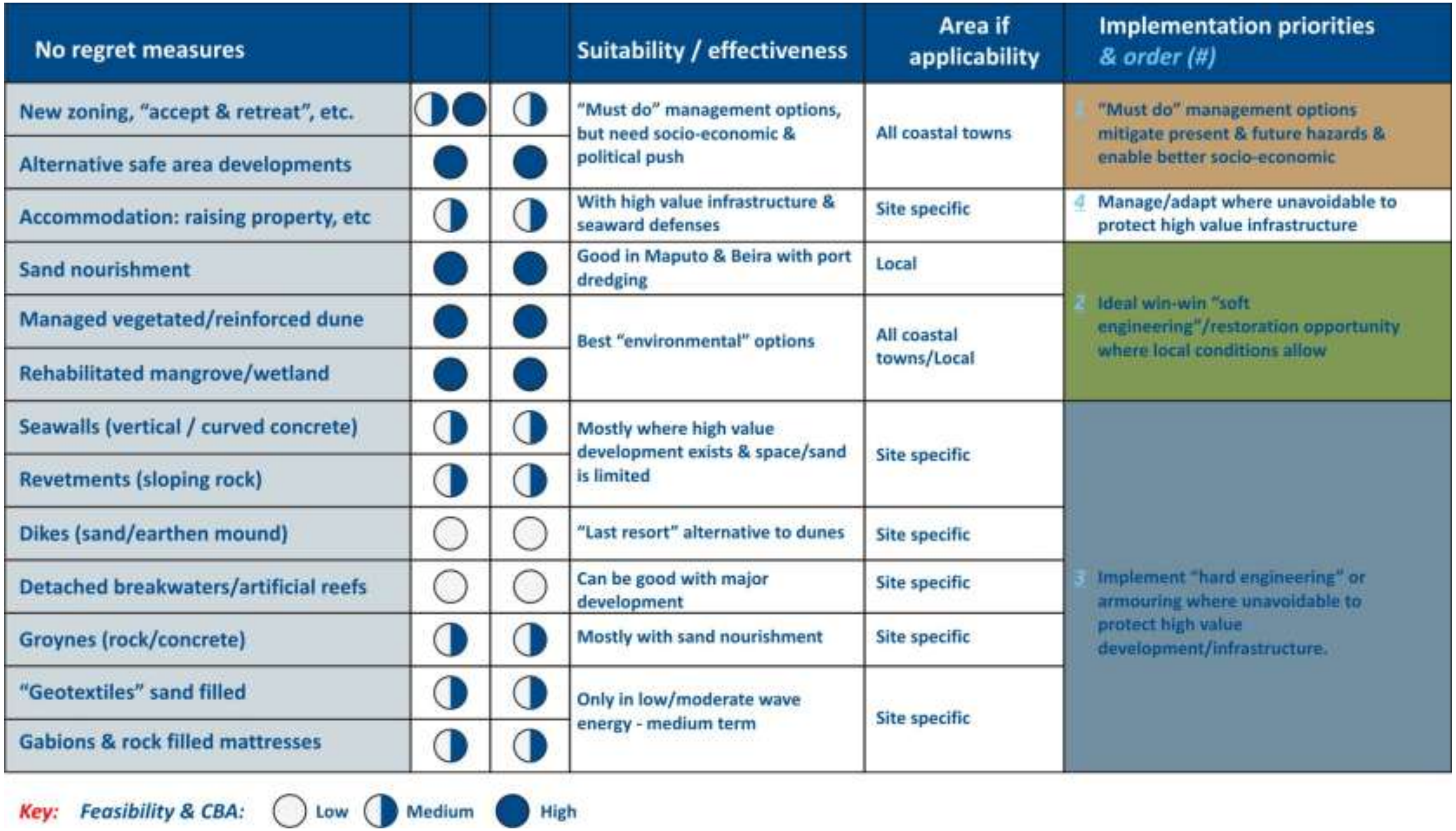
- The 1st column lists 9 adaptation alternatives/options. Columns 2 to 4 assess the functionality of each option, respectively in terms of: “shoreline stability” (i.e. how effectively will the shoreline location be “fixed” in place), “wave attenuation potential” (i.e. how effectively will wave energy be dissipated), and “inundation due to SLR (sea level rise) mitigation potential” (i.e. how effectively will flooding due to SLR be prevented). The most direct measure of effectiveness in meeting the objective of reducing the coastal CC impacts is "inundation due to SLR mitigation potential". Thus, a score of "nil" here should almost eliminate such options.
- Columns 5 to 9 assess the suitability of each option, respectively in terms of: adverse “environmental or social impacts”, relative cost of each option, relative design life (or

durability), cost of maintenance required for each option, and required frequency of maintenance.

- To facilitate a quick comparison of the different options, all "good" assessments of functionality/suitability have been coloured in green, while unfavourable assessments are coloured in red. Thus, in general, the "better" or "more suitable" options have relatively many green blocks and few red blocks. Of the 9 options listed here, "shoreline nourishment" and "revetments" are therefore generally preferred. Note, however, that the effectiveness, impacts and costs can vary significantly due to local site characteristics, availability of materials, access and transport costs.
- Four of the options have been identified as generally not suitable to most of the study sites in Mozambique (in terms of effectiveness in meeting the objective of reducing coastal CC impacts); red lines have been drawn through these options in Table 7.5.
- All of the structural options would have significant environmental impacts, including enhanced downdrift coastal erosion.
- Some of the best options available are to address the causes of existing erosion (i.e. for Maputo: feed dredged port entrance channel sand to the main beachfront area with appropriately coarse sand or large scale ad hoc nourishments). All large sand nourishment projects are likely to benefit a much more extensive (alongshore) area in the long-term. In this respect, the opportunities presented by future capital dredging projects for port expansions must be fully exploited. Even if a fairly large percentage of such dredged material is considered less suitable or inappropriate (too much fine sediment) for "ideal" beach nourishment, this must be critically reviewed. In view of the present and future erosion impacts and hazard prone state of the coastal environment, the negative ecological environmental impacts (probably temporary) from pumping otherwise too fine material onto the beaches, are likely to be considerably less than the ultimate environmental (and socio-economic) good that would result from beach nourishment even with a much lower than "normally" acceptable proportion of coarser sediment.

Based on the foregoing evaluation consideration and criteria, and including all appropriate options, the priority adaptation/"no-regret" measures were grouped according to type and impact, covering the most relevant Climate Change issues for Mozambique coastal towns and cities, as summarized in Table 7.6 below. The measures were assessed in terms of general feasibility, cost/benefit applicability (CBA), suitability/effectiveness and area of applicability. Thereafter the general priorities for implementation were identified and the preferred order of implementation was determined as also indicated in the table.

Table 7.6: *Priority adaptation/no-regret measures*



No regret measures			Suitability / effectiveness	Area if applicability	Implementation priorities & order (#)
New zoning, "accept & retreat", etc.	◐●	◐	"Must do" management options, but need socio-economic & political push	All coastal towns	1 "Must do" management options mitigate present & future hazards & enable better socio-economic
Alternative safe area developments	●	●			
Accommodation: raising property, etc	◐	◐	With high value infrastructure & seaward defenses	Site specific	4 Manage/adapt where unavoidable to protect high value infrastructure
Sand nourishment	●	●	Good in Maputo & Beira with port dredging	Local	2 Ideal win-win "soft engineering"/restoration opportunity where local conditions allow
Managed vegetated/reinforced dune	●	●	Best "environmental" options	All coastal towns/Local	
Rehabilitated mangrove/wetland	●	●			
Seawalls (vertical / curved concrete)	◐	◐	Mostly where high value development exists & space/sand is limited	Site specific	3 Implement "hard engineering" or armouring where unavoidable to protect high value development/infrastructure.
Revetments (sloping rock)	◐	◐			
Dikes (sand/earthen mound)	○	○	"Last resort" alternative to dunes	Site specific	
Detached breakwaters/artificial reefs	○	○	Can be good with major development	Site specific	
Groynes (rock/concrete)	◐	◐	Mostly with sand nourishment	Site specific	
"Geotextiles" sand filled	◐	◐	Only in low/moderate wave energy - medium term	Site specific	
Gabions & rock filled mattresses	◐	◐			

Key: Feasibility & CBA: ○ Low ◐ Medium ● High

Key:

(Note, a high CBA (Cost/Benefit Assessment) is taken as a positive indicator, meaning in fact that the benefits outweigh the costs, and could thus perhaps be stated more logically as BCA (Benefit/Cost Assessment) in terms of a positive metric. However, to remain consistent with the terminology used in the other themes, CBA is retained here.)

CHAPTER 8: DISCUSSION ON POSSIBLE ADAPTATION OPTIONS PER STUDY SITE

Before going into the detailed adaptation recommendations for each city/town, it is important to reiterate that **the strategic principles and guidelines on planning for and responding to coastal impacts and including specifically climate change impacts, as discussed in Section 7.1, should be adopted and implemented forthwith**. This will go a long way in reducing the need for constructing expensive coastal defences in many instances, especially in the long-term.

8.1 SITE SPECIFIC ANALYSIS AND RECOMMENDED PRIORITIZED ADAPTATION ACTIONS

The derivation of final recommendations for site specific ‘no regret’ adaptation measures entailed the following tasks/actions:

- A literature survey (Chapter 7)
- Assessment against the evaluation considerations and criteria (Section 7.3)
- Use of coastal engineering practice and experience
- On site observations and surveys during a field mission in May 2010
- Consensus within a multi-disciplinary coastal specialist team

Following a conservative and precautionary approach with the aim to be pro-active and prevent or lower the risk to lives, livelihoods and infrastructure, a list of prioritized adaptation response actions for each town and city was derived and is provided in the form of annotated diagrammes on Google-Earth$_{TM}$ images (Figures 8.1 to 8.17). The specific engineering design details and accurate costing of each option can only be done once site specific engineering and environmental investigations have been carried out. It is absolutely critical to involve experienced coastal engineering and coastal environmental professionals in the detailed planning, design and implementation of the chosen options.

To illustrate the assessment approach and the way the results are presented for each study site, the city of Beira is used as the example in section 8.1.1 below. The results for the other study sites are presented in a similar manner.

8.1.1 Beira

Large areas in and around the city of Beira are low-lying (Figure 6.5) and thus are vulnerable to the forces from the sea. Major areas could be flooded at present should a cyclone reach Beira at the same time that the tide is at the Mean High Water Spring (MHWS) tide level. Due to the projected increase in the frequency of cyclones under climate change scenarios (Chapter 5), this situation will occur more often as the sea level rises in time. A Google-Earth$_{TM}$ image of Beira with numbered yellow location markers at 0.5 km intervals along the coastline is shown in Figure 8.1.

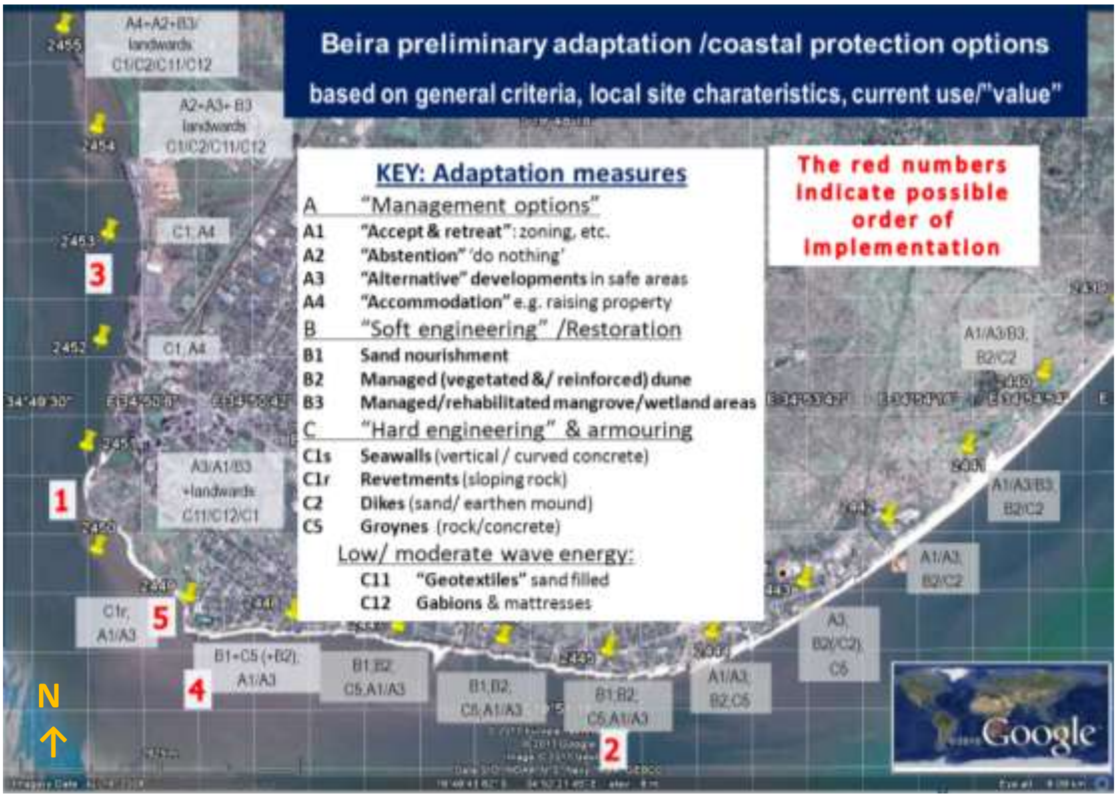


Figure 8.1: Beira. Adaptation / coastal protection options based on general criteria, local site characteristics and current use/"value."

Using the information discussed in Chapter 7 as the basis, the short-list of the key adaptation measures found to be most suitable for Beira (summarised in the large white block in Figure 8.1), which includes four "Management options" (labelled A1 to A4), three "Soft engineering"/Restoration measures (B1, B2 & B3), four "Hard engineering" & armouring options (C1s, C1r, C2, C5), and two options more suitable for low/moderate wave energy sites (C11 & C12). (Note that the focus of this project is on longer term adaptation measures such as those recommended here. However, emergency response options/actions, such as marking flood evacuation routes and keeping them open are also critical response actions. It appears that the INGC has already been successful in applying such measures.)

The three or four options or combination of options considered most suitable for each 0.5 km alongshore section of the coast are indicated in the small white block adjacent to each marker on the map. The labels within each small block (e.g. A1 or C5, etc.) refer to the labelled options described in the large white block.

The large red numbers (1 to 4) on the figures indicate the recommended order of implementation of the identified coastal adaptation measures for Beira. In other words, Figure 8.1 represents a "plan" or "map" summarising the preferred adaptation options along each 0.5 km section of the western, southern and south-eastern Beira coast.

Referring to the discussions in Chapters 5 and 6, the "sea water flooding hazard" levels for Beira (Figures 5.32 and 6.3) show that along the semi- exposed and exposed locations, labelled 2440 to

2455 in Figure 8.1, for a 1m sea level rise (by 2100) plus a run-up of +1.5 m during cyclonic events, that areas below +7.4 m MSL will be in danger of being flooded. In lieu of better topography data and detailed flood inundation modelling, the 8 m MSL contour is taken as the line roughly up to where the sea water could potentially reach from such an event. (Note that as indicated before in Section 6.2.2, although this is the correct theoretical flooding level for this combination of events, the actual landward extent of the flooded area would not extend all the way to the +8 m contour in many locations, as "on-land" factors such as the roughness (due to buildings, trees, etc.) will reduce the actual landward extent of the flooded area. This is not accounted for in most run-up models, including the Nielsen & Hanslow model applied in this project. In addition, the contours are not based on accurate topographical data, and therefore can only give a rough indication of where the accurate contour location is in reality. These comments are applicable to all of the study areas.) This intermediate flooding level is appropriate for planning and management of infrastructure along the semi- exposed locations # 2451 to 2455 in Figure 8.1, or with a structural design life of less than 50 years along the exposed locations # 2440 to 2450.

The low hazard risk level along the exposed locations # 2440 to 2450 for important infrastructure with a design life of more than 50 years (such as ports and airports) is +9.9 m MSL, taken as the rough +10 m MSL contour (arriving from the extreme scenario of a +2 m sea level rise along with a 3 m storm run-up level during cyclones).

The recommended adaptation options along parts of the Beira coast are shown and discussed in more detail in the following pages.


Beira detail adaptation /coastal protection options
Priorities 1 and 3

Figure 8.2: Western Beira. Adaptation / coastal protection options based on general criteria, local site characteristics, current use / "value"

The preferred option for the mangrove/wetland and informal settlement area on the western side of Figure 8.2 between markers 2449 and 2451 (the Ponta Gea – Cabedelo area) is management actions such as alternative developments in "safe" areas, zoning and "accept and retreat". This area is very low-lying, highly vulnerable to flooding and erosion, with very limited present infrastructure investment and should preferably be managed as a more natural area, as portions of this area are still functioning at present. The natural wetland also provides a valuable natural filtering and nursery habitat 'ecosystem service' which is impacted on by the informal activities.

The landward edge of this mangrove/wetland area (at the edge of the existing formal development), as indicated by the dashed orange line in Figure 8.2, should eventually be protected by preferably a rock revetment (or potentially a concrete seawall if affordable). (Note that this requires a suitable source of rock material, including an adequate stockpile of material for timeous repairs after damages resulting from extreme events.) As this location is at present relatively sheltered, the revetment could also be constructed by means of gabions (on rock mattresses or even sand filled geotextile structures if suitable rock is not readily available). Such constructions can be significantly cheaper to build than conventional rock revetments, but may require more maintenance.

Quay walls, warfs, storage areas, transport infrastructure, etc. located in the vicinity of the existing port infrastructure will have to be raised in stages to an estimated level of at least +7.4 m MSL by 2100, but this level should be revised (say at 10 year intervals) as more accurate SLR projections become available in future. The protecting seawalls will have to be similarly raised where possible, or new walls constructed. The existing infrastructure is already too low at present (i.e. excluding SLR) and needs to be upgraded and maintained as a matter of urgency (Priority # 3 for Beira). (Note, this recommendation means that the port infrastructure should be upgraded to deal with CC risks in its present location, including raising the infrastructure in stages, eventually to above the level of +7.4 m MSL, *not* that the port should be relocated to landward of the +7.4 m MSL contour line, which would render it inoperable. The same interpretation goes for the other ports, e.g. Beira and Nacala.)

Figure 8.3: Southern Beira. Adaptation / coastal protection options based on general criteria, local site characteristics, current use/ "value".

Figure 8.3 shows the recommended adaptation options along the southern Beira coast in more detail.

The preferred option here is for beach nourishment, i.e. increasing the beach width and volume by placing additional sand on the beach. The source of this sand feeding should ideally be *suitable sand* from the sediment dredged from the entrance channel to the port (maintenance dredging to maintain shipping access to/from the port). At some locations along the access channel, the sand reportedly has similar characteristics as the sand of the shoreline (Achimo, pers. com. 2012).) This will result in significant cost savings (compared to alternative dredging from other marine sediment sources), and will also return "riverine"/coastal sediments to the inshore zone where a large proportion of it would naturally have been transported to, were it not "artificially" removed from the area by dredging.

The longshore sediment transport is usually from east to west along this area. (as can be seen by the accumulation of sand on the eastern side of the existing groynes). Therefore, the sand feeding should be done in the eastern part of this coastal sector (in the area of the solid green arrow in Figure 8.3). In this way, the sand can be transported towards the west by the natural wave and current action, thus eventually nourishing the whole of the southern Beira coastal area (indicated by the dashed green arrows). (The small photographs indicate the 2 main means of delivering the sand, namely by "rainbowing" (sand-spraying) directly from the dredger – also see Figure 7.1 - or by means of pumping and spreading through pipelines – also see Figure 7.2.) Where shallow areas prevent the dredger from coming close in to the shore, such as some areas of Maputo and Beira, pumping through pipelines may be required, which is likely to increase the cost.). At present the beach along much of this area is too narrow to accommodate a sufficiently wide and high dune to adequately protect landward development. However, after implementation of the sand feeding scheme and ongoing beach nourishment the beach width should increase sufficiently to enable a proper managed dune system. A dune of sufficient volume will greatly bolster the natural resilience of the coast against climate change impacts. The dune area is indicated by the double green line (dashed).

To enhance the accreted beach width further or potentially "trap" a portion of the alongshore sand transport, groynes could also be added later if required. The additional beach area thus "secured" as well as multifunctional structures (e.g. piers/groynes), can provide alternative coastal development potential, whilst also planning for potential down-drift erosion effects. (This again requires a suitable source of rock material.)

The large red numbers in the Figures 8.3 and 8.4 indicate the possible order of implementation of coastal adaptation measures. Thus, it is preliminarily recommended that the sand feeding scheme should be the 2nd coastal adaptation measure to be implemented. (The other 4 of the 1st five measures to be implemented are indicated in the rest of the figures relating to Beira.)

Figure 8.4: South-western Beira. Adaptation / coastal protection options based on general criteria, local site characteristics, current use/"value".

Figure 8.4 shows the recommended adaptation options along the south-western Beira coast in more detail.

The beach nourishment scheme from the east (Figure 8.4) would continue westward into this coastal area (alongshore) up to the Ponta Gea area (adjacent to Comandante Gaivao Ruo Do). At this location a relatively long terminal groyne (i.e. the "last" or "end" groyne in a groyne field) should be added. This structure should be constructed from concrete or rock if available, as indicated by the red "4" on the figure. The purpose of this groyne would be to increase the beach width and to reduce the amount of sand that could potentially be transported into the harbour entrance channel (by "trapping" a portion of the alongshore sand transport). The additional beach area thus "secured" as well as a multifunctional structure (e.g. pier/groyne), can provide alternative coastal development potential, possibly as a PPP initiative associated with a hotel complex.

To protect the area north-west of this groyne as well as to prevent down-drift erosion effects (on the western side of the groyne), a 400 m long revetment should be constructed, from concrete or preferably rock if available, as indicated by the red "5" on Figure 8.4. A small rock revetment is already present in this area.

Figure 8.5: South-eastern Beira. Adaptation / coastal protection options based on general criteria, local site characteristics, current use/"value".

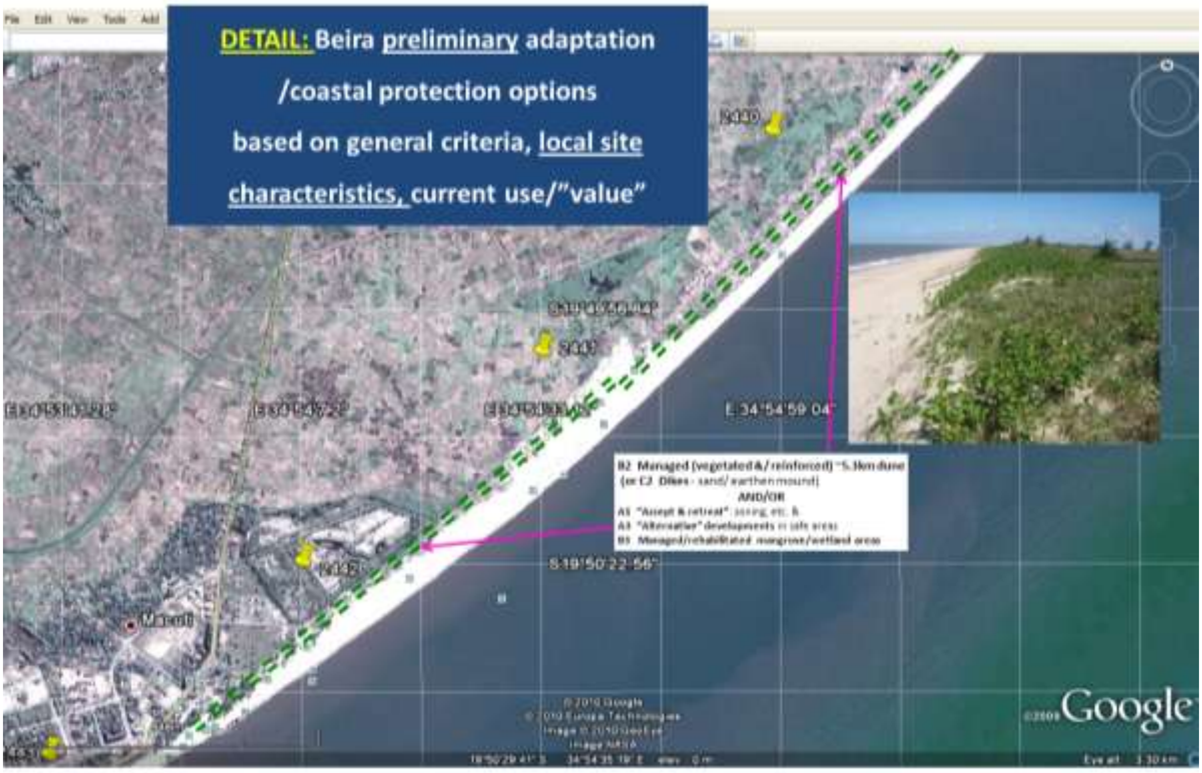


Figure 8.6: South-eastern Beira. Adaptation / coastal protection options based on general criteria, local site characteristics, current use/"value".

Figures 8.5 and 8.6 show the recommended adaptation options along the south-eastern Beira coast in more detail. The preferred option here is for a managed dune (i.e. vegetated and maintained). (Eventually, as the sea level increases, the dune could also be extended or expanded into a "dike" type defence measure.) "Managed" includes installing and maintaining effective people control mechanisms such as providing sufficient (many) formal access pathways across the foredune and information signage. This is required to prevent the damage and loss of dune vegetation and resultant loss of dune volume due to wind-blown sand. The initial alongshore extent of the dune area is indicated by the double green line (dashed).

The dune construction (and enhancement of the existing dune towards the east) should be done in conjunction with management actions such as coastal development setbacks, zoning and alternative developments in "safe" areas.

Cost estimates for priority Beira adaptation measures

Cost estimates were made for the two locations which will have the highest adaptation costs (being the areas where the most infrastructure and development occurs), namely Maputo and Beira. Based on the foregoing, costs have been estimated roughly for implementation of the priority adaptation measures as summarized in Table 8.1 below. However, our recommended 1st priority for Beira is "alternative development in safe location" of the present informal settlement in the wetland area, and re-zoning of this area (no development and rehabilitation of the mangroves and wetland; see Figure 8.2. A cost estimate for this adaptation measure has not been made since there are many external and socio-economic factors which will determine the cost of implementing such recommendations, versus the direct and indirect benefits (and "future cost savings"); this could only be properly considered in an in-depth socio-economic study.

8.1.2 Maputo

The short-list of the key adaptation measures found to be most suitable for Maputo includes four “Management options” (labelled A1 to A4), three “Soft engineering”/Restoration measures (B1, B2 & B3), four “Hard engineering” & armouring options (C1s, C1r, C2, C5), and two options more suitable for low/moderate wave energy sites (C11 & C12). (As mentioned before, the focus of this project is on longer term adaptation measures such as those recommended here. However, emergency response options/actions, such as marking flood evacuation routes and keeping them open are also critical response actions in Maputo and all other coastal cities. It appears that the INGC has already been successful in applying such measures.)

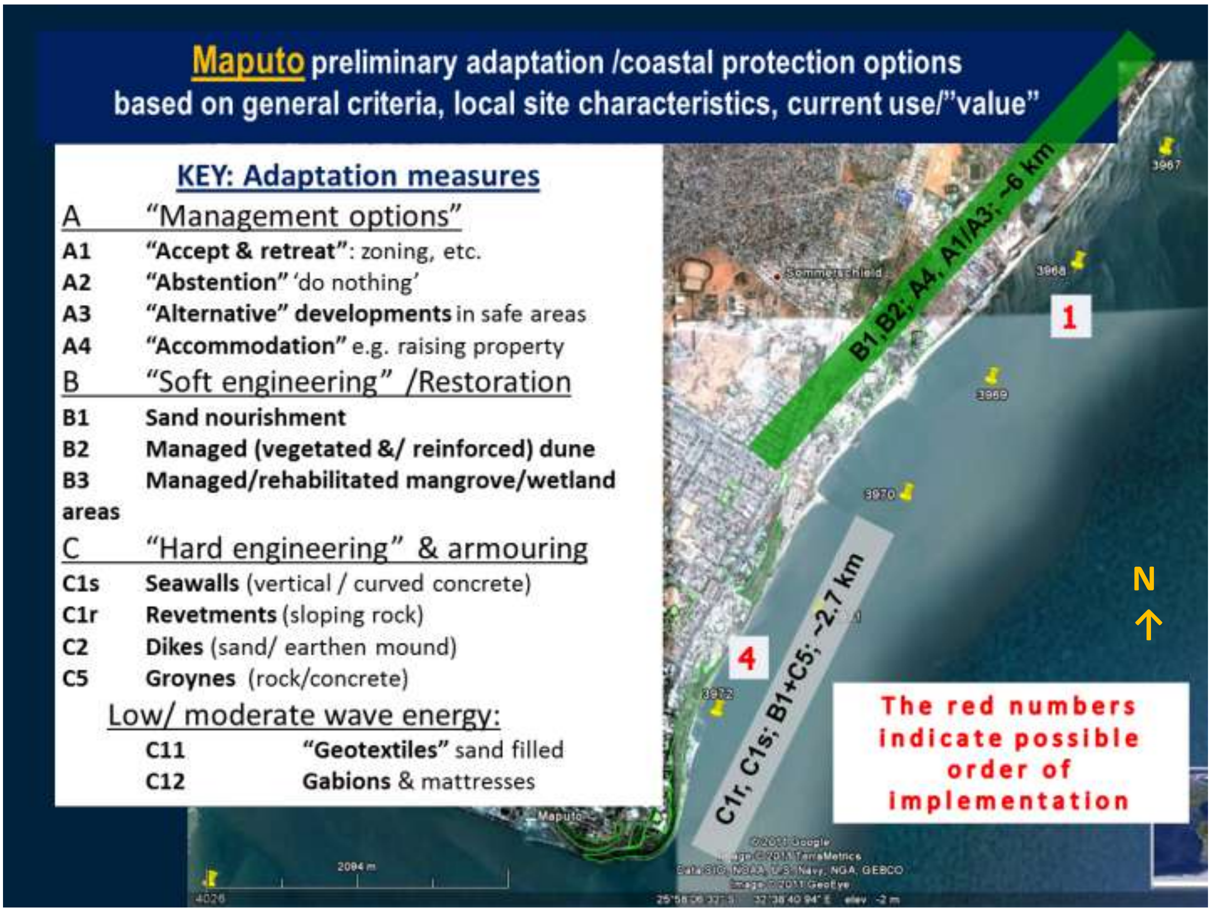
Referring to the discussions in Chapters 5 and 6, the “sea water flooding hazard” levels for the Maputo and Matola area (Figures 5.33 and 6.3) show that along the semi- exposed and exposed locations for a 1m sea level rise (by 2100) plus a run-up of +1.5 m during cyclonic events, that areas below the +6 m contour will be in danger of being flooded. This intermediate flooding level is appropriate for planning and management of infrastructure along the semi- exposed south-western Maputo shoreline, or with a design life of less than 50 years along the exposed south-eastern Maputo shoreline. Taking a conservative and precautionary approach, the low hazard risk level along the exposed south-eastern Maputo shoreline for important infrastructure with a design life of more than 50 years (such as ports and airports) is +8.5 m MSL, (based on the extreme scenario of a +2 m sea level rise along with a 3 m storm run-up level during cyclones).

The recommended adaptation options along parts of the Maputo coast are shown and discussed in more detail in the following pages.

Table 8.1: Summary of some adaptation option costs for Beira - coastal construction capital cost estimates (2011).

Possible order of implementation	DESCRIPTION	Approximate Minimum Costs (excl tax) for 1km	Approximate Maximum Costs (excl tax) for 1km	Approximate length (or number of) proposed for Beira (km)	Approximate Minimum Costs (excl tax) for Beira	Approximate Maximum Costs (excl tax) for Beira
2	Sand feeding (beach nourishment) new* @ rate of 300 000 m^3/a for 10 yrs)	$4 000 000	$60 000 000	1	$4 000 000	$60 000 000
5	Revetments & walls (permeable)	$2 300 000	$24 000 000	2.3	$5 290 000	$55 200 000
4	Rock groynes**	$1 000 000	$29 200 000	1	$1 000 000	$29 200 000
3	Sheet piling seawall (shore parallel)	$2 700 000	$36 000 000	3.5	$9 450 000	$126 000 000
3	Heightening quay walls, berths, other port infrastructure	$2 000 000	$25 000 000	3.5	$7 000 000	$87 500 000
				POTENTIAL TOTAL COST FOR IMPLEMENTING ALL ABOVE ($)	**$26 740 000**	**$357 900 000**

NB:
Costs of “management” options (A1 to A4) not included, e.g. relocation, alternative development of infrastructure, etc.
* Actual nourishment to a point by means of either pipelines with booster pumps from dredger quay or possibly distributed by means of dredger rainbowing off beaches
** Cost estimate for 1 long groyne or 2 shorter groynes



Maputo preliminary adaptation /coastal protection options
based on general criteria, local site characteristics, current use/"value"

KEY: Adaptation measures

A	"Management options"
A1	**"Accept & retreat"**: zoning, etc.
A2	**"Abstention"** 'do nothing'
A3	**"Alternative" developments** in safe areas
A4	**"Accommodation"** e.g. raising property
B	"Soft engineering" /Restoration
B1	**Sand nourishment**
B2	**Managed (vegetated &/ reinforced) dune**
B3	**Managed/rehabilitated mangrove/wetland areas**
C	"Hard engineering" & armouring
C1s	**Seawalls** (vertical / curved concrete)
C1r	**Revetments** (sloping rock)
C2	**Dikes** (sand/ earthen mound)
C5	**Groynes** (rock/concrete)
	Low/ moderate wave energy:
C11	**"Geotextiles"** sand filled
C12	**Gabions** & mattresses

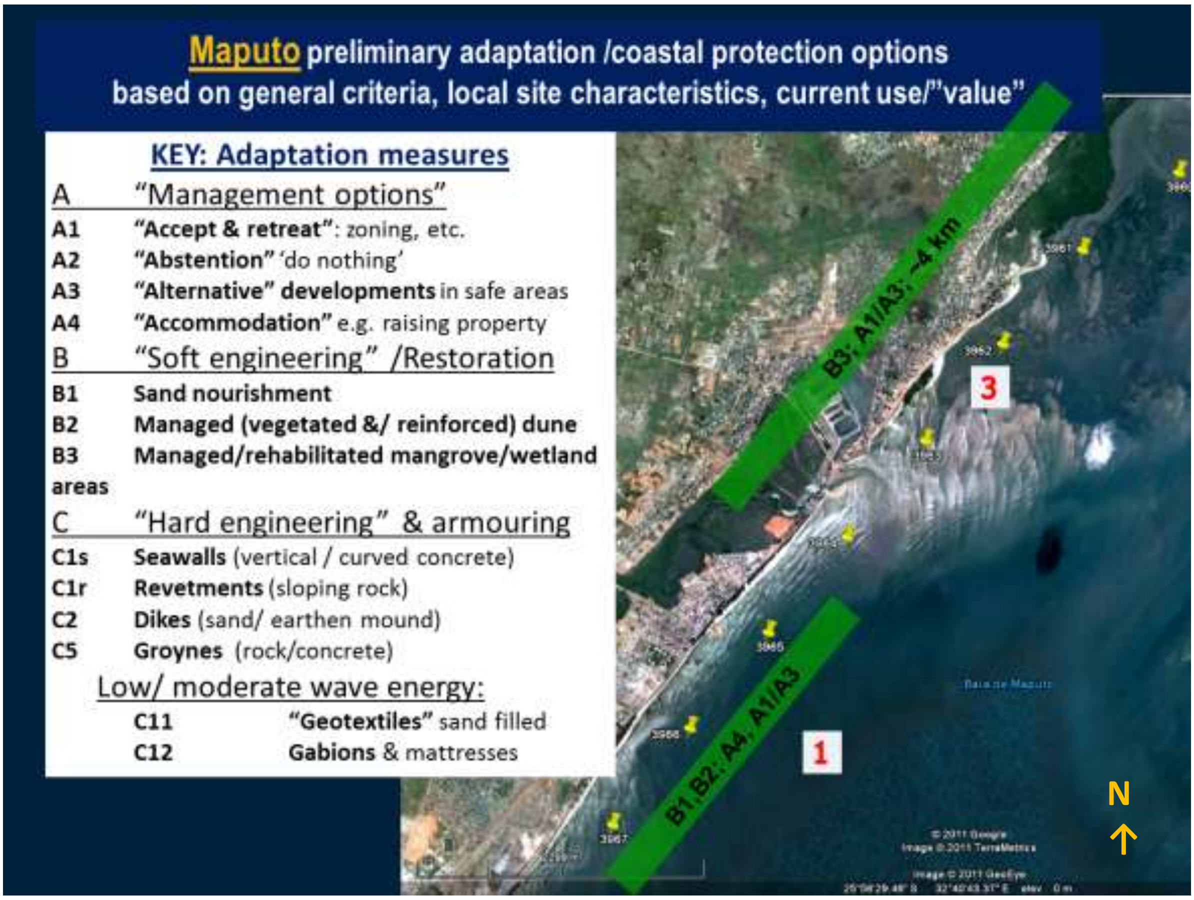
The red numbers indicate possible order of implementation

Figure 8.7: Eastern Maputo. Recommended adaptation /coastal protection options

As before, the three or four options or combination of options considered most suitable for each alongshore section of the coast are indicated on the map in the narrow text blocks adjacent to each section of the coast. The labels within the alongshore text blocks (e.g. A1 or C5, etc.) refer to the labelled options described in the large white block. The large red numbers (1 to 4) on the figures indicate the recommended order of implementation of the identified coastal adaptation measures for Maputo. In other words, Figure 8.7 and the following Figures 8.8 to 8.10 represent plans/maps summarising the preferred adaptation options along each section of the Maputo coast.

As seen in Figures 8.7 and 8.8, there are a lot of areas along the Maputo coastal edge that are low-lying and thus vulnerable to the effects of climate change. The most vulnerable area in the short term is the approximately 6 km stretch of coastal road along the beachfront up to the Costa Do Sol. Management decision-making options (A1, A3 and A4) are mostly the most sustainable and ultimately less costly options along with a number 'soft-engineering' options as indicated in Figures 8.7 and 8.8.

To combat any existing erosion problems, emphasis should be placed on determining the root causes of the problem. (This is the best way to ensure that potential solutions are successful, and could also be more cost effective, more environmentally friendly and sustainable.) Here a practical solution to the erosion of this important section of coastline is to collaborate with the Port of Maputo. The port entrance channel is regularly dredged to keep it deep enough. Our investigations indicate that maintenance dredging that is conducted to facilitate shipping access to the port, is likely to play a significant part in the erosion. Coastal sediments are transported to the shipping channel by currents and are then deposited in this relatively deeper "trap".



Maputo preliminary adaptation /coastal protection options
based on general criteria, local site characteristics, current use/"value"

KEY: Adaptation measures

A "Management options"
A1 **"Accept & retreat"**: zoning, etc.
A2 **"Abstention"** 'do nothing'
A3 **"Alternative" developments** in safe areas
A4 **"Accommodation"** e.g. raising property

B "Soft engineering" /Restoration
B1 **Sand nourishment**
B2 **Managed (vegetated &/ reinforced) dune**
B3 **Managed/rehabilitated mangrove/wetland areas**

C "Hard engineering" & armouring
C1s **Seawalls** (vertical / curved concrete)
C1r **Revetments** (sloping rock)
C2 **Dikes** (sand/ earthen mound)
C5 **Groynes** (rock/concrete)

Low/ moderate wave energy:
C11 **"Geotextiles"** sand filled
C12 **Gabions** & mattresses

Figure 8.8: Eastern Maputo. Recommended adaptation /coastal protection options

The channel is occasionally dredged out and the sediments are disposed of (dumped) in deeper water away from the shoreline (Figure 8.9; Mather pers com 2009). It seems very likely that if suitable dredged sediments could rather be returned to the shoreline, this could alleviate the erosion problems.

A recent investigation by a coastal engineering expert (Dr Andrew Mather) from the Ethekwini Municipality came to the same conclusions. In the bigger scheme of things, both parties would benefit significantly by linking the Port Operations (especially the maintenance dredging) to the municipal coastal protection. The sediments would have to be uncontaminated and of suitable grain size (not too fine), while suitable means of placing the sand on the shore would be required (e.g. "rainbowing" where the dredger can get in sufficiently near to the shoreline and/or pumping – Figures 7.1 and 7.2).

It has also been recently announced that the port is to be upgraded in the near future and this will most likely also entail dredging more areas of the channel. The suitable sand fraction of the material dredged during the maintenance work as well as for any future expansion could be placed along the beachfront by suitable means (Option B1), thereby restoring the natural sediment feeding process. (Much of the dredged material is reportedly very fine sediment, which might be unsuitable for beach nourishment (Achimo, *pers. com.* 2012.) However, selective utilization of the suitable sediment fraction or deposition areas still leave this as an attractive option, that should be investigated in detail.) An alternative reservoir of suitable sand might be the area adjacent to Xefina Island. However, not being a dredging requirement for port access, this option would probably be more expensive. (Considering the volumes of sand required for beach nourishment, delivery by mean of trucks is considered impractical in terms of road congestion, road damage/maintenance, etc.). Combining the sand feeding option with the active management of the dunes (Option B2) will restore the natural buffer in the area.

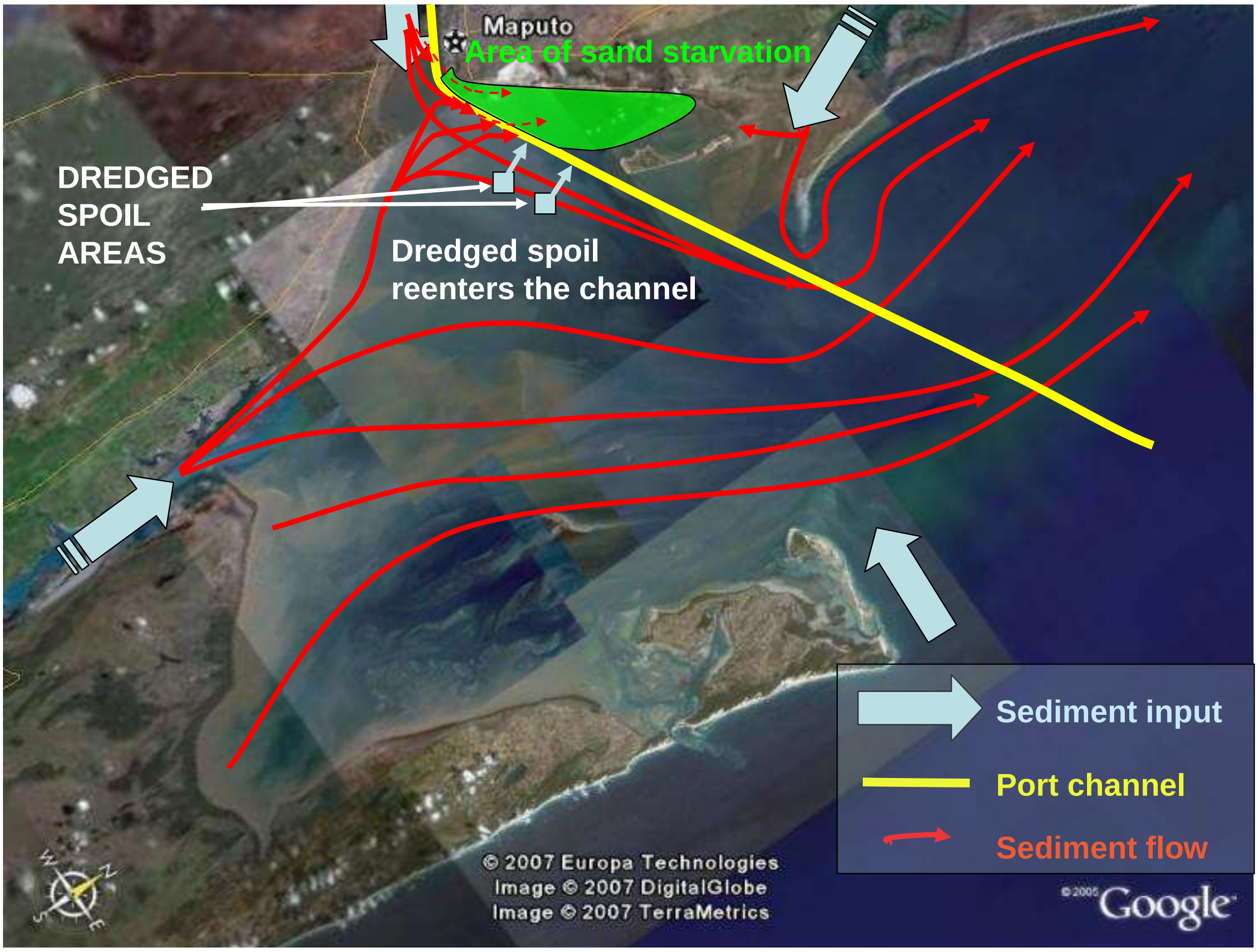


Figure 8.9 : Sediment transport patterns at Maputo (A Mather, pers com 2009)

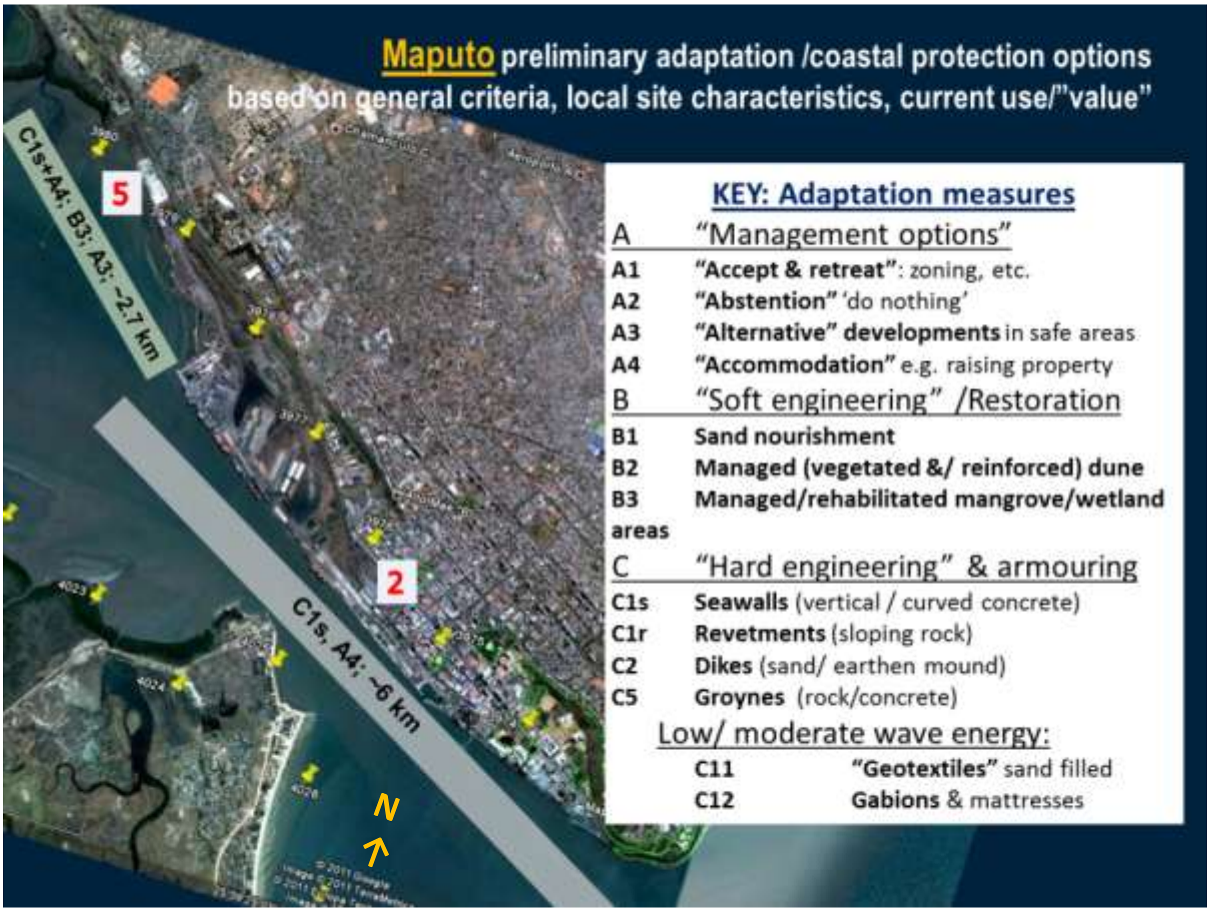


Figure 8.10: Western Maputo. Recommended adaptation/coastal protection options

As can be seen in Figure 8.10, the current port infrastructure is vulnerable to expected climate change impacts. Options C1s and A4 are the only practical options for this area. Quay walls, warfs, storage areas, transport infrastructure, etc. located in the vicinity of the existing port infrastructure will have to be raised in stages. The protecting seawalls will have to be similarly raised where possible, or new walls constructed. It is recommended that the design of future port expansion works or refurbishment of the existing infrastructure should include the option of future heightening of the structures (in stages) to at least the +6 m MSL level and ideally to the +8.5 m MSL level by 2100. The western portion of the port area (from Point # 3977 westwards in Figure 8.10) and the river shoreline further inland (# 3978 to # 3980), are not vulnerable to wave setup and run-up. Potentially, the design flooding level along these areas could be as low as +4.5 m MSL for "sea" flooding events. However, the joint effects of an extreme river flood (not within the scope of Theme 2) with high inshore seawater levels (both resulting from a cyclone) could foreseeably result in higher flooding levels. It is also more practical to have all port infrastructure at the same "ground" level where possible. Thus, the +6 m MSL design level is also recommended for these areas. This level should be revised as accurate river flooding levels and more accurate SLR projections become available in future. Based on the information available it appears that the existing infrastructure is already too low in places at present (i.e. excluding SLR) and needs to be upgraded and maintained as a matter of urgency (Priority # 2 for Maputo).

Cost estimates for the priority Maputo adaptation measures

As mentioned before, cost estimates were made for the two locations which will have the highest adaptation costs (due to most infrastructure /developed), namely Maputo and Beira. These large cities should also have relatively more resources available for coastal protection, and as stated before, this should be linked to port management/maintenance. Based on the foregoing recommendations, costs have been roughly estimated for implementation of the priority adaptation measures as summarized in Table 8.2 below.

Note, however, that the costs of "management" options (A1 to A4) are not included (e.g. relocation, alternative development of infrastructure, etc.) and therefore a cost estimate for these adaptation measures has not been included in Table 8.2. There are many external and socio-economic factors which will determine the cost of implementing such recommendations, versus the direct and indirect benefits (and "future cost savings"); this could only be properly considered in an in-depth socio-economic study.

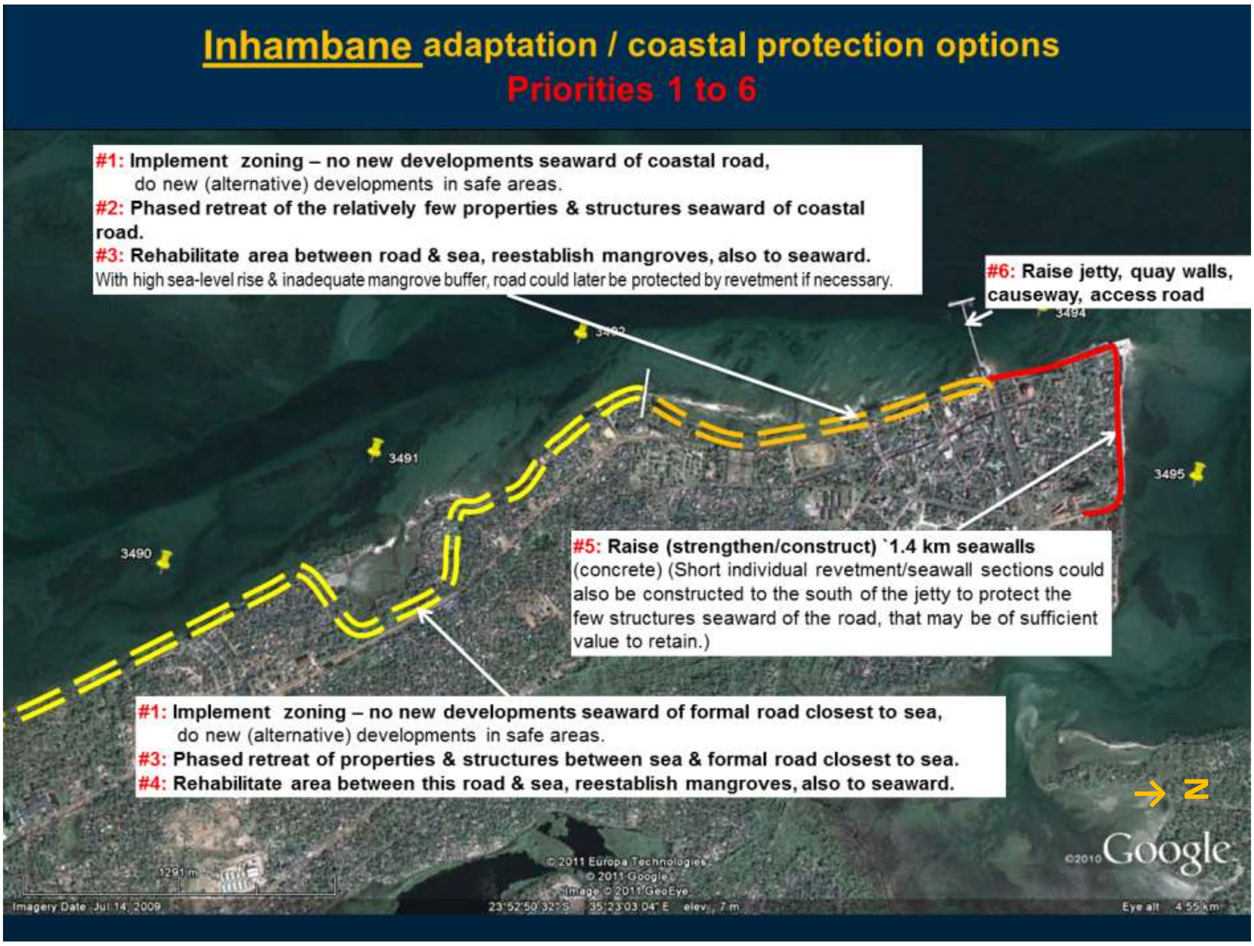
8.1.3 Inhambane & Maxixe

Referring to the discussions in Chapters 5 and 6, the “sea water flooding hazard” levels for the Inhambane and Maxixe area (Figure 6.3) show that for a 1m sea level rise (by 2100) plus a run-up of +1.5 m during cyclonic events, that areas below the +6 m contour will be in danger of being flooded. The extensive sandbanks seaward of Inhambane and Maxixe provide partial shelter from the full extent of wave impacts such as extreme flooding levels. Thus, the intermediate flooding level of +6 m MSL is appropriate for planning and management of infrastructure along the shoreline with a design life of less than 50 years. Due to the partial wave sheltering, extreme wave runup is not expected to exceed the 1.5 m already allowed for in the +6 m MSL flooding level. However, taking a conservative and precautionary approach, the extreme scenario of 2 m SLR by 2100 should be considered. Thus, the low hazard risk level for important infrastructure with a design life of more than 50 years such as airports is +7 m MSL (as the extreme scenario of a +2 m sea level rise along with a 1.5 m storm run-up level during cyclones).

Table 8.2: Summary of some adaptation option costs for Maputo - coastal construction capital cost estimates (2011).

Possible order of implementation	DESCRIPTION	Approximate Minimum Costs (excl tax) for 1km	Approximate Maximum Costs (excl tax) for 1km	Approximate length (or number of) proposed for Maputo (km)	Approximate Minimum Costs (excl tax) for Maputo	Approximate Maximum Costs (excl tax) for Maputo
1	Sand feeding (beach nourishment) new* @ rate of 300 000 m^3/a for 10 yrs)	$4 000 000	$60 000 000	1	$4 000 000	$60 000 000
3	Revetments & walls (permeable)	$2 300 000	$24 000 000	2.7	$6 210 000	$64 800 000
4	Vegetated dune	$750 000	$7 200 000	6	$4 500 000	$43 200 000
2.5	Sheet piling seawall (shore parallel)	$2 700 000	$36 000 000	8.7	$23 490 000	$313 200 000
2	Heightening quay walls, berths, other port infrastructure	$2 000 000	$25 000 000	6	$12 000 000	$150 000 000
				POTENTIAL TOTAL COST FOR IMPLEMENTING ALL ABOVE ($)	**$50 200 000**	**$631 200 000**

NB:
Costs of “management” options (A1 to A4) not included, e.g. relocation, alternative development of infrastructure, etc.
* Actual nourishment to a point by means of either pipelines with booster pumps from dredger quay or possibly distributed by means of dredger rainbowing off beaches



Inhambane adaptation / coastal protection options

Priorities 1 to 6

#1: Implement zoning – no new developments seaward of coastal road, do new (alternative) developments in safe areas.
#2: Phased retreat of the relatively few properties & structures seaward of coastal road.
#3: Rehabilitate area between road & sea, reestablish mangroves, also to seaward.
With high sea-level rise & inadequate mangrove buffer, road could later be protected by revetment if necessary.

#6: Raise jetty, quay walls, causeway, access road

#5: Raise (strengthen/construct) `1.4 km seawalls (concrete) (Short individual revetment/seawall sections could also be constructed to the south of the jetty to protect the few structures seaward of the road, that may be of sufficient value to retain.)

#1: Implement zoning – no new developments seaward of formal road closest to sea, do new (alternative) developments in safe areas.
#3: Phased retreat of properties & structures between sea & formal road closest to sea.
#4: Rehabilitate area between this road & sea, reestablish mangroves, also to seaward.

Figure 8.11: Inhambane. Recommended adaptation /coastal protection options

As can be seen in Figure 8.11, the only real affordable long term option to adapt to the effects of climate change is to ensure that development is located beyond the reach of the natural processes (A1). This can be achieved by implementing zoning to prevent development from taking place below the + 7 m MSL contour level (Priority #1). (For "greenfield" or undeveloped areas, this more conservative level allowing for 2 m SLR is recommended.) Gradual relocation (A3) of existing development to alternative safer areas should be included in the Structure Plan (Priorities #2 and #3). The active rehabilitation (B3) of mangrove areas (Priority #3 and #4) will form a natural barrier against storm waves and surges (flooding).

Much of the historical area to the north of the town is very low-lying and at serious risk of being flooded under the climate change factors. Other than retreating from the area (A1 & A3) as the storm surges become more threatening in time, more costly hard-engineering options (C1s, C1r and/or C2) will be the only solution in the long run. Options for forming Public-Private-Partnerships (PPP) type of development could be considered and new developments should be designed to cater for the climate change factors and also to assist the municipality with the required adaptation works.

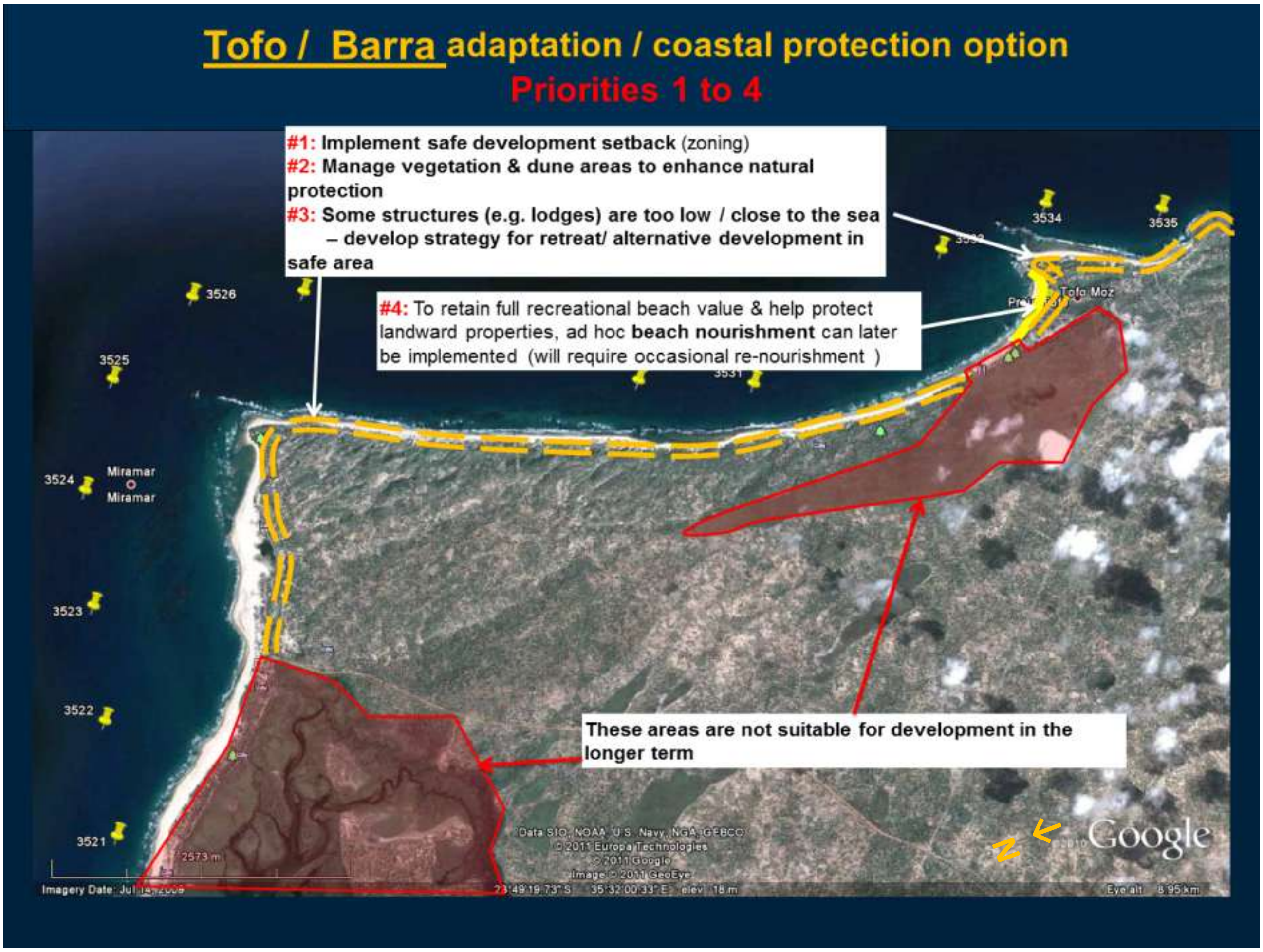
Although the current jetty has recently been upgraded, the raising or reinforcement of areas may be necessary in the far future (A4).

Of greater concern is the fact that the current international airport is in a low-lying area and adequate protection of the runway as well as the other infrastructure should be incorporated in any future redevelopment or upgrading plans (possibly C2 supported by B3 and A4).

(In the greater Inhambane region, there are many coastal lakes around which people live, in some instances in vulnerable locations. This is however beyond the scope of the present investigation, which focuses more on specific urban centres and surrounds located along and close to the influence of forces from the sea).

8.1.4 Tofo and Barra

The "sea water flooding hazard" levels for the Tofo/Barra area (Figure 6.3) show that for a 1m sea level rise (by 2100) plus a run-up of +1.5 m during cyclonic events, that areas below the +6.5 m contour will be in danger of being flooded. This intermediate flooding level of +6.5 m MSL is appropriate for planning and management of infrastructure along the shoreline with a design life of less than 50 years. The low hazard risk level for important infrastructure is +9 m MSL (rounded up from 8.9 m MSL) as the extreme scenario of a +2 m sea level rise along with a 3 m storm run-up level during cyclones.



Tofo / Barra adaptation / coastal protection option

Priorities 1 to 4

#1: Implement safe development setback (zoning)
#2: Manage vegetation & dune areas to enhance natural protection
#3: Some structures (e.g. lodges) are too low / close to the sea – develop strategy for retreat/ alternative development in safe area

#4: To retain full recreational beach value & help protect landward properties, ad hoc beach nourishment can later be implemented (will require occasional re-nourishment)

These areas are not suitable for development in the longer term

Figure 8.12: Tofo & Barra. Recommended adaptation /coastal protection options

As can be seen in Figure 8.12, the only real affordable long term option to adapt to the effects of climate change is to ensure that development is located beyond the reach of the natural processes (A1 & A3). This can be achieved by implementing zoning to prevent development from taking place in the hazard zone (Priority #1). For the open Tofo coast, which is exposed to high wave run-up, this 'no-development zone' is typically above the + 9 m MSL contour level and a minimum of 100 m from the high water mark. (For "greenfield" or undeveloped areas, this more conservative level allowing for 2 m SLR is recommended.)

Priority #2 is seen as the active rehabilitation of damaged foredunes and the conservation of the dune vegetation and volume (B2) will ensure that a natural barrier against storm waves and surges (flooding) is maintained. Gradual relocation of existing low-lying development to alternative lower risk areas (A1 & A3) should be included in the Structure Plan (Priority #3).

8.1.5 Vilanculos

The "sea water flooding hazard" levels for Vilanculos (Figure 6.3) show that for a 1m sea level rise (by 2100) plus a run-up of +1.5 m during cyclonic events, that areas below the +6.5 m contour will be in danger of being flooded. This intermediate flooding level of +6.5 m MSL is appropriate for planning and management of infrastructure along the shoreline with a design life of less than 50 years. The low hazard risk level for important infrastructure such as airports is +9 m MSL as the extreme scenario of a +2 m sea level rise along with a 3 m storm run-up level during cyclones.

Vilankulo adaptation / coastal protection options
Priorities 1, 2 & 3

#2: **Implement safe development setback** (i.e. zoning), **manage dune / coastal veg. areas** (conserve sand/dune volume)

#1: **Implement safe development setback** (zoning) (+ do alternative developments in safe areas)
#3: **Construct seawalls (/revetments) only where *high* value property warrants** (concrete/rock, or gabions for medium term)

Figure 8.13a: Vilanculos. Recommended adaptation /coastal protection options


Vilankulo adaptation / coastal protection options
Priorities 1, 2 & 3

#2: Implement safe development setback (i.e. zoning), **manage dune / coastal veg. areas** (conserve sand/dune volume)

#1: Implement safe development setback (zoning)
(+ do alternative developments in safe areas)

#3: Construct seawalls (/revetments) only where *high* value property warrants (concrete/rock, or gabions for medium term)

Figure 8.13b: Vilanculos. Recommended adaptation /coastal protection options

As can be seen in Figures 8.13a and b, the only real affordable long term option to adapt to the effects of climate change is to ensure that development is located beyond the reach of the natural processes (A1 & A3). This can be achieved by implementing zoning to prevent development from taking place in the hazard zone (Priority #1). For the relatively open Vilanculos coast, which can be exposed to high wave run-up, this 'no-development zone' is typically above the + 9 m MSL contour level and a minimum of 100 m from the high water mark. (For "greenfield" or undeveloped areas, this more conservative level allowing for 2 m SLR is recommended.)

The active rehabilitation of damaged foredunes (B2) and the conservation of the dune vegetation and volume (Priority #2) will ensure that a natural barrier against storm waves and surges (flooding) is maintained. Gradual relocation of existing low-lying development to alternative safer areas (A3) should be included in the Structure Plan.

Options for forming PPP type of developments could be considered and new developments should be designed to cater for the identified climate change factors and also to assist the municipality with implementation of the required hard-engineering adaptation works (possibly C1s, C1r, C5 along with B1). (The offshore islands and San Sebastian Peninsula are important for tourism income and should be incorporated in any future studies with scope beyond the current study areas.)

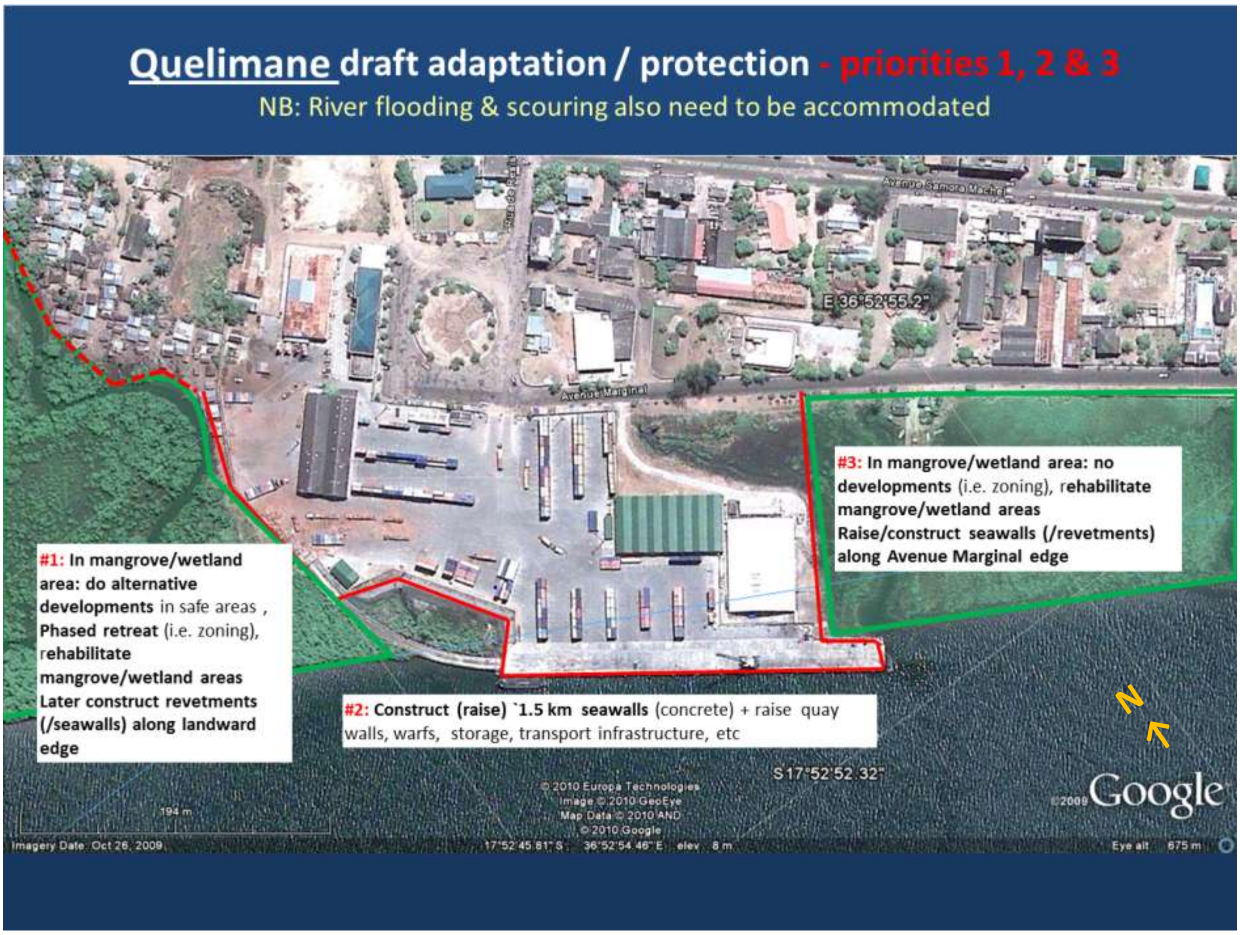
The current fishing harbour area is in need of upgrading and it is recommended that new designs should allow for the raising and protection of the infrastructure (A4). Ideally the harbour should be part of the tourist infrastructure and redevelopment as part of a PPP is probably an appropriate option.

It is important to verify the current estimate that the existing runway at the Vilankulo International Airport is located above the relevant flooding hazard level (Figure 6.3) where an adaptation option is possibly C2 in time.

8.1.6 Quelimane

Quelimane is located away from the sea along a river and therefore sea-storm wave forces and run-up can be ignored. Scouring, inundation and other forces from river flows should be considered however.

The only effect of climate change is therefore the sea level rise of either 1m or 2 m. The “sea water flooding hazard” levels for Quelimane (Figure 6.3) show that for a 1m sea level rise (by 2100) during cyclonic events, areas below the +5.5 m contour will be in danger of being flooded. The safe hazard level for “normal” development is recommended to be +6.5 m MSL and for key infrastructure such as ports and airports the low hazard risk level should be +8 m MSL.



Quelimane draft adaptation / protection - priorities 1, 2 & 3

NB: River flooding & scouring also need to be accommodated

#1: **In mangrove/wetland area: do alternative developments** in safe areas , **Phased retreat** (i.e. zoning), **rehabilitate mangrove/wetland areas Later construct revetments (/seawalls) along landward edge**

#2: **Construct (raise) `1.5 km seawalls** (concrete) + raise quay walls, warfs, storage, transport infrastructure, etc

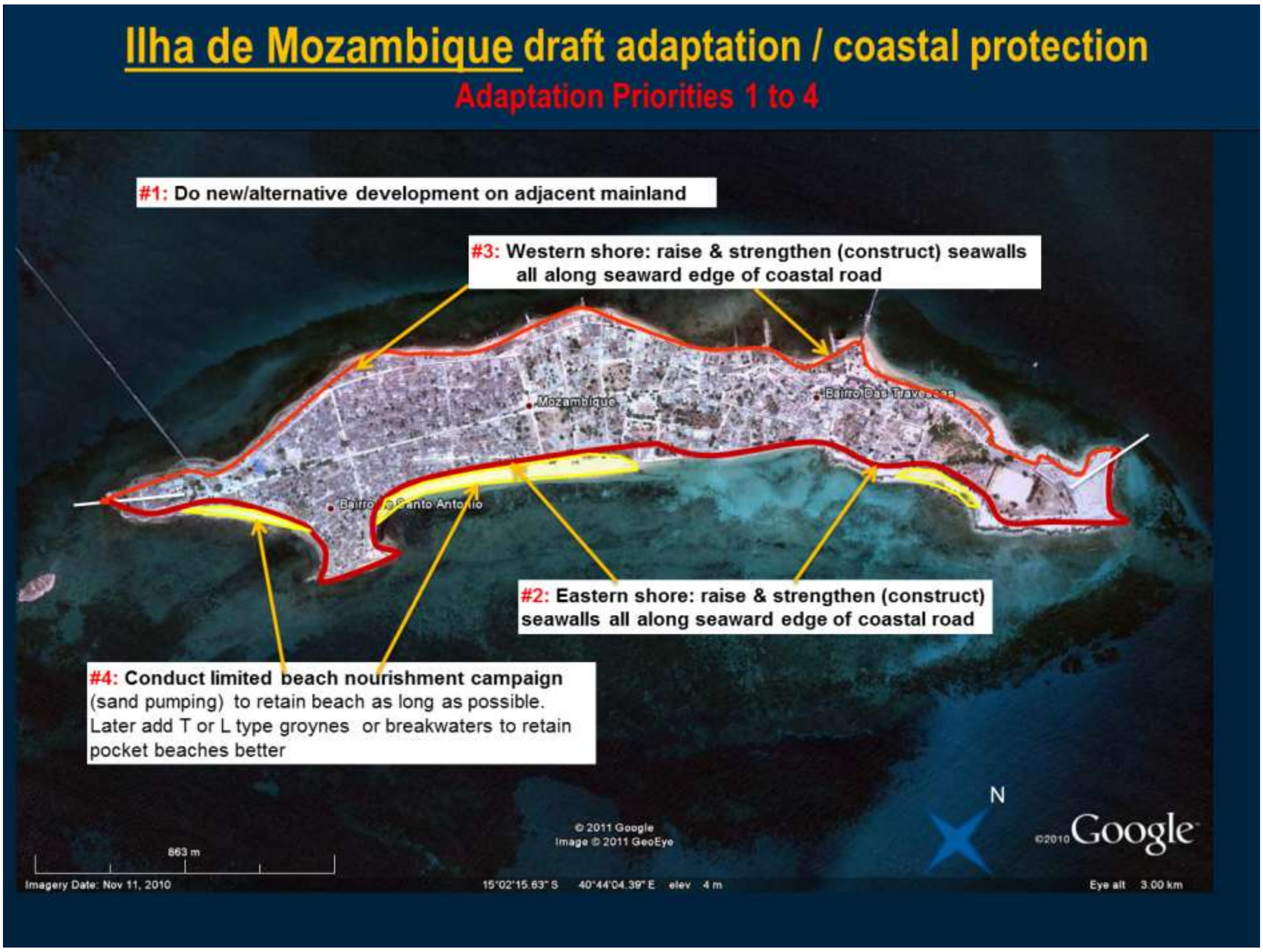
#3: **In mangrove/wetland area: no developments** (i.e. zoning), **rehabilitate mangrove/wetland areas Raise/construct seawalls (/revetments) along Avenue Marginal edge**

Figure 8.14: Quelimane adaptation/coastal protection options

Figure 8.14 shows the recommended first priority action (#1) being the implementation of adaptation options A1, A2 and B3. In the medium to long terms option C1r, C1s and C2 could be necessary. The second priority (#2) is to ensure the protection of the port infrastructure by implementing adaptation options C1s and A3.

Of utmost importance is to reinforce and maintain the natural buffer that the mangroves provide to the city waterfront area and priority #3 is to protect (A1) and rehabilitate (B3) the area. In time the existing seawall will have to be reconstructed and/or raised (C1s and A3). Job creation opportunities for actively rehabilitating and reinstating mangrove swamp areas could be considered as a PPP (possibly funded through Carbon Trading Mechanisms – this should be investigated).

8.1.7 Ilha de Moçambique



Ilha de Mozambique draft adaptation / coastal protection

Adaptation Priorities 1 to 4

#1: Do new/alternative development on adjacent mainland

#3: Western shore: raise & strengthen (construct) seawalls all along seaward edge of coastal road

#2: Eastern shore: raise & strengthen (construct) seawalls all along seaward edge of coastal road

#4: Conduct limited beach nourishment campaign (sand pumping) to retain beach as long as possible. Later add T or L type groynes or breakwaters to retain pocket beaches better

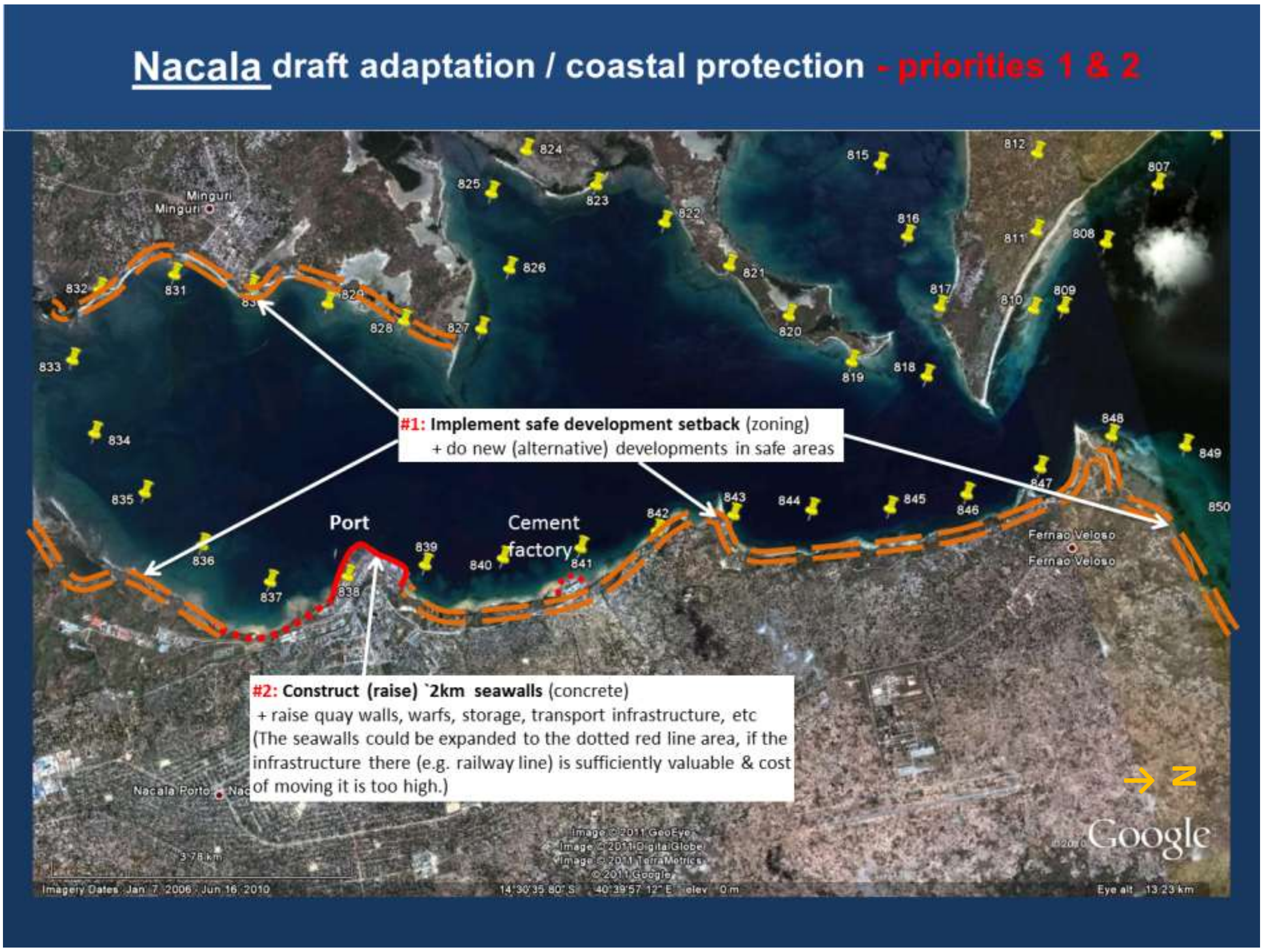
Figure 8.15: Ilha de Moçambique recommended adaptation /coastal protection options

Even though the Ilha de Moçambique is partially protected by offshore islands, the low-lying areas on the island are extremely vulnerable to the effects of climate change. Prioritised action points are shown in Figure 8.15 although the most sensible adaptation options are A2 and A3. The design of any redevelopment or rehabilitation activities on the island should allow for extreme climate change conditions. (Many of the other islands are also especially vulnerable to climate change impacts, and are important for tourism, etc, for example the Quirimbas Archipelago located to the north of Pemba. They should be incorporated in any future studies with scope beyond the current study areas.)

8.1.8 Nacala

Most of the Nacala and Minguri shoreline is relatively well sheltered from the open sea (Figure 8.16). Only very limited ocean wave penetration into the bay is possible from the north, while only moderate local wave generation inside the bay is possible due to the limited fetch (e.g. resulting from cyclone winds over the bay). The "sea water flooding hazard" levels for the bay shorelines of Nacala and Minguri (Figure 6.3) show that for a 1m sea level rise (by 2100) plus spring high tides and limited local raising of water levels (through barometrics and wind), that areas below the +6.5 m contour (rounded up from +6.3 m MSL) will be in danger of being flooded. This intermediate flooding level of +6.5 m MSL is appropriate for planning and management of infrastructure along the bay shoreline with a design life of less than 50 years. However, taking a conservative and precautionary approach, the extreme scenario of 2 m SLR by 2100 should be considered. Thus, the low hazard risk level for important infrastructure inside the bay such as the port and airport with a design life of more than 50 years is +7.5 m MSL.

Only the shoreline outside of the bay (to the north of Fernao Veloso) is relatively exposed to cyclone waves approaching from the north-east or north. Here, the intermediate flooding level of +8 m MSL is appropriate for planning and management of infrastructure with a design life of less than 50 years (allowing for the scenario of a +1 m sea level rise along with a 1.5 m storm run-up level during cyclones).



Nacala draft adaptation / coastal protection - priorities 1 & 2

#1: Implement safe development setback (zoning)
+ do new (alternative) developments in safe areas

#2: Construct (raise) `2km seawalls (concrete)
+ raise quay walls, warfs, storage, transport infrastructure, etc
(The seawalls could be expanded to the dotted red line area, if the infrastructure there (e.g. railway line) is sufficiently valuable & cost of moving it is too high.)

Figure 8.16: Nacala & Minguri adaptation / coastal protection options

As can be seen in Figure 8.16, the only real affordable long term option to adapt to the effects of climate change is to ensure that development is located beyond the reach of the natural processes. This can be achieved by implementing zoning to prevent development from taking place in the hazard zone (Priority #1). The recommended 'no-development zone' for the bay shoreline area is typically above the + 7.5 m MSL contour level and a minimum of 100 m from the high water mark. (For "greenfield" or undeveloped areas, this more conservative level allowing for 2 m SLR is recommended.)

Although accurate topography data was not available, the current infrastructure at the port and the cement factory appears to be somewhat vulnerable to expected climate change impacts. Options C1s and A4 are the only practical suggestions for this area. It is recommended that the design of future port expansion works or refurbishment of the existing infrastructure should include the option of future heightening of the structures (in stages) to at least the +7.5 m MSL level by 2100. Options for forming PPP type of developments could be considered and new developments should be designed to cater for the identified climate change factors and also to assist the municipality with implementation of the required hard-engineering adaptation works.

8.1.9 Pemba

The eastern and northern shores of Pemba outside of the bay (Figure 8.17) are exposed to cyclone waves approaching from the north-east or north. On first impression it may seem that the Bay shoreline is well sheltered from wave action. However, of importance is that, due to the large expanse of water in Pemba Bay (i.e. relatively large wind fetch), the Pemba peninsula provides only partial protection from cyclonic forces (waves and sea water flooding) when a cyclone moves inland across Pemba. This has implications for the design of coastal protection around the port and the shoreline around the whole bay in that significant local water level set-ups and local wave run-up can occur. The "sea water flooding hazard" levels for locations inside Pemba Bay (Figure 6.3) show that for a 1m sea level rise (by 2100) plus a run-up of +1.5 m during cyclonic events, that areas below the +8 m contour will be in danger of being flooded. This intermediate flooding level of +8 m MSL is appropriate for planning and management of infrastructure along the bay shoreline with a design life of less than 50 years. However, taking a conservative and precautionary approach, the extreme scenario of 2 m SLR by 2100 should be considered. Thus, the low hazard risk level for important infrastructure inside the bay with a design life of more than 50 years such as the port is +9 m MSL.

Along the more exposed eastern and northern shores outside of Pemba Bay, the intermediate safety hazard level of +9 m MSL is appropriate for planning and management of infrastructure with a design life of less than 50 years (allowing for the scenario of a +1 m sea level rise along with a 3 m storm run-up level during cyclones.)

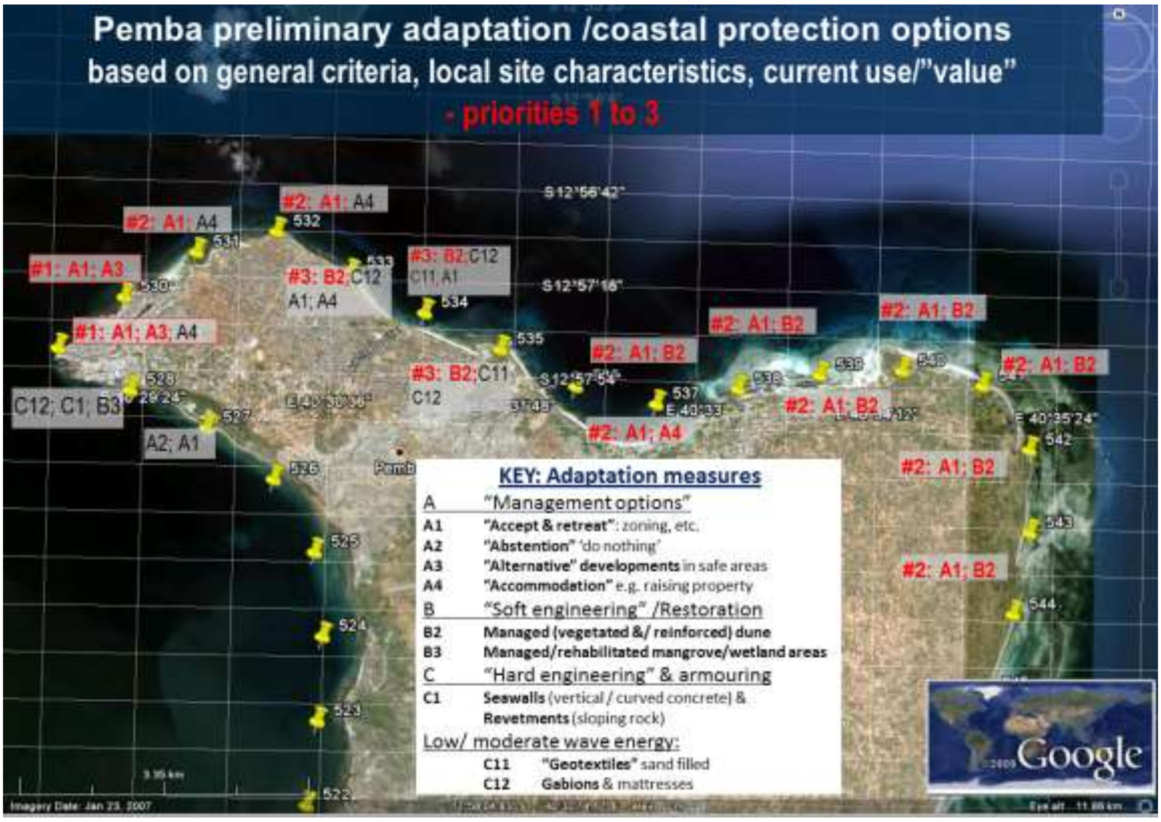


Figure 8.17: Pemba recommended adaptation /coastal protection options

As can be seen in Figure 8.17, the only real affordable long term option to adapt to the effects of climate change is to ensure that development is located beyond the reach of the natural processes. This can be achieved by implementing zoning (A1) to prevent development from taking place in the hazard zone (Priority #1). The 'no-development zone' for the bay shoreline area (# 522 to # 528) is typically above the + 8 m MSL contour level, while outside of Pemba Bay (Porto Amelia to # 544), the level of +9 m MSL is appropriate, and a minimum of 100 m from the high water mark in all instances.

Actively rehabilitating and managing the foredunes (adaptation option B2) is also a practical and inexpensive way to prevent damage to the coastline along the northern and eastern coasts of Pemba.

Options for forming PPP type of developments could be considered and new developments should be designed to cater for the identified climate change factors and also to assist the municipality with implementation of the required adaptation works. This is a particularly practical option for managing the highly vulnerable area at the north-western tip of the city where the village of Paquite is regularly threatened by sea inundation. Harbour development in the deep bay can also boost income to offset coastal protection costs.

Although it might not appear so at first glance, the current infrastructure at the port is relatively vulnerable to expected climate change impacts in conjunction with a cyclone moving over the bay. Options C1s and A4 are the only practical suggestions for this area. It is recommended that the design of future port expansion works or refurbishment of the existing infrastructure should include the option of future heightening of the structures (in stages) to the +9 m MSL level by 2100. (This level should be revised (say at 10 year intervals) as more accurate SLR projections become available in future.)

8.2 THE REHABILITATION OF MANGROVE AREAS (B3) TO FORM EFFECTIVE NATURAL BUFFER AREAS ALL ALONG THE INNER SHORELINE OF THE BAY SHOULD BE ENCOURAGED AND COULD BE AN EXCELLENT JOB CREATION OPPORTUNITY. CONCLUSION

In addition to the recommendation that the strategic principles and guidelines on planning for and responding to coastal impacts and including specifically climate change impacts as discussed in Section 7.1, should be adopted and implemented forthwith, site specific analysis and recommended prioritised adaptation options for each of the study sites were presented.

Noted is that the specific engineering design details and accurate costing of each option can only be done once site specific engineering and environmental investigations have been carried out where it is absolutely critical to involve experienced coastal engineering and coastal environmental professionals in the detailed planning, design and implementation of the chosen options.

In most cases sound planning and future development beyond the reach of the sea forces can be implemented successfully. Many opportunities for entering into PPP exist which has the potential to co-fund the implementation of the more costly “hard”-engineering adaptation options

CHAPTER 9: INTERACTION WITH MUNICIPALITIES

Following a formal workshop/seminar in Maputo organised by the INGC in June 2011, the researchers along with a senior representative from INGC, visited the municipalities at the key study sites and engaged with a number of municipal officials and role players responsible for the technical and/or management aspects of the coastal areas within the specific municipal areas and the Port of Maputo.

9.1 PURPOSE

The purpose of the interaction with the municipalities was to achieve the following:

- To discuss the preliminary results of the Theme 2 study with relevant municipal officials.
- To reach an understanding on the implications of climate change and the need to influence and incorporate recommendations into current and future plans.
- To comment on current and future infrastructure and structure plans if available. This was done during the meeting. Areas where a follow-up note on relevant aspects was needed were identified.
- To identify existing specialist studies on climate change in order to harmonise recommendations if possible.
- Site investigation of current coastal protection activities and provide observations if relevant.

The detail and notes from the interaction is provided in Appendix 2.

9.2 KEY POINTS FOR CONSIDERATION

The following important points and observations were identified:

- The current structure plans of the municipalities do incorporate general environmental issues but do not specifically consider climate change issues.

- At all meetings the technical staff of the municipality found the information to be relevant for current and future structure plans and they are willing to use the results of the study for this propose.

- Common to all the interaction was a request to disseminate the results of the study to a broader stakeholder base.

- There is a need to obtain validation from the State and the Provinces before implementation can be achieved. There is therefore a need to engage with the higher level authorities at the municipality as well as other decision makers so-as to facilitate the successful incorporation of the findings and recommendations on current and future structure plans.

- There is a critical shortage of skills and management capacity at both a technical and administrative level and the need for active development and transfer of technology and skills was highlighted in all cases.

- Various studies and overlapping initiatives are taking place within the study area and the municipal officials highlighted the need to coordinate and align these to avoid confusion and to avoid the duplication of efforts and conflicting recommendations.

- Some of the actions required adaptation to climate change can be costly and may not be supportable by the municipality. It was indicated that there is a high potential for public-private partnerships (PPP) in all coastal municipalities and this type of cost-sharing mechanisms should be considered in the assessment or request for development proposals. This forms part of Theme 4: Building resilience in partnership with the private sector.

CHAPTER 10: SUMMARY, CONCLUSION AND RECOMMENDATIONS

10.1 BACKGROUND

Mozambique is recognized as one of the countries in Africa that is most vulnerable to climate change. Hazards such as droughts and floods, variable rainfall and tropical cyclones already significantly affect the country.

The country's coastal zone is particularly vulnerable to the expected impacts of climate change. Contributing factors include:

- Vast low-lying coastal plains such as delta coasts;
- High population concentrations in close proximity to the sea;
- Poverty;
- Low capacity to defend infrastructure;
- Susceptibility to cyclone activity;
- Soft erodible coasts; and
- Inadequate and ageing coastal defences.

This situation is aggravated by direct exposure to high wave energy regimes in some parts, a potential increase in cyclone impacts, and impacted natural coastal defences such as dunes, mangroves and coral reefs. Large numbers of the local population also rely heavily on goods and services and economic benefits provided by the coastal zone.

In this regard, the National Institute for Disaster Management (INGC) initiated two studies to define and locally contextualise important drivers and impacts of climate change in the country. Phase I, completed in 2009, focused on determining the impacts of climate change on Mozambique at the macro level. The current project, Phase II, focuses on both the macro and the micro levels, with an emphasis on the implementation of adaptation measures and providing strategic and scientific evidence-based guidance for decision-making.

Led by the Mozambican government, the overall goal of the Phase II project is to help protect the country against the potential impacts of climate change, and to plan for and kick start prevention through the implementation of adaptation measures at national scale, on the basis of science and in support of sustainable development.

As such, a multi-disciplinary group of scientists from Mozambique and other institutions formulated 9 themes to encapsulate the research challenges faced, namely:

- *Theme 1*: Early Warning at a Different Scale
- *Theme 2*: Coastal planning and adaptation to mitigate climate change impacts
- *Theme 3*: Cities prepared for climate change
- *Theme 4*: Building resilience in partnership with the private sector
- *Theme 5*: Water – doing More with less
- *Theme 6*: Food – Meeting demands.
- *Theme 7*: Preparing People
- *Theme 8*: Extremes
- *Theme 9*: National Strategy: 'Climate Change and Disaster Risk Reduction"

While this study is primarily concerned with Theme 2, it is closely aligned with Themes 3 and 4, and addresses the following key questions:

- Where are the most vulnerable areas along the coast, at the local/micro level?
- What will these areas look like, with climate change, in future?
- Which key infrastructure and future investment plans are at risk in these areas?
- What recommendations are in order for planned investments along the coast, with emphasis on Beira and Maputo?
- What structural coastal protection measures are needed to compensate for the potential effects of climate change?
- What shoreline management plans are most appropriate for these areas?
- What should be the strategic framework on which all coastal structures and sea defences can be evaluated?
- What should go into a coastal zone information system?
- What input can be provided for in a coastal management policy?

The INGC also emphasised the need for a pro-active approach to protect lives and infrastructure, while at the same time finding sustainable solutions that are durable and low cost.

10.2 KEY CONSIDERATIONS AND FINDINGS

10.2.1 Drivers of change

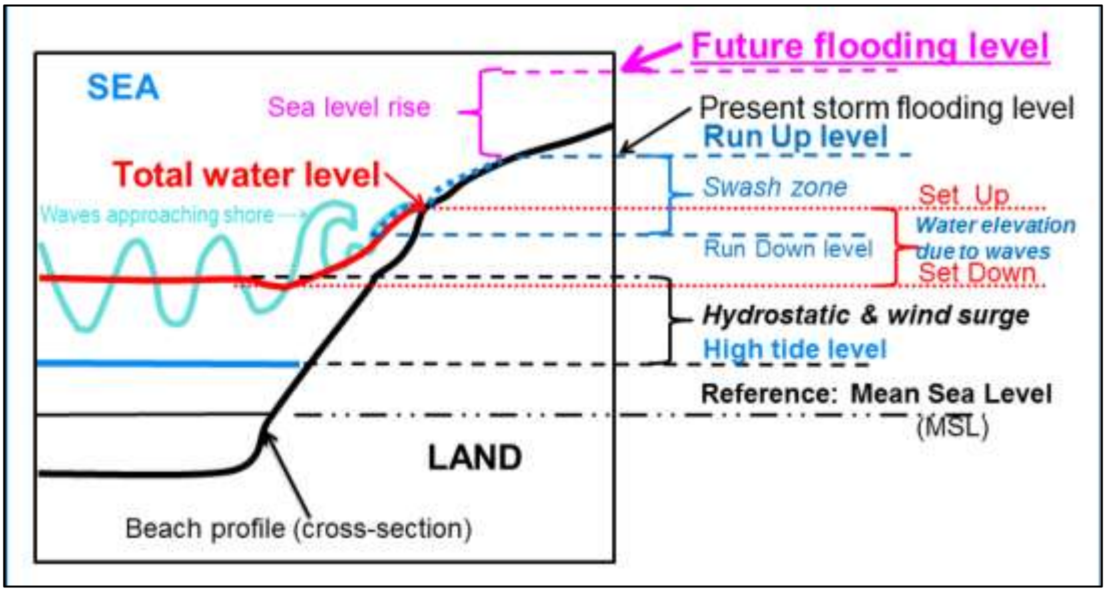
In Theme 2 the physical factors that influence the risk to coastal infrastructure and development in current and future climate scenarios were identified. This included consideration of the current situation along with future sea-level rise scenarios of 0.5m, 1.0m or 2m by 2100. These are further considered both with and without taking cyclones into account and the consideration of possible increases in "storminess" being another component of climate change.

The primary hazards to physical (abiotic) coastal infrastructure related to sea storms and climate change are:

- Extreme inshore sea water levels resulting in flooding and inundation of low lying areas.
- Changes in cyclone characteristics, winds and local wave regime resulting in direct wave impacts.
- Coastal erosion and under-scouring of, for example, foundations and structures.
- System complexities, thresholds and non-linearities, for example related to sand transport.

- A combination of extreme events, such as sea storms during high tides plus sea level rise, will have the greatest impacts and will increasingly overwhelm existing infrastructure as climate change related factors set in time.

The main drivers of change related to the above are thus waves and sea water levels (and to a lesser extent winds and currents). A detailed discussion can be seen in Chapters 5 and 6.

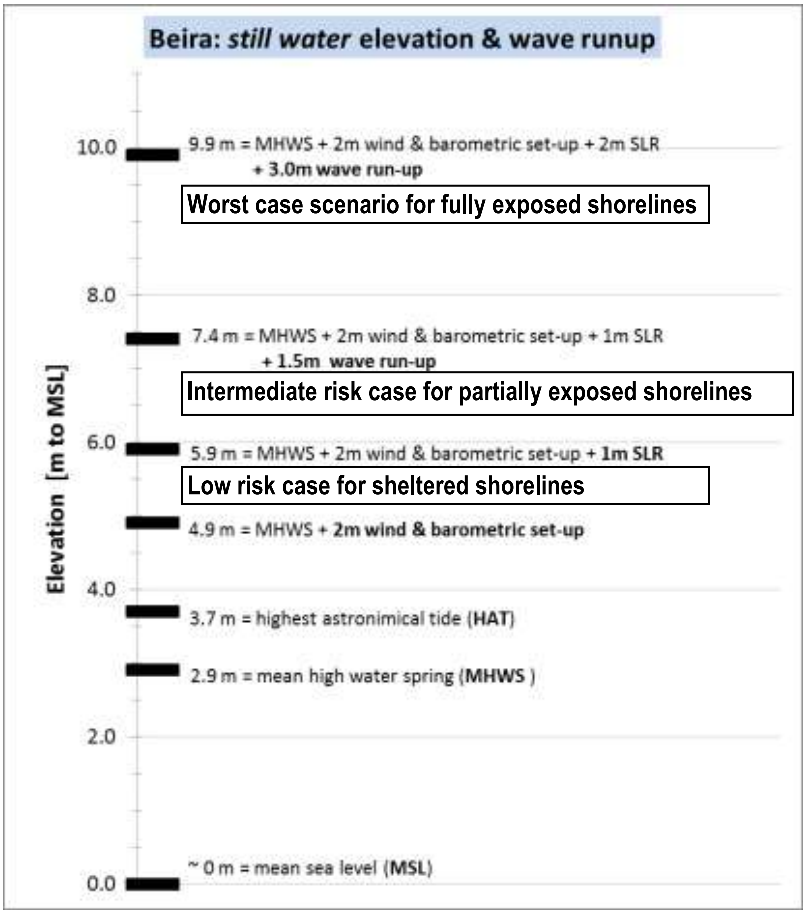


Definition sketch of the various components leading to extreme inshore sea water levels (See Figure 5.3 in Chapter 5)

The various components that lead to extreme inshore sea water levels are shown in the sketch above.

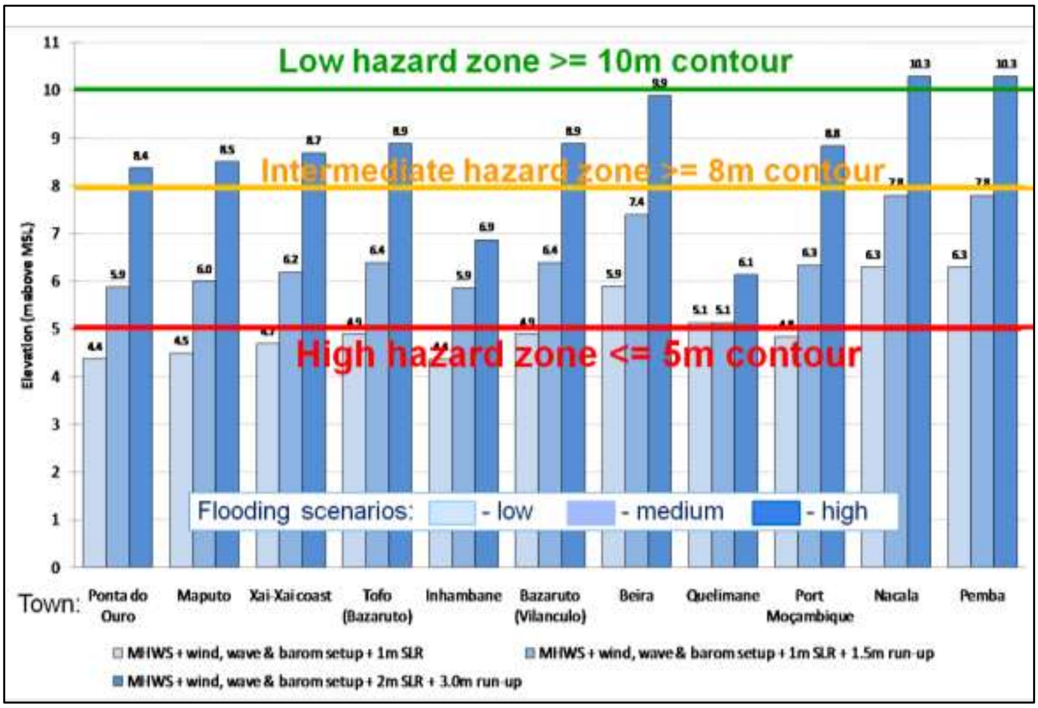
The shoreline response and flooding impact is influenced by coastal parameters/processes such as: topography, geology, inshore wave action, sea level (including the tidal state and future rise), bathymetry and foredune volume.

To be of more use in hazard quantification and ultimately in finding ways of reducing risks and deriving practical adaptation measures, it is necessary to be able to predict or forecast the coastal response and severity of impacts. To this end, given the lack of historic data and information along the Mozambican coastline, three flooding scenarios are defined to establish the hazard levels at the specific sites in terms of possible flooding due to the various factors associated with 'normal' meteorological factors as well as the effects of climate change.To illustrate how the components of the inshore sea water levels have been calculated for each location, Beira is used as an example in the figure below.



Beira coastal flooding and wave run-up levels (see Figure 5.32 in Chapter 5).

These three flooding level scenarios were calculated for each of the study towns and cities as depicted in the figure below (the 3 bars for each town).



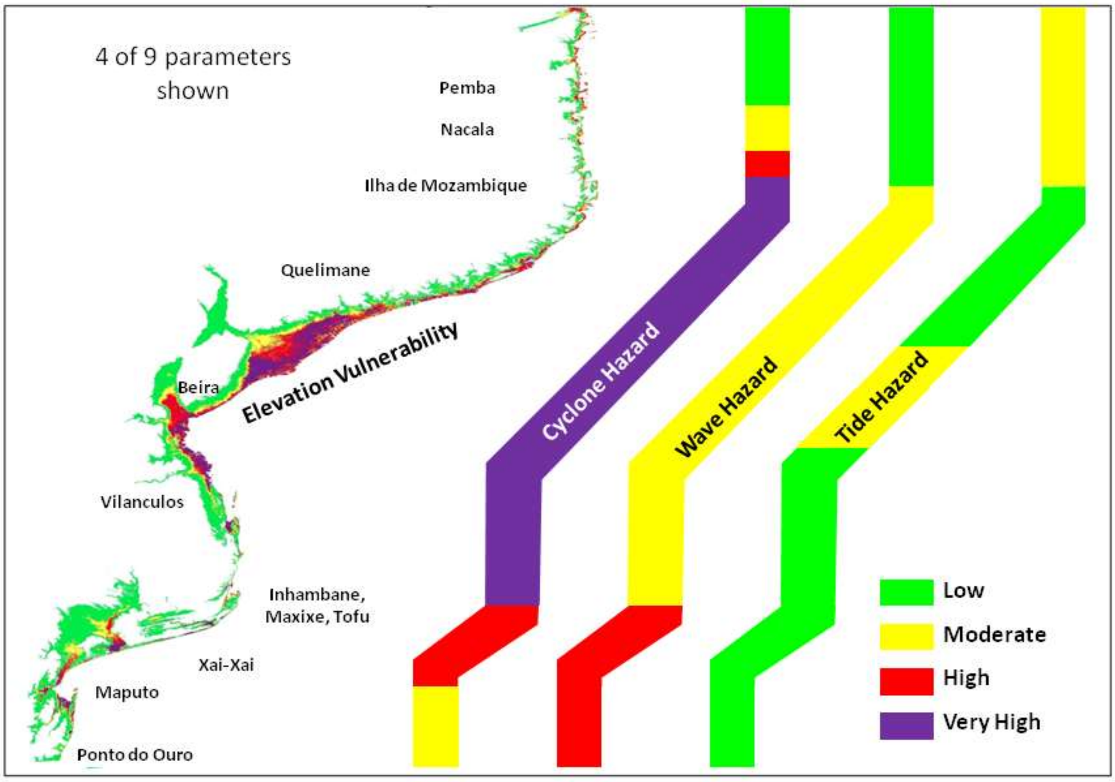
Coastal flooding levels for 11 towns/cities (see Figure 6.3 in Chapter 6)

10.2.2 Coarse scale coastal vulnerability assessment

Broadly speaking, the low lying central delta coast areas (e.g. Beira) are very vulnerable in terms of elevation (see figure below). The highest occurrence of cyclones (very high hazard) is found along the central parts of Mozambique, tapering off to the south (from roughly Tofo) and also sharply to the north (from about Ilha de Mocambique).

In terms of wave height (excluding cyclones) the hazard increases slightly from north to south, with most of the coast subject to moderate offshore wave attack. Due to the particular bathymetry off Mozambique and (amongst others) the location of tidal nodes, the northern coast (e.g. Nacala and Pemba) as well as parts of the central coast (e.g. Beira) face the highest tidal hazard (note that the hazard here is still rated as moderate relative to coastlines in some other parts of the world where tidal extremes are much higher).

The coarse hazard assessment is useful in comparing vulnerability on a more regional level, and does give an indication of how some important hazards are spatially distributed.



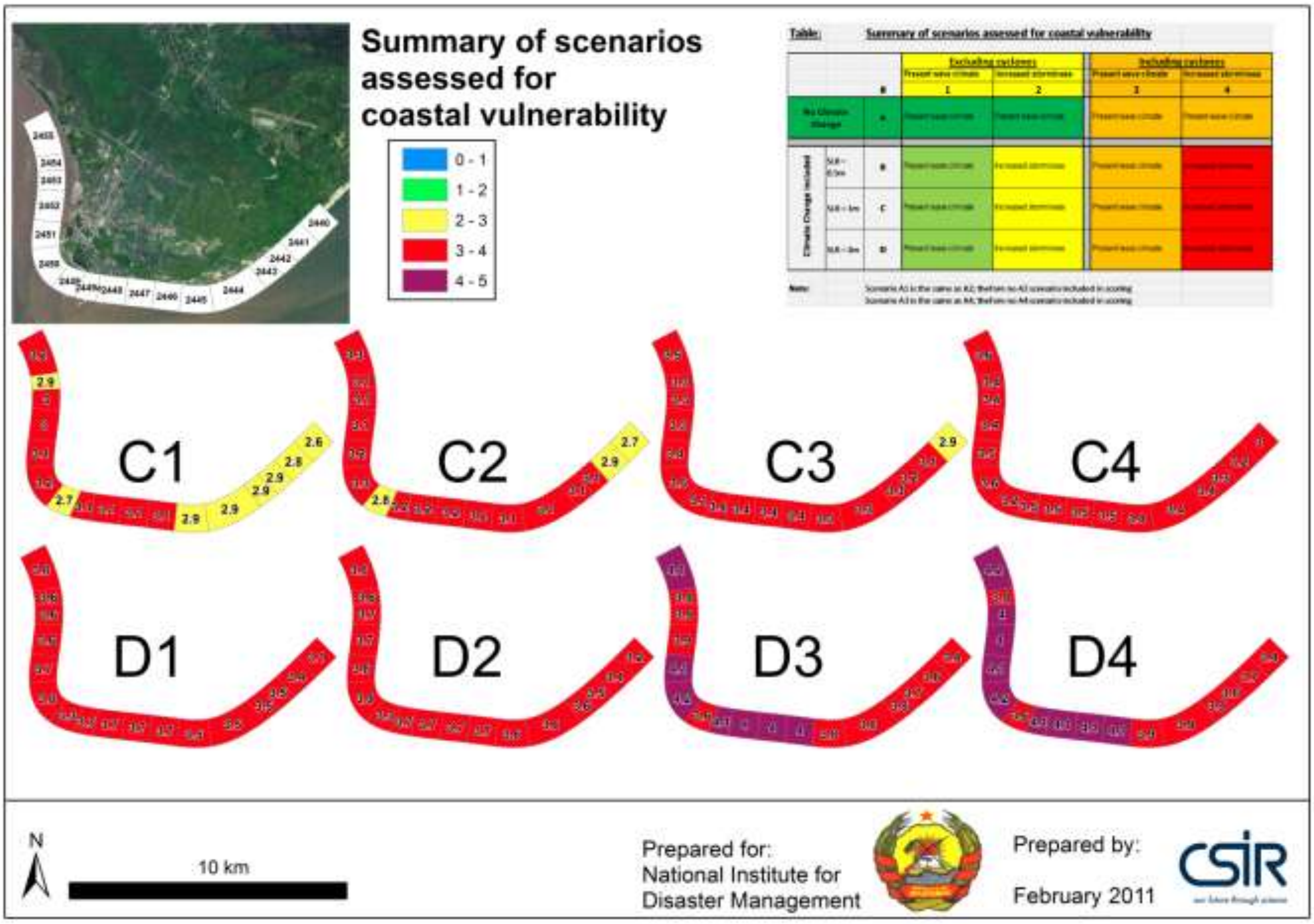
Coarse overview of hazards and vulnerability of Mozambican coast (See Figure 6.21 in Chapter 6)

10.2.3 Local / micro scale coastal vulnerability assessment

Analyses were carried out to determine the vulnerability of key coastal cities and towns (identified by the INGC) to the impact of a range of biophysical change scenarios.

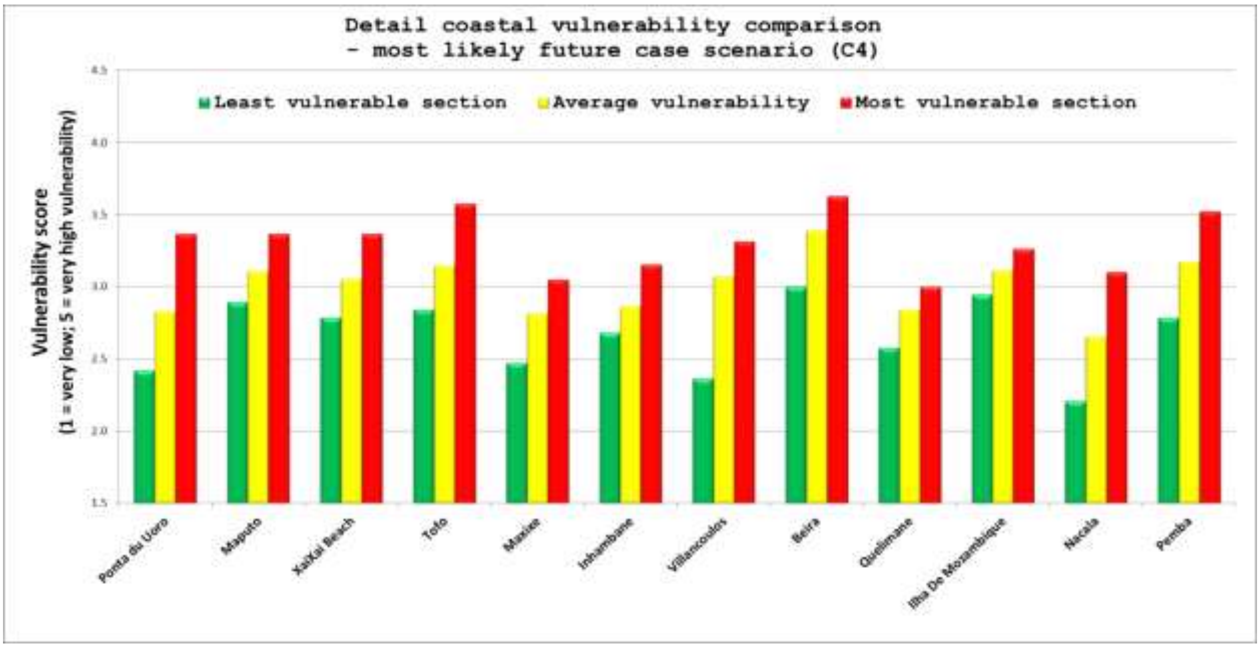
The vulnerability to the forces from the sea of approximately 10 km of shoreline at each site was assessed by evaluating 14 abiotic parameters against an agreed to set of criteria (see Table 6.1 in Chapter 6). The vulnerability assessment was done with and without climate change factors, and also with and without the effect of cyclones.

The figure below summarises the results of the micro scale assessment for 1km coastline stretches at Beira under the various scenarios (C1 to C4 and D1 to D4) showing overall vulnerability rating when the 14 parameters in Table 6.1 are combined.



Beira detail vulnerability mapping: Scenarios C & D (See Figure 6.24b in Chapter 6)

Similar total vulnerability maps are available for each of the other study sites, for the 8 scenarios that include cyclones (i.e. C1 to D4). The figure below shows the detailed coastal vulnerability comparison of the 12 coastal study sites when the most likely future climate change scenario, C4, is used. (Scenario C4 considers a 1m sea-level rise by 2100 and includes both the effects of cyclones and an increase in storminess due to climate change.



A comparison of the vulnerabilities of the 12 study sites under the most likely future case scenario (C4) (See figure 6.36 in Chapter 6)

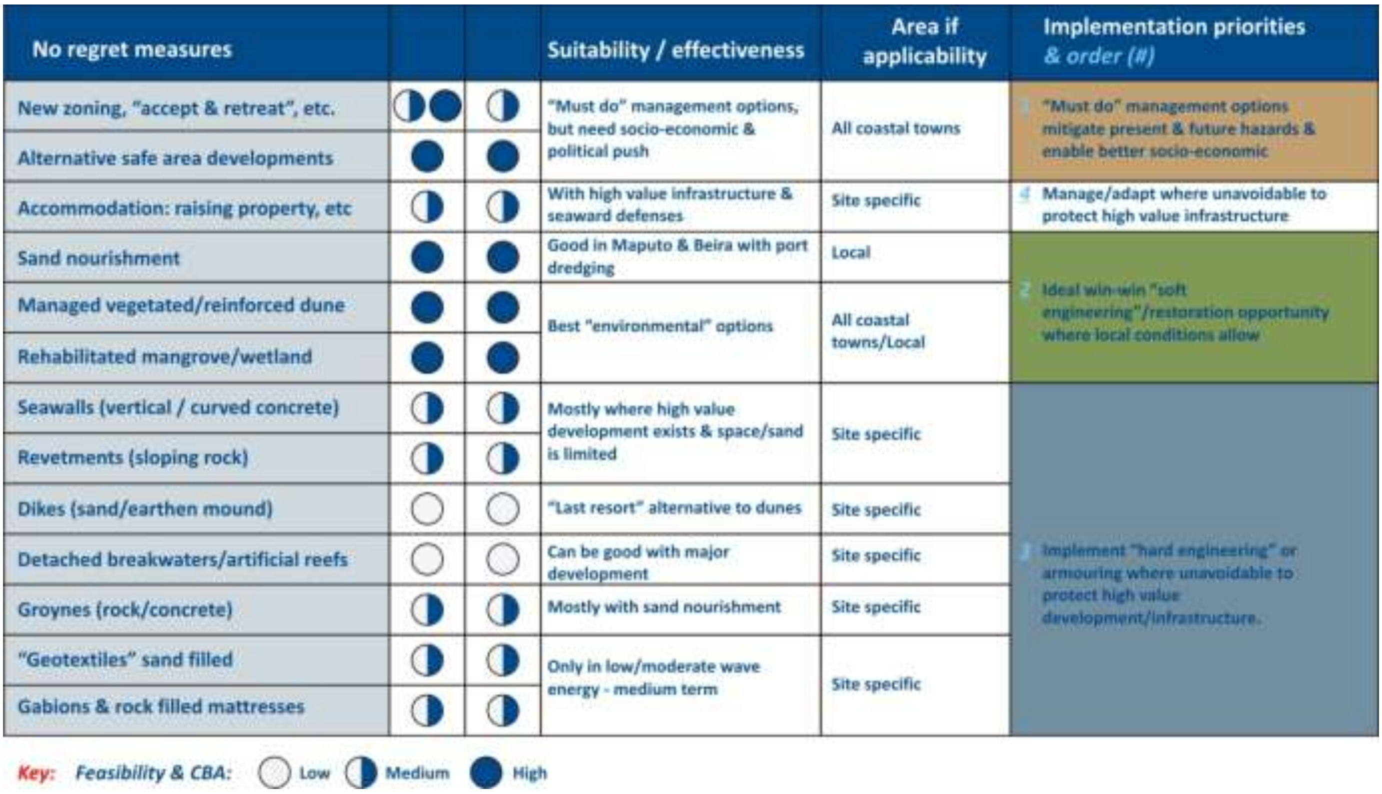
Results show that the most vulnerable towns are Ponta do Ouro, Maputo, XaiXai Beach, Tofo, Villanculos, Beira and Pemba. Beira is identified as the most vulnerable city.

10.2.4 Appropriate adaptation measures

A comprehensive literature review led to the identification of a number of management options and “soft” and “hard” coastal engineering methods available to protect the shoreline (see Chapter 7). By considering the coastal processes and characteristics of the study area, and factors governing suitability for coastal development, various potential response options were identified.

Based on the foregoing evaluation consideration and criteria, and including all appropriate options, the priority adaptation/”no-regret” measures were grouped according to type and impact, covering the most relevant climate change issues for Mozambique coastal towns and cities, as summarized in the table below.

Priority adaptation/no-regret measures (see Table 7.6 in Chapter 7)



No regret measures			Suitability / effectiveness	Area if applicability	Implementation priorities *& order (#)*
New zoning, "accept & retreat", etc.	◐●	◐	"Must do" management options, but need socio-economic & political push	All coastal towns	1 "Must do" management options mitigate present & future hazards & enable better socio-economic
Alternative safe area developments	●	●			
Accommodation: raising property, etc	◐	◐	With high value infrastructure & seaward defenses	Site specific	4 Manage/adapt where unavoidable to protect high value infrastructure
Sand nourishment	●	●	Good in Maputo & Beira with port dredging	Local	2 Ideal win-win "soft engineering"/restoration opportunity where local conditions allow
Managed vegetated/reinforced dune	●	●	Best "environmental" options	All coastal towns/Local	
Rehabilitated mangrove/wetland	●	●			
Seawalls (vertical / curved concrete)	◐	◐	Mostly where high value development exists & space/sand is limited	Site specific	3 Implement "hard engineering" or armouring where unavoidable to protect high value development/infrastructure.
Revetments (sloping rock)	◐	◐			
Dikes (sand/earthen mound)	○	○	"Last resort" alternative to dunes	Site specific	
Detached breakwaters/artificial reefs	○	○	Can be good with major development	Site specific	
Groynes (rock/concrete)	◐	◐	Mostly with sand nourishment	Site specific	
"Geotextiles" sand filled	◐	◐	Only in low/moderate wave energy - medium term	Site specific	
Gabions & rock filled mattresses	◐	◐			

Key: Feasibility & CBA: ○ Low ◐ Medium ● High

The results together with site investigations allowed coastal engineers to determine the most appropriate adaptation options to introduce for a particular area within the study areas. Following a conservative and precautionary approach, a list of prioritised adaptation response actions for each town and city was recommended (Chapter 8)

10.3 KEY RECOMMENDATIONS

10.3.1 Integrated coastal planning and management

The adoption and implementation of the strategic principles and guidelines on planning for and responding to coastal impacts and including specifically climate change impacts, as discussed in Chapter 7 is seen as the first and most important action point. Most of the response options are purposefully what can be termed "soft" options or "working with nature". Following an integrated coastal planning approach is in line with strategic principles and best practise guidelines in terms of coastal management and responding to climate change. This simple management level decision will go a long way in reducing the need for constructing expensive coastal defences in many instances, especially in the long-term. Activities are, amongst others:

- Plan any coastal construction so that it is a safe distance away from the high-water mark and reinstate natural defence mechanisms with the necessary environmental authorisations.

- Undertake holistic planning and implementation through the development and implementation of Coastal Management Programmes that incorporate Shoreline Management Plans.
- Establish a coastal development setback line which is designed to protect both the natural environment from encroachment from buildings as well as protecting beachfront developments from the effects of storms and accelerated coastal erosion.
- Work with nature by protecting the integrity of buffer dune systems, which should be vegetated with appropriate dune species as per the original natural zones and maintained.
- Maintain, or even better, increase the sand reservoir (volume) stored in the dune system.
- Protection, restoration and maintenance of natural systems like mangroves and coral reefs.

10.3.2 Site specific adaptation options

To illustrate the assessment approach and the way the results are presented for each study site, the city of Beira is used as the example below. The results for the other study sites are presented in a similar manner in Chapter 8.

Beira preliminary adaptation /coastal protection options

based on general criteria, local site charateristics, current use/"value"

KEY: Adaptation measures

A "Management options"

A1 **"Accept & retreat"**: zoning, etc.

A2 **"Abstention"** 'do nothing'

A3 **"Alternative" developments** in safe areas

A4 **"Accommodation"** e.g. raising property

B "Soft engineering" /Restoration

B1 **Sand nourishment**

B2 **Managed (vegetated &/ reinforced) dune**

B3 **Managed/rehabilitated mangrove/wetland areas**

C "Hard engineering" & armouring

C1s **Seawalls** (vertical / curved concrete)

C1r **Revetments** (sloping rock)

C2 **Dikes** (sand/ earthen mound)

C5 **Groynes** (rock/concrete)

Low/ moderate wave energy:

C11 **"Geotextiles"** sand filled

C12 **Gabions & mattresses**

The red numbers indicate possible order of implementation

Adaptation / coastal protection options based on general criteria, local site characteristics and current use/"value" for Beira. (See Figure 8.1 in Chapter 8)

The key adaptation measures found to be appropriate for Beira is summarised in the large white block in the figure, which include four "Management options" (labelled A1 to A4), three "Soft engineering"/Restoration measures (B1, B2 & B3), four "Hard engineering" & armouring options

(C1s, C1r, C2, C5), and two options more suitable for low/moderate wave energy sites (C11 & C12).

The three or four options or combination of options considered most suitable for each 0.5 km alongshore section of the coast at Beira are indicated in the small white block adjacent to each marker on the map. The labels within each small block (e.g. A1 or C5, etc.) refer to the labelled options described in the large white block.

The large red numbers (1 to 4) on the figures indicate the recommended order of implementation of the identified coastal adaptation measures for Beira. In other words, Figure 8.1 represents a "plan" or "map" summarising the preferred adaptation options along each 0.5 km section of the western, southern and south-eastern Beira coast.

It should be noted that specific engineering design details and accurate costing of each option can only be done once site specific engineering and environmental investigations have been carried out. It is absolutely critical to involve experienced coastal engineering and coastal environmental professionals in the detailed planning, design and implementation of the chosen options.

10.3.3 Seek opportunities for public-private-partnerships (PPP)

In many cases sound planning and future development beyond the reach of the sea forces can be implemented successfully. Many opportunities for entering into 'design-&-build' type PPP exist which have the potential to co-fund the implementation of the more costly "hard"-engineering adaptation options.

10.3.4 Continue active engagement and communication with stakeholders to disseminate the outputs and facilitate uptake

Observations by the study team during interaction with stakeholder groups at various levels of authority leads to the following recommendations presented for consideration:

The recommendations fall into three categories, namely (a) those that relate to the various decision-makers, (b) those at a more technical/scientific level, and (c) those that relate to decision-making.

(a) Leadership aspects

The following actions can be implemented immediately and maintained on an ongoing basis:

1. Local leaders (Authorities as well as Traditional) should be encouraged to respect the fact that climate change may lead to a threat to lives, livelihoods and infrastructure.

2. Leaders should be encouraged to endorse the adoption and application of the strategic principles and best practice guidelines for adaptation measures (Section 7.1) in all Integrated Coastal Zone Management, coastal governance and planning of coastal developments.

3. Leaders should be encouraged to implement the prioritised "no-regret" adaptation measures as soon as possible. In most cases this means adhering to sound planning and design principles.
4. Leaders should be encouraged to incorporate the results of the studies into the current and future plans such as municipal structure plans and public and privately funded development plans.
5. Leaders should be encouraged to consider following a PPP approach to obtain co-funding for the more costly but critically important adaptation measures.

(b) Technical and scientific aspects

The following technical and scientific aspects are recommended for immediate implementation over the next 6 to 12 months:

1. Due to the importance of knowing the actual elevation of the identified high risk areas, it is of utmost importance to carry out detailed topographic surveys of the coastal strip in all towns and cities.
2. The current municipal structure plans and other development planning along the coastline should be updated to incorporate the identified climate change factors.
3. Approved coastal development plans should be revised to ensure the relevant climate change related factors are taken into consideration and that private developers are aware of the potential risk of not taking a precautionary approach. (Tourism could be one of the sources of income for implementation of adaptation measures.)
4. A formal system for monitoring, evaluating, and reporting on the key parameters identified in this study should be set up and maintained by a competent authority.

(c) Knowledge dissemination and decision Support

To enable informed, evidence based decision-making, the following actions can be implemented within 12 to 24 months:

1. Develop decision support tools such as maps, GIS database, reports and practical rule-based guidelines for use by the coastal management community at National, Provincial and Municipal levels.
2. Carry out a process to effectively disseminate results of this study at National, Provincial and Municipality levels. Also, embark on an information and education drive to raise wider local population awareness.
3. Establish a regional extension/advisory service. This can possibly be done via the INGC regional offices supported by relevant scientific, engineering and technological expertise

located at the universities, relevant Ministries and in partnership with regional and international service providers until a national capability is established.

4. Introduce formal climate change adaptation related skills development programmes at all decision support levels (Management, Administration and Technical levels).

(Early warning systems (e.g. via cell phones), emergency response plans and measures for extreme events, such as cyclones, are not the focus of this investigation, but are obviously also of critical importance. The INGC has demonstrated good foresight and implementation in this regard in the past.)

10.4 MONITORING AND EVALUATION REQUIREMENTS

10.4.1 Establish a baseline

Following on the present Phase II work, it is expected that there will be an implementation phase. In any follow up phase of work, it is essential to include as priority additional data collection and monitoring to address the critical gap in regional, national and local level data and information required to enable detailed planning and design and to increase the level of confidence in the key sets of information on which the adaptation measures identified in this study are based.

The parameters and issues which should be monitored include the following:

- ✓ Cyclone characteristics – done when appropriate.
- ✓ Winds and local wave regime (and sea storms) – ongoing.
- ✓ Inshore sea water levels (tides and sea level trends) - ongoing
- ▪ Shoreline stability and trends (erosion/accretion)- a baseline survey as soon as possible followed by repeat surveys every three to five years, and after each major cyclone.
- ▪ Integrity of built coastal defences/structures - a baseline survey followed by repeat surveys every three to five years. This should be a critical input into an effective infrastructure maintenance plan.
- ▪ Integrity of natural coastal defences (dunes, mangroves, coral reefs, wetlands) – a baseline followed by regular repeats as appropriate. This should also be a critical input into an effective maintenance and wider integrated coastal zone management plan.
- ▪ It is of utmost importance to collect sufficiently detailed topographic and bathymetric data at identified priority areas. This can mostly be a “once off” baseline data collection task, but should be repeated at longer intervals, perhaps every 10 years for the topographic data, or immediately after any major change caused by, for example, a cyclone that will then form the new baseline.

As far as can be determined, the first three items (indicated by a tick) are being monitored to some degree or can be derived indirectly from existing monitoring actions. However, the last four items (indicated by a square dot) are not being monitored (as far as it is known). These items are also critical for any proper integrated coastal zone management and sustainable coastal developments assessments and plans. Thus, it is strongly recommended that actions be taken to ensure that effective monitoring of all the above mentioned parameters is undertaken.

As indicated, while some of the parameters need to be collected at very short time intervals (e.g. sub-hourly wind data), others need only be collected every few years (e.g. topographic data).

10.4.2 *Ongoing monitoring, evaluation, dissemination and response*

Building onto the recommendation on decision-support that arose through the interaction with stakeholder groups, it is considered of strategic and tactical importance to implement a national programme of ongoing monitoring and reporting of key environmental indicators that are relevant to the climate change parameters identified during this study.

The INGC has a well established and proven network for near real-time information gathering, evaluation and response during the lead up and in emergency events, such as cyclones, floods, fires etc. It is therefore recommended that a complementary network for data gathering, evaluation and information dissemination regarding climate change effects, possible trends in the identified hazard drivers, and resulting impacts to build up the scientific database and knowledge on which informed decisions can be made be set up as soon as possible.

CHAPTER 11: REFERENCES

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CHAPTER 12: GLOSSARY OF TERMS (DEAD & P, 2010)

Accretion	The accumulation of (beach) sediment, deposited by natural fluid flow processes
Alongshore	Parallel to and near the shoreline; same as longshore
Astronomical tide	The tidal levels and character which would result from gravitational effects, e.g. of the earth, sun and moon, without any atmospheric influences.
Bar	An offshore ridge or mound of sand, gravel, or other unconsolidated material which is submerged (at least at high tide), especially at the mouth of a river or estuary, or lying parallel to, and a short distance from, the beach.
Bathymetry	The measurement of depths of water in oceans, seas and lakes; also the information derived from such measurements.
Bay	A recess or inlet in the shore of a sea or lake between two capes or headlands, not as large as a gulf but larger than a cove.
Beach	(1) a deposit of non-cohesive material (e.g. sand, gavel) situated on the interface between dry land and the sea (or large expanse of water) and actively “worked” by present-day hydrodynamics processes (i.e. waves, tides and currents) and sometimes by winds. (2) the zone of unconsolidated material that extends landward from the low water line to the place where there is marked change in material or physiographic form, or to the line of permanent vegetation. The seaward limit of a beach – unless otherwise specified – is the mean low water line. A beach includes foreshore and backshore. (3) (smp) the zone of unconsolidated material that is moved by waves, wind and tidal currents, extending landward to the coastline.
Beach erosion	The carrying away of beach materials by wave action, tidal currents, littoral currents or wind.
Beach profile	A cross-section taken perpendicular to a given beach contour, the profile may include the face of a dune or seawall, extend over the backshore, across the foreshore, and seaward underwater into the nearshore zone.
Bed	The bottom of a watercourse, or any body of water.
Benefits	The economic value of a scheme, usually measured in terms of the cost of damages avoided by the scheme, or the valuation of perceived amenity or environmental improvements.
Buffer area	A parcel or strip of land that is designed and designated to permanently remain vegetated in an undisturbed and natural condition to protect an adjacent aquatic or wetland site from upland impacts, to provide habitat for wildlife and to afford limited access.
Cay	A small, low island composed largely or coral or sand.
Cliff	A high steep face of rock.
Climate change	Refers to any long-term trend in mean sea level, wave height, wind speed, drift rate etc.
Coast	A strip of land of indefinite length and width (may be tens of kilometres) that extends from the seashore inland to the first major change in terrain features.
Coastal management	The development of a strategic, long-term and sustainable land use policy, sometimes also called shoreline management.
Coastal processes	Collective term covering the action of natural forces on the shoreline, and the nearshore seabed.
Coastal zone	The land-sea air interface zone around continents and islands extending from the landward edge or a barrier or shoreline of coastal bay to the outer extent of the continental shelf. In its wider meaning it is often taken as extending landward up to where littoral processes are active or could have an effect (which could be some kilometres inland in certain areas).

Coastline	(1) technically, the line that forms the boundary between the coast and the shore. (2) commonly, the line that forms the boundary between land and water. (3) (smp) the line where terrestrial processes give way to marine processes, tidal currents, wind waves, etc.
Conservation	The protection of an area, or particular element within an area, accepting the dynamic nature of the environment and therefore allowing change.
Continental shelf	The zone bordering a continent extending from the line of permanent immersion to the depth, usually about 100 m to 200 m, where there is a marked or rather steep descent toward the great depths.
Contour line	A line connecting points, on a land surface or sea bottom, which have equal elevation. It is called an isobaths when connecting points of equal depth below a datum.
Cross-shore	Perpendicular to the shoreline.
Debris line	A line near the limit of storm wave up-rush marking the landward limit of debris deposits.
Deep water	In regard to waves, where depth is greater than one-half the wave length. Deep-water conditions are said to exist when the surf waves are not affected by conditions on the bottom.
Deep water waves	A wave in water the depth of which is greater than one-half the wave length.
Depth	Vertical distance from still-water level (or datum as specified) to the bottom.
Design storm	Coastal protection structures will often be designed to withstand wave attack by the extreme design storm. The severity of the storm (i.e. return period) is chosen in view of the acceptable level of risk of damage or failure. A design storm consists of a design wave condition, a design water level and a duration.
Design wave	In the design of harbours, harbour works, etc. the type or types of waves selected as having the characteristics against which protection is desired.
Direction of waves	Direction from which waves are coming.
Direction of wind	Direction from which wind is blowing.
Dunes	(1) Accumulations of windblown sand on the backshore, usually in the form of small hills or ridges, stabilized by vegetation or control structures. (2) a type of bed form indicating significant sediment transport over a sandy seabed.
Duration	In forecasting waves, the length of time the wind blows in essentially the same.
Ecosystem	The living organisms and the non-living environment interacting in a given area.
Erosion	Wearing away of the land by natural forces. (1) On a beach, the carrying away of beach material by wave action, tidal currents or by deflation. (2) The wearing away of land by the action of natural forces.
Estuary	(1) a semi-enclosed coastal body of water which has a free connection with the open sea. The seawater is usually measurably diluted with freshwater. (2) the part of the river that is affected by tides.
Event	An occurrence meeting specified conditions, e.g. damage, a threshold wave height or a threshold water level.
Fetch	The length of unobstructed open sea surface across which the wind can generate waves (generating area).
Fetch length	(1) the horizontal distance (in the direction of the wind) over which a wind generates seas or creates wind setup. (2) the horizontal distance along open water over which the wind blows and generates waves.
Gabion	(1) steel wire-mesh basket to hold stones or crushed rock to protect a bank or bottom from erosion.
Geology	The science which treats of the original, history and structure of the earth, as recorded in rocks, together with the forces and processes now operating to modify rocks.
Georeferencing	The process of scaling, rotating, translating and de-skewing the image to match a particular size and position (2) establishing the location of an image in terms of map projections or coordinate systems.
High water (HW)	Maximum height reached by a rising tide. The height may be solely due to the periodic tidal forces or it may have superimposed upon it the effects of prevailing meteorological

	conditions. Non-technically, also called the high tide.
High water mark	A reference mark on a structure or natural object, indicating the maximum stage of tide or flood.
Mean high water springs (MHWS)	The average height of the high water occurring at the time of spring tides.
Mean sea level (MSL)	The average height of the surface of the sea for all stages of the tide over a 19-year period, usually determined from hourly height readings.
Ocean	The great body of salt water which occupies two-thirds of the surface of the earth, or one of its major subdivisions.
Offshore	(1) in beach terminology, the comparatively flat zone of variable width, extending from the shoreface to the edge of the continental shelf. It is continually submerged. (2) the direction seaward from the shore. (3) the zone beyond the nearshore zone where sediment motion induced by wave alone effectively ceases and where the influence of the sea bed on wave action is small in comparison with the effect of wind. (4) the breaker directly seaward of the low tide line.
Offshore wind	A wind blowing seaward from the land in the coastal area.
Outcrop	A surface exposure of bare rock, not covered by soil or vegetation.
Overtopping	Water carried over the top of a coastal defence due to wave run-up or surge action exceeding the crest height.
Peak period	The wave period determined by the inverse of the frequency at which the wave energy spectrum reaches it's maximum.
Photogrammetry	The science of deducing the physical dimensions of objects from measurements on images (usually photographs) of the objects.
Port	A place where vessels may discharge or receive cargo.
Reach	(1) an arm of the ocean extending into the land. (2) a straight section of restricted waterway of considerable extent; may be similar to a narrows, except much longer in extent.
Recession	(a) a continuing landward movement of the shoreline. (2) a net landward movement of the shoreline over a specified time.
Refraction	The process by which the direction of a wave moving in shallow water at an angle to the bottom contours is changed. The part of the wave moving shoreward in shallower water travels more slowly than that portion in deeper water, causing the wave to turn or bend to become parallel to the contours.
Retum period	Average period of time between occurrences of a given event.
Revetment	(1) a facing of stone, concrete, etc., to protect an embankment, or shore structure, against erosion by wave action or currents. (2) a retaining wall. (3) (smp) facing of stone, concrete, etc., built to protect a scarp, embankment or shore structure against erosion by waves of currents.
Rocks	An aggregate of one or more minerals rather large in area. The three classes of rocks are the following: (1) igeneous rock – crystalline rocks formed from molten material. Examples are granite and basalt. (2) sedimentary rock – a rock resulting from the consolidation of loose sediment that has accumulated in layers. Examples are sandstone, shale and limestone. (3) metamorphic rock – rock that has formed from pre-existing rock as a result of heat or pressure.
Run-up	The rush of water up a structure or beach on the breaking of a wave. The amount of run-up is the vertical height above still-water level that the rush of water reaches.
Sand	An unconsolidated (geologically) mixture of inorganic soil (that may include disintegrated shells and coral) consisting of small but easily distinguishable grains ranging in size from about .062 mm to 2.0 mm.
Scour protection	Protection against erosion of the seabed in front of the toe.
Sea defences	Works to prevent or alleviate flooding by the sea.
Sea level rise	The long-term trend in mean sea level.
Seawall	(1) a structure built along a portion of a coast primarily to prevent erosion and other damage by wave action. It retains earth against its shoreward face. (2) (smp) a structure

	separating land and water areas primarily to prevent erosion and other damage by wave action. Generally more massive and capable of resisting greater wave forces than a bulkhead.
Sediment transport	The main agencies by which sedimentary materials are moved are: gravity (gravity transport); running water (rivers and streams); ice (glaciers); wind; the sea (currents and longshore drift). Running water and wind are the most widespread transporting agents. In both cases, three mechanisms operate, although the particle size of the transported material involved is very different, owing to the differences in density and viscosity of air and water. The three processes are: rolling or traction, in which the particle moves along the bed but is too heavy to be lifted from it; saltation and suspension, in which particles remain permanently above the bed, sustained there by the turbulent flow of the air or water.
Setback	(smp) a required open space, specified in shoreline master programs, measured horizontally upland from a perpendicular to the ordinary high water mark. More commonly used in CZM and coastal engineering terms as a required distance landward of a selected contour line (or the shoreline) to safeguard e.g. infrastructure from marine impacts (such as storm waves or esosion).
Shallow water	Water of such depth that surface waves are noticeably affected by bottom topography. Typically this implies a water depth equivalent to less than half the wave length.
Shoal	(1) (noun) a detached area of any material except rock or coral. The depths over it are a danger to surface navigation. Similar continental or insular shelf features of greater depths are usually termed banks. (2) (verb) to become shallow gradually. (3) to cause to become shallow. (4) to proceed from a greater to a lesser depth of water.
Shore	That strip of ground bordering any body of water which is alternatively exposed, or covered by tides and/or waves. A shore of unconsolidated material is usually called a beach. The *shoreline* is often used as the term for delineating between the land and the sea (e.g. selected as the 0 m to MSL contour line).
Significant wave height	Average height of the highest one-third of the waves for a stated interval of time.
Significant wave period	Average period of the highest one-third of the waves for a stated interval of time.
Soft defences	Usually refers to beaches (natural or designed) but may also relate to energy –absorbing beach-control structures, including those constructed of rock, where these are used to control or redirect coastal processes rather than opposing or preventing them.
Spring tide	A tide that occurs at or near the time of new or full moon, and which rises highest and falls lowest from the mean sea level (msl).
Stillwater level (SWL)	The surface of the water if all wave and wind action were to cease. In deep water this level approximates the midpoint of the wave height. In shallow water it is nearer to the trough than the crest. Also called the undisturbed water level.
Surf zone	The nearshore zone along which the waves become breakers as the approach the shore.
Surf zone	The zone of wave action extending from the water line (which varies with tide, surge, set-up, etc). Out to the most seaward of the zone (breaker zone) at which waves approaching the coastline commence breaking, typically in water depths of between 5 m and 10 m.
Surge	(1) long-interval variations in velocity and pressure in fluid flow, not necessarily periodic, perhaps even transient in nature. (2) the name applied to wave motion with a period intermediate between that of an ordinary wind and that of a tide. (3) changes in water level as a result of meteorological forcing (wind, high or low barometric pressure) causing a difference between the recorded water level and that predicted using harmonic analysis, may be positive or negative. (2) NOAA: *Storm surge*: "A rise or piling-up of water against shore, produced by strong winds blowing onshore. A storm surge is most severe when it occurs in conjunction with a high tide." (3) Expansion by the authors:In southern Africa, sea storms (i.e. high waves with run-up, impacts and scouring) are also a big risk; these can be exacerbated by strong winds and high tides.

Survey, control	A survey that provides coordinates (horizontal or vertical) of point to which supplementary surveys are adjusted.
Survey, hydrographic	A survey that has as its principal purpose the determination of geometric and dynamic characteristics of bodies of water.
Survey, photogrammetric	A survey in which monuments are placed at points that have been determined photogrammetrically.
Survey, topographic	A survey which has, for its major purpose, the determination of the configuration (relief) of the surface of the land and the location of natural and artificial objects thereon.
Swash zone	The zone of wave action on the beach, which moves as water levels vary, extending from the limit of run-down to the limit of run-up.
Swell	Waves that have travelled a long distance from their generating area and have been sorted out by travel into long waves of the same approximate period.
Toe	(1) lowest part of sea- and portside breakwater slope, generally forming the transition to the seabed. (2) the point of break in slope between a dune and a beach face.
Topographic map	A map on which elevations are shown by means of contour lines.
Updrift	The direction to which the predominant longshore movement of beach material approaches.
Wave crest	(1) the highest part of the wave. (2) that part of the wave above still water level.
Wave direction	The direction from which the waves are coming.
Wave height	The vertical distance between the crest (the high point of the wave) and the trough (the low point).
Wave hindcast	The calculation from historic synoptic weather charts of the wave characteristics that probably occurred at some past time.
Wave length	The distance, in meters, between equivalent points (crests or troughs) on waves. Wave period: (1) the time required for two successive wave crests to pass a fixed point. (2) the time, in seconds, required for a wave crest to traverse a distance equal to one wave length.
Wave rose	Diagram showing the long-term distribution of wave height and direction.
Wave set-up	Elevation of the still-water level due to breaking waves.
Wave steepness	The ratio of wave height to its length. Not the same thing as the slope between a wave crest and its adjacent trough.
Wave train	A series of waves from the same direction.
Wave trough	The lowest part of the wave form between crests. Also that part of a wave below still water level.
Wave variability	(1) the variation of heights and periods between individual waves within a wave train. Wave trains are not composed of waves of equal heights and periods which vary in a statistical manner. (2) the variability in direction of wave travel when leaving the generating area. (3) the variation in height along the crest.
Wind rose	Diagram showing the long-term distribution of wind speed and direction.
Wind setup	(1) the vertical rise in the stillwater level on the leeward side of a body of water caused by wind stresses on the surface of the water. (2) the difference in stillwater levels on the windward and the leeward sides of a body of water caused by wind stresses on the surface of the water. (3) synonymous with wind, tide and storm surge. (Storm surge is sometimes reserved for use on the ocean and large bodies of water. Wind setup is sometimes reserved for use on reservoirs and smaller bodies of water. This “incorrect” distinction is not employed in this report.)
Wind waves	(1) waves formed and growing in height under the influence of wind. (2) loosely, any wave generated by wind.
World Geodetic System, 1984 (revised 2004)	An earth fixed global reference frame used for defining coordinates when surveying and by GPS systems.

APPENDICES

APPENDIX 1: SATELLITE REMOTE SENSING FOR COASTAL CHANGE

APPENDIX 2: THEME 2 MISSION TO INTERACT WITH MUNICIPALITIES

APPENDIX 3: COASTAL PROTECTION: SCOPE OF WORK (PHASE 2)

APPENDIX 1: SATELLITE REMOTE SENSING FOR COASTAL CHANGE

Satellite Remote Sensing for Coastal Change Detection: Mozambique case study.

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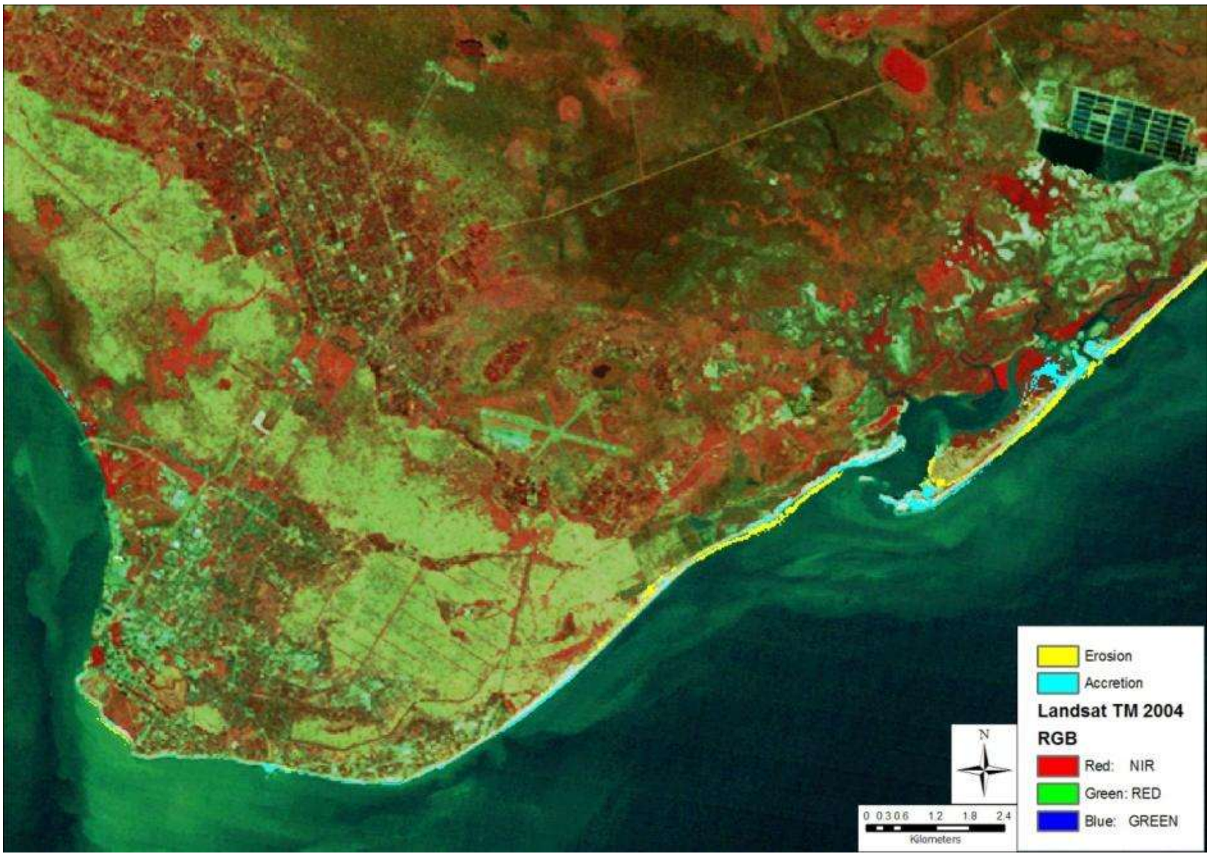

Pretoria / Stellenbosch 14th February 2011

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EXECUTIVE SUMMARY

Coastal vulnerability to large storm events and or sea level rise is dependent on the state of the coastline and the morphological processes acting on that coastline. In the present analyses satellite remote sensing data were assessed in terms of its ability to identify erosive and or accretive processes. The Mozambican coastline is subject to large storm events associated with Indian Ocean low pressure systems, large storm surges are generally associated with these events placing coastal populations and infrastructure under threat. Identifying zones of potential critical change would go a long way to determining where coastal infrastructure could be used to protect coastal communities. A vital step in this process is determining where erosive and accretive processes are taking place along the coastline focussing initially on populated areas. Four study areas were identified for the satellite remote sensing assessment; Maputo, Maxixe, Vilanculos and Beira.

Three change detection methods were assessed at the Maputo (Object-Oriented Image Analysis, Change Vector Analysis and Spectral Change Analysis) site while two were used for the Maxixe, Vilanculos, and Beira sites (Change Vector Analysis and Spectral Change Analysis). Results presented in this report show that the Change Vector and Spectral Change Analyses report consistent results while the Object-Oriented Image Analysis returned inconsistent results. All three image analysis procedures were affected by tides which made differentiating between ocean, beach and shallow water very difficult. This resulted in commission and omission type errors depending on the nature of the tides and the imagery used.

Spatial resolution also played a role in the quality of the results with a ±60 metre accuracy deemed too inaccurate. While the Landsat 5 Thematic Mapper (TM) and 7 Enhanced Thematic Mapper Plus (ETM+) archive provide free and easy to access satellite data, this report suggests that the mapping scale of these sensors is only suitable for contextual coastal studies.

In the future either high resolution satellite imagery or digital aerial photography should be used to assess coastal stability. The authors acknowledge that this data are not always readily available, however, when access to historical aerial photography is possible, every means should be used to acquire and use this data. Further, it is suggested that high resolution Interferometric synthetic aperture radar (InSAR) be explored for identifying either erosive or accretive processes at work along the coastline.

1.0 INTRODUCTION

1.1 Satellite Remote Sensing for change detection studies – Landsat TM

This project component sought to use the Landsat archive to monitor coastal erosion and or accretion at specified locations along the Mozambican coastline. Satellite remote sensing imagery has long been identified as a suitable change detection tool, as the synoptic scale of many sensors in particular allows for the analysis of large areas within one image. Satellite remote sensing platforms also enable direct monitoring of a particular land surface at regular intervals. This characteristic of satellite based earth observation means that a particular multispectral sensor could (depending on swath width and spatial resolution) collect multiple scenes per year of the same area. However, especially in tropical regions the acquisition of cloud free of imagery is usually challenging. The longest running medium resolution archive of satellite data is the Landsat Thematic Mapper (TM) series owned and operated by the United States Geological Survey (USGS). The archive dates back to early 1980s providing a wealth of information for the monitoring of both natural and anthropogenic land cover change. Figure 1 shows the sites where the change detection analyses were conducted within this project.

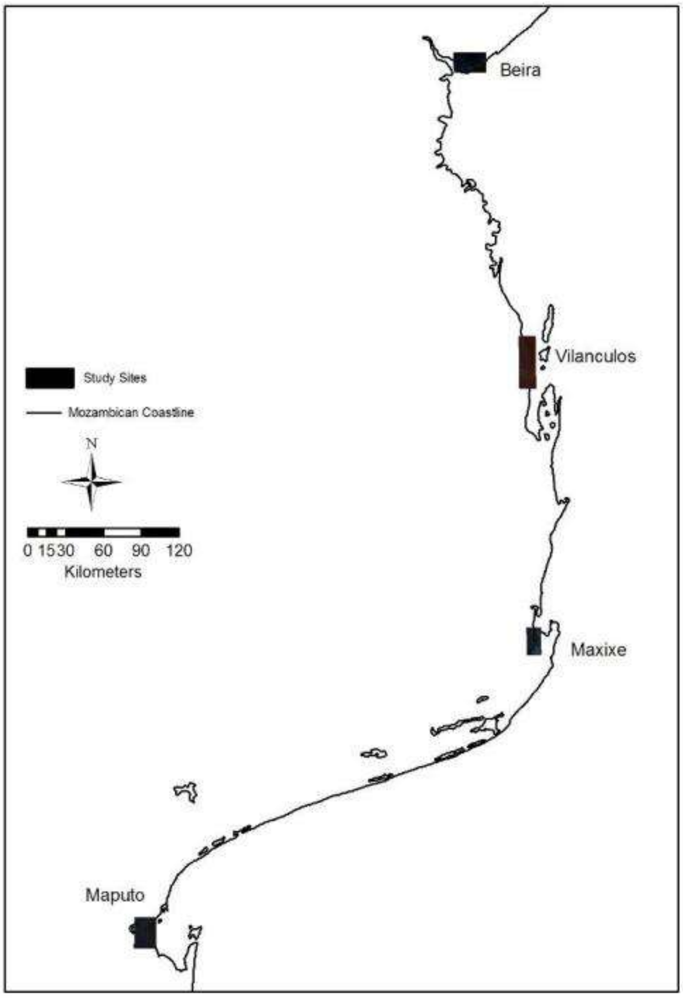

Figure 1 Location of study sites

Landsat TM data were chosen for this study as the system has a comprehensive archive for the region of interest which dates back to the early 1980s. The task was to monitor the location of the coastline at regular intervals (± 5 years) where possible. Further the entire Landsat Archive is made available for free through the Global Land Cover Facility (http://www.landcover.org) and the United States Geological Survey Global Visualisation Viewer (http://glovis.usgs.gov/), data were also sourced from the CSIR's Satellite Applications Centre (SAC). Data are directly downloadable from the Global Land Cover Facility and the USGS Global Visualisation Viewer. The goal of the change detection analysis was to identify areas along the coastline (within our areas of interest) that displayed unusual change both in terms of accretion and erosion. In particular those areas which display large amounts of eroding could be identified and flagged as zones of potential critical change.

The Mozambican coastline is susceptible to weather events which result in large storm surges threatening both public infrastructure and the wellbeing of those living in close proximity to the coastal areas. It was therefore necessary to investigate if and where the coastline is being eroded and attempt to understand why this is happening with a view to presenting a plan for adapting to future coastal climate related threats. On the other hand accretion is a sign of changes to coastal morphology resulting from either natural or anthropogenic influences. Mapping accreting zones would help to plan for the future changes.

Several studies have shown the utility for mapping both erosion and or accretion using various Landsat satellites. Alesheikh *et al*. (2007) employed histogram rationing and band thresholding techniques to monitor the shoreline of a saline lake in north western Iran. The authors were able to determine, through the use of Landsat imagery and change detection methods that, the area of the lake had decreased by up to 20% over a 5 year period. Accuracy assessments indicated that their proposed methodology was accurate to 1.3 pixels (±39m). Chen *et al*. (2005) employed Landsat MSS and TM imagery to measure coast line reclamation in Lingding Bay in Southern China. Their analyses were able to identify and map coastal accretion of between 3.6 and 6 km seaward due to urban expansion and coastal reclamation projects. Similarly Vanderstraete *et al*. (2006) made use of Landsat TM and ETM+ data to map zones of accretion and erosion resulting from changing land use activities. Their study was able to definitively map zones of change and incorporate those into future planning activities.

While all three studies indicate that satellite remote sensing proves useful for coastal change studies, Boak and Turner (2007) do indicate that a limiting factor when utilising multispectral data is the pixel resolution and cost. The recently published Landsat archive are free of charge however any analysis conducted using Landsat imagery is limited to an accuracy of ±60m for Landsat TM and ETM+ and ±120m for the older MSS sensors.

1.2 Methods employed

As mentioned above change detection techniques were employed to analyse change in coast line location over the predefined study period in the following locations: Maputo, Beira, Maxixe and Vilanculos. Landsat imagery was downloaded from the GLOVIS and SAC archive for various dates for each location. Table 1 shows the dates and locations for which data was collected (Not all input data was employed in either of the three change detection methods).

Table 1 Input imagery (sources: CSIR SAC & USGS GLOVIS)

Maputo	Beira	Maxixe	Vilanculos
15/03/1984	01/06/1984	05/22/1992	27/02/1987
18/03/1986	13/12/1988	03/02/1995	31/05/1992
27/03/1991	20/05/1991	01/06/2001**	21/03/1995
09/07/1992	04/06/1996		13/05/2000**
18/06/1996	01/09/2000**		01/06/2004
14/01/2000**	24/06/2004		31/08/2008
14/09/2003	07/09/2008		30/05/2009
10/07/2004			
07/09/2008			
Landsat 7ETM+ ** (All others are Landsat 5 TM)			

The USGS distributes Landsat imagery corrected to level 1T, which indicates that a geometric correction has been applied to the imagery with both sensor and terrain specific geometric errors removed. It is thus not necessary to perform any geometric corrections to the imagery, while the SAC distributes their data at level 1G, which usually requires some correction for terrain effects. Therefore SAC data were corrected using a Shuttle Radar Topography (SRTM) derived digital elevation model (DEM), with final image to image registration employing USGS data. Radiometric corrections were required as both data sources are distributed as scaled digital numbers. Using the ATCOR software DN values have been converted to at-surface reflectance using gains and biases and other solar parameters derived from the metadata files which accompany the respective input images.

Quality control was employed by analysing spectral signatures of characteristic surfaces within each of the resulting reflectance images and comparing with reference signatures. Following completion of the pre-processing three change detection methods were employed. The first method employed object oriented image analysis (OOIA) to extract the coastline from each of the input images and then plot these lines within a geographical information system. The second method employed change vector analysis (CVA) to identify pixels along the coastline which displayed change outside of normal expected range. Finally a spectral change technique was used to analyse the changes in spectra per pixel. Three separate methods were employed as this provided the researchers with the opportunity to fully explore the application of medium resolution satellite remote sensing for coastal change studies. For the interpretation of the images, for all acquisition dates also the tidal state at the time of image acquisition was assessed using the WXTide40 tool.

Object Oriented Image Analysis (OOIA)

The first coastline change analysis method used was OOIA which as described above sought to identify the coastline which was defined as the interface between the ocean and the land mass. In contrast to pixel based classifiers OOIA conducts its classification on image objects as opposed to single pixels. These objects are defined using a segmentation algorithm which seeks to identify homogenous regions within the image based on predefined parameters. The present project made use of a Multiresolution Segmentation algorithm developed by Baatz and Schäpe (2000) and implemented within the Definiens Developer 7 image analysis software. The parameters required for the segmentation include *shape* and *compactness* which control both the size and shape of the segments based on the image content. No definitive rule exists for the selection of optimal *shape* and *compactness* values; rather, image analysts use a trial and error to determine the optimal selection for each image. The result of the segmentation is a number of image objects. Each of these image objects has certain characteristics depending on the pixels within it. The characteristics of these pixels are then assigned to the object and used to further partition the objects into predefined classes. Further partition is conducted using thresholding as well as colour, object shape and object adjacency.

Employment of spatial adjacency as a measure of class association allows for the classification of image objects based on their proximity to a class or feature within the image. In the present analysis OOIA was used to locate the interface between the land and ocean and then convert this area into a vector designating the coastline. The definition of the coastline changed depending on the land cover present, in some cases the coastline was the interface between an urban area and the ocean, at other locations the interface between vegetation and ocean and still others the interface between white sand and vegetation adding to the complexity of the analyses. Results of the OOIA procedure are presented in section 2.1.

Change Vector Analysis (CVA)

The second change detection method employed was the Change Vector Analysis (CVA) technique (Johnson and Kasischke, 1998). The technique uses Euclidean distance to calculate the magnitude of change between two spatially coincident pixels from two images of the same area captured on different dates. In contrast to the OOIA technique CVA attempts to quantify the amount of change taking place between two images at the pixel level. Further, the method also offers the opportunity to determine the direction of change based on Cartesian coordinates. Equation 1 outlines the calculation of the magnitude M of change between pixels, where ya is band 1 from the first date image and yb is band one from the second image and xa and xb are bands 2 from the first and second images respectively (equation 1 is suitable for change detection studies using two input bands per image date)

$$M = \sqrt{(yb - ya)^2 + (xb - xa)^2} \qquad (1)$$

Using this equation, CVA quantifies the length of the change vector between two spatially coincident pixels. Further, CVA presents the opportunity to quantify the particular direction of the change vector. If we were to draw the change space on a Cartesian plane and plot the location of the pixels in date 1 and the location of the pixels in date 2 (based on x & y coordinates) we would then be shown not only the magnitude of change but also the direction of change. See figure 2 for a graphical explanation.

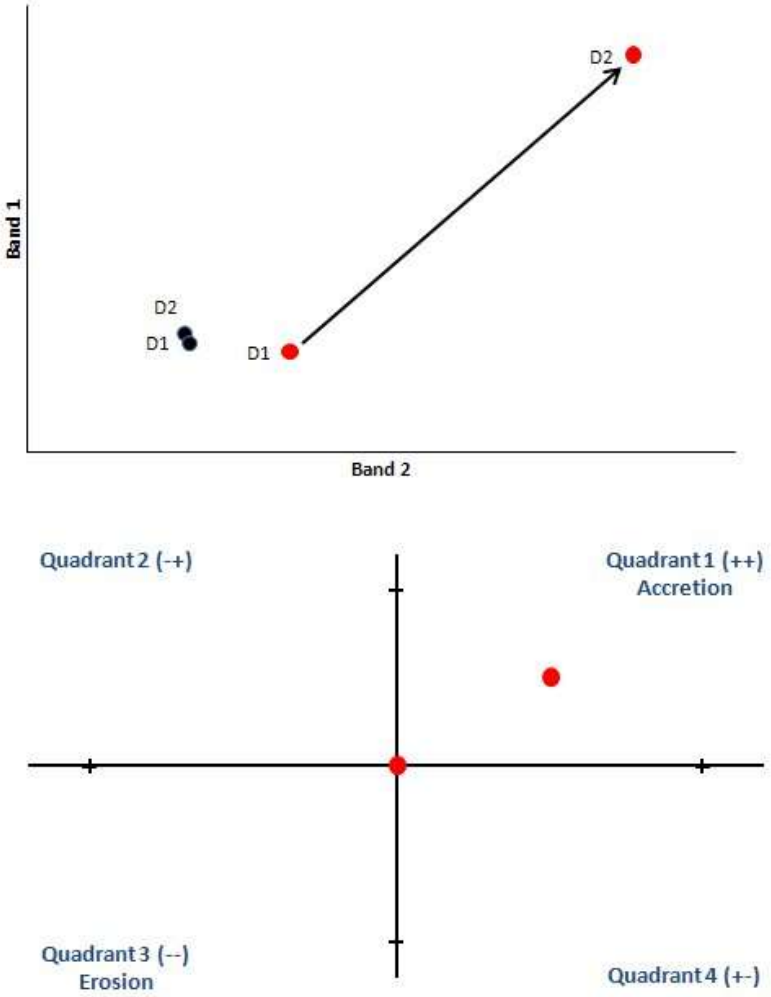

Figure 2 Graphical Representation of CVA: Top shows the magnitude of the change vector while the bottom shows the direction.

The lower half of Figure 2 graphically illustrates that, depending on the type of change the direction of that change may be used to deduce certain characteristics about the change.

In the present analysis two derivative bands from each date were used, namely the near-Infrared (IR) band and the first component of a Principal Component Analysis (PCA). These two bands were chosen because firstly, near-IR electromagnetic radiation is strongly absorbed by water and largely reflected by non-water surfaces thus making this band sensitive to changes between land and water, while the first component of a PCA displays the information which is common among all input bands, i.e. similar reflectance and absorption. This means, areas of change are displayed by either increases or decreases in spectral reflectance as quantified by the input bands. Thus combined, the near-IR band and the first PC make for an effective tool for monitoring coastline change as they are both sensitive to changes in land reflectance and water absorption. For example, in the present study a particular pixel was deemed to be accreting if both the near-IR and the 1st PC increased in brightness between the two dates. An increase in brightness would indicate that the pixel has moved from a predominantly water based pixel to a land based pixel. Similarly, if the brightness decreased then the pixel has moved from a land based pixel to a water based pixel indicating erosion. This is the basis for the CVA analysis with the output of the analysis being an image depicting magnitude of change as well as direction, either quadrant 1, 2, 3, or 4 with 1 and 3 being the focus. Following this several trials were run with regards to selecting and appropriate magnitude threshold, the authors settled on the 90th percentile as representing significant change from one date to the next. Following this those pixels displaying change larger than the 90th percentile were selected and used to mask the direction output where only quadrants 1 and 3 were retained. A CVA was conducted for each date pair at each location. The acquisition years of the images compared in the change vector analysis are given in table 2 below.

Table 2 CVA date pairs

Maputo	Beira	Maxixe	Vilanculos
1992 - 1996	1991 - 1996	1992 - 1995	1987 - 1995
1996 - 2004	1996 - 2000	1992 - 2001	1995 - 2000
2004 - 2008	2000 - 2004	1995 - 2001	2000 - 2009

Change for the entire time period was then determined using raster mathematics, with pixels consistently returning erosion and or accretion identified as critical change zones. The results are illustrated in section 0.

Spectral Change Analysis (SCA)

The third change detection method employed for the Maputo test region involved the use of Spectral Change Analyses (SCA). As with all change detection algorithms, the Spectral Change Analysis required meticulous geometric correction of the input data as any inaccuracies would result in false detection of change. To detect spectral changes over time, a bi-temporal comparison of the geometrically and atmospherically pre-processed data was undertaken. For that purpose, an image differencing was performed, subtracting the respective younger image from the respective older one.

From the resulting 6-band composite, the ratio of band 3 / band 4 was calculated, band 3 being the difference of the Landsat TM bands 3: $RED_{old} – RED_{new}$ and band 4 being the near infrared difference $NIR_{old} – NIR_{new}$.

Using this band3/band4 ratio and the difference bands 3 and band 4 themselves, a decision tree classifier was developed, based on image analysis-derived threshold values for those three bands.

The following change classes were derived:

0: no change,
1: vegetation in image old changed to bare soil in image new,
2: bare soil changed to vegetation,
3: vegetation to water,
4: water to vegetation,
5: bare soil to water, and
6: water to bare soil.

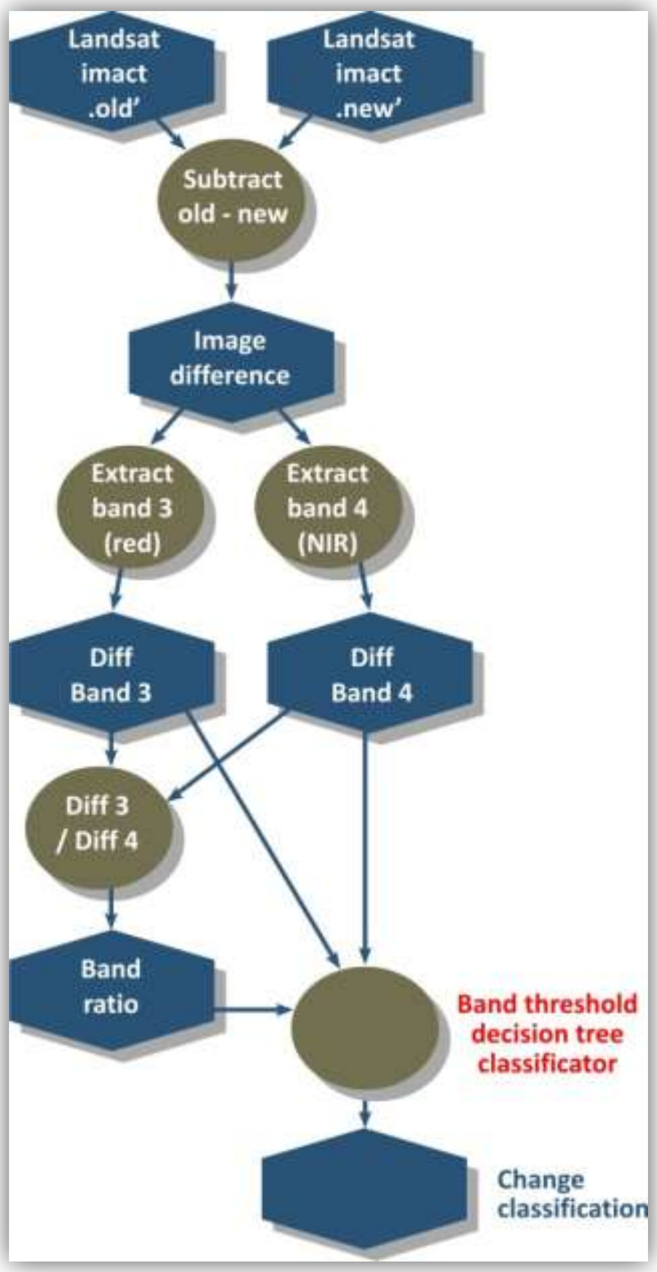

Figure 3 Schematic overview of spectral change workflow

Relevant for this work were only the classes 1 and 2, indicating a change of the edge between coastal (dune) vegetation and beach, and the classes 5 and 6, indicating a change in the water line. In order to avoid misclassifications of the change of the waterline due to tidal variances of the compared images, only high tide images were used for this approach. The tidal state of the respective Landsat images at the image acquisition time has been assessed using the WXtide40 tool. Accordingly, the following Landsat TM and ETM+ images for the Maputo region have been compared:

1986-11-14 – 2009-12-23,
1986-11-14 – 1999-07-05,
1999-07-05 – 2003-09-02,
2003-09-02 – 2009-12-23.

2.0 RESULTS

2.1 Object Oriented Analysis

Object-oriented image analysis (OOIA) was conducted on all but one of the sites; due to data irregularities no OOIA was performed on the Maxixe site. As mentioned in section 1.2.1 Definiens eCognition software was used to map the location of the coastline which was defined as the interface between the ocean and the land. Figure 4 shows the results from the OOIA around the capital Maputo. The analyses were conducted at several temporal intervals including 1984, 1986, 1992, 1996, 2000, 2004, and 2008. The extracted coastlines are shown in Figure 4 where no clear identification of coastal erosion or accretion has been detected. While the algorithm managed to identify the general location of the coastline determining trends and or systematic change is largely a quantitative procedure which is very limiting when compared to the methods used by coastal engineers.

Figure 4 Object Oriented Image Analysis Results (Maputo)

While the data may be difficult to interpret one can clearly see that there have been few catastrophic changes associated with either floods and or hazardous events. Changes in the river mouth, seen on the top left side of figure 4 highlight the continued problems encountered with regards to the exact definition of the coastline. In some images the tide was *in* while on others the tide was clearly *out*. Given the shallow depths of Maputo bay low-tide images returned a coastline much further seaward than a high-tide scene. After the analysis of the tidal state of employed Landsat images, those changes clearly related to differences in the tidal state and have been excluded from the change analysis.

Figure 5 shows a similar analysis for the Beira region where OOIA procedures were employed to map coastal changes. Unfortunately due to time limitations it was not possible to conduct the OOIA for all the input images.

Figure 5 Object Oriented Image Analysis Results (Beira)

Figure 5 also highlights the issues of the tidal range around Beira. Shallow coastal waters display a bright white hue in contrast to deep coastal waters which appear dark. Especially during low tides, the shallow sandy coastal areas frequently become spectrally indistinguishable from water-free beaches. This means, during low-tide cycles it becomes very difficult to establish an accurate location of the coastline (using Landsat TM imagery) with a bias towards identifying accretion as opposed to erosion events. Due to technical issues it was not possible to run the OOIA on the Maxixe study site however figure 6 shows the Vilanculos area and its extracted coastlines for 1992 and 2004. Similarly, data analysis was hampered by inconsistent tidal ranges between image capture dates. The two coastlines presented in figure 6 show a slight amount of accretion in the 2004 scene when compared to the 1992 image. This accretion is most likely the result of inconsistent tidal ranges between the two scenes. Furthermore, the method employed may well be able to identify coastal accretion or erosion but quantifying how much has taken place and identifying any meaningful trends is very difficult using a two-dimensional method as precise as OOIA.

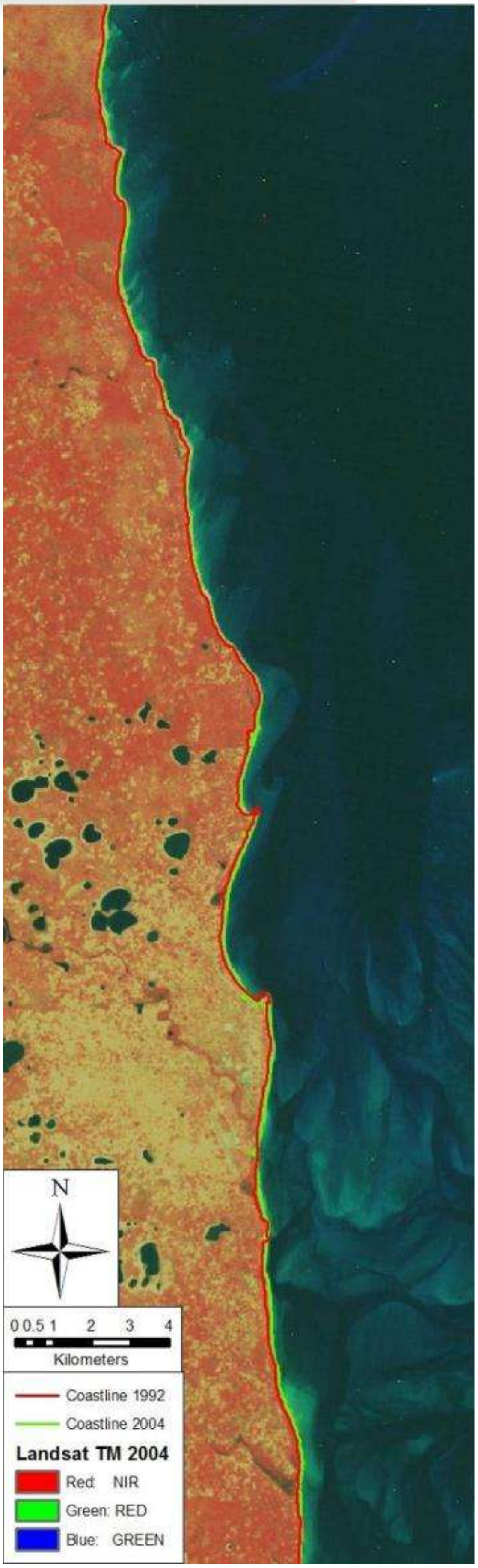

Figure 6 Object Oriented Image Analysis Results (Vilanculos)

2.2 Change Vector Analysis

Change vector analysis was also conducted using the same image data. In the analyses, image pairs were analysed using the CVA method, table 2 shows the dates of the analyses while figure 7 shows the results for the Maputo analysis. While up to three comparisons were made not all change vectors could be mapped onto a single map, instead only those pixels which returned consistent change in the same direction were retained and identified as zones of potential critical change. Figure 5?? where erosion is depicted in yellow and accretion in cyan, shows that in areas around the city and indeed across the bay a small amount of accretion is taking place along the coastline with little or no erosion present.

Interpretation of the results focussed on the coastal areas as this is the area of interest, not on the inland areas. While spectrally similar changes may have taken place inland of the coast, these changes are likely the result of land use / land cover change during the analyses periods. Figure 8 shows the results of the CVA analysis of the Beira region. Once again erosion is depicted in yellow with accretion in cyan. The CVA analysis conducted between 1991 and 2004 shows persistent erosion and accretion in several places. To the right of the image a river / marsh delta appears highly dynamic with both erosive and accretive process occurring in more than two of the image pairs while mangrove swamps in the region return what appear to be erosive processes. When interpreting these results one should remember that the Beira region experiences inter-tidal fluctuations of ±6 meters (range between spring high and low tides) thus any changes identified should be confirmed using traditional methods.

Figure 7 Change Vector Analysis Results (Maputo)

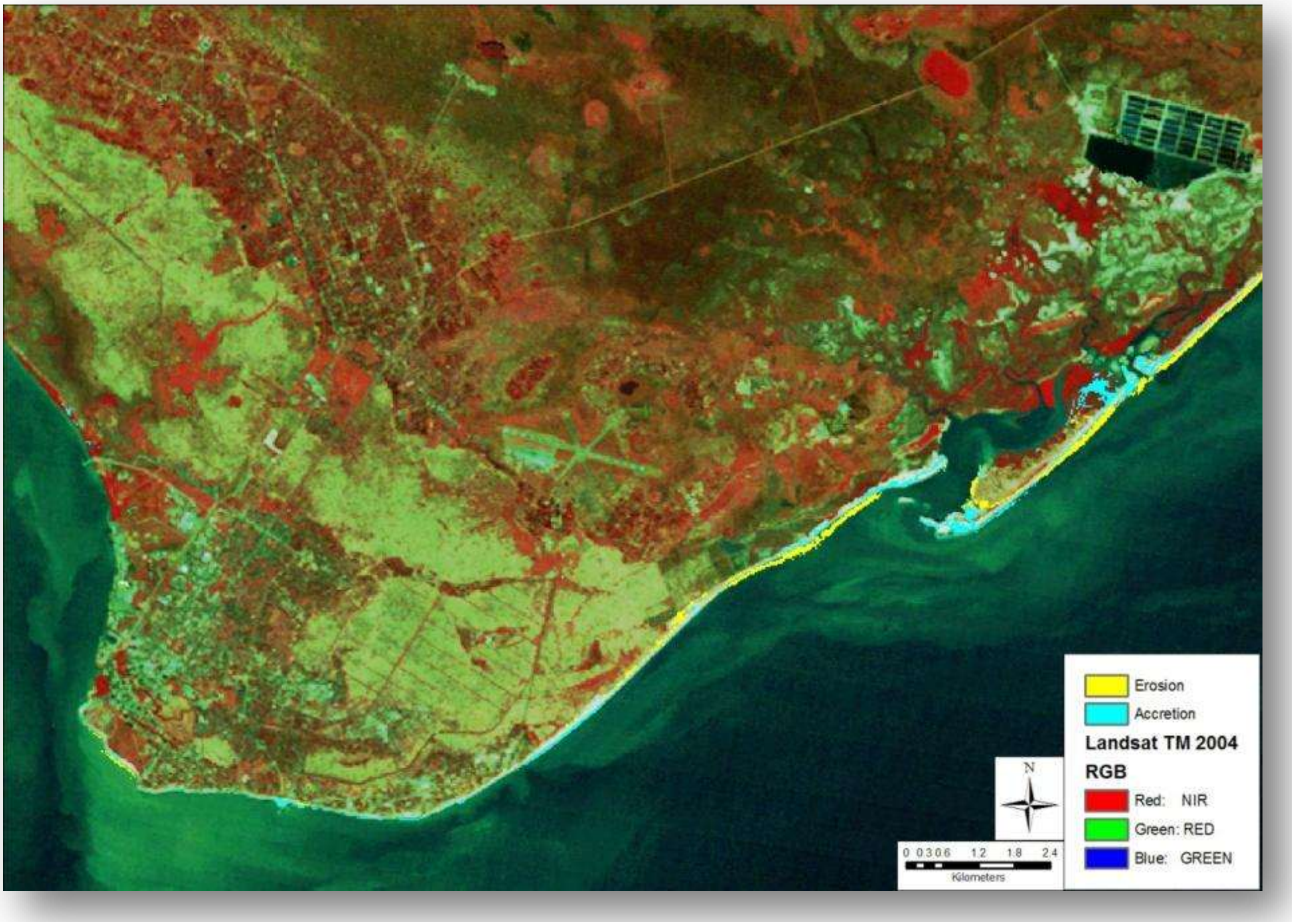

Figure 8 Change Vector Analysis Results (Beira)

Figure 9 presents the results of the CVA analysis for the Maxixe site where both erosive and accretive processes have been detected. Accretive processes in the top right of the image are the result of cloud cover. North of Maxixe, the CVA analysis returns consistent erosive processes north of the town while the coastal areas adjacent to Maxixe appear to be accreting. Further south, erosive processes are evident especially in the inland bays where at least two of the three CVA analyses returned a decrease in spectral brightness indicating a move from predominantly land based pixels (which reflect more light than water) to darker water pixels. No significant change is seen further south but several smaller regions within the bay / estuary do return consistent erosive processes. Interpreting the erosive process should once again be conducted with the knowledge that tidal ranges play an important role in the dynamics of coastal morphology. The present analysis identifies many areas which could potentially be eroding and may, in the future, present a problem to infrastructure and the people of the area.

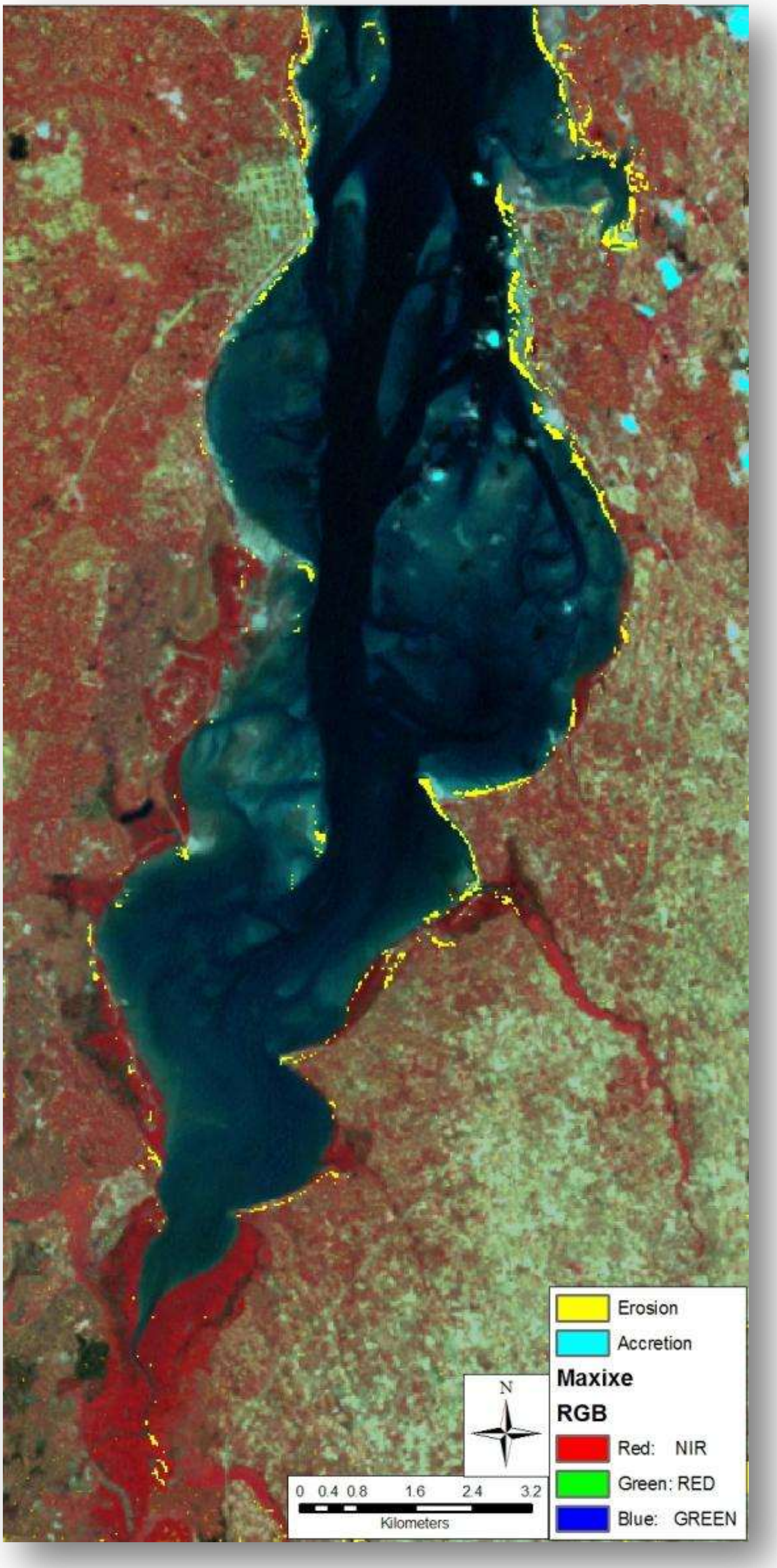

Figure 9 Change Vector Analysis Results (Maxixe)

Figure 10 shows the results for the Vilanculos study area, where erosive processes have been detected. Of all the study sites Vilanculos appears to be most affected by the tidal issues mentioned above. The problem is best illustrated off shore just south of the town where shallow water is identified as having erosive processes which, is obviously impossible. The very same processes leading to the “off-shore erosion” may well be in place all along the coastline. Off-shore the obvious change from a bright pixel to a dark pixel (erosion) is the result of tidal changes whereby the initial image was captured at low tide and the second image captured at high tide. The result is that in many cases commission errors (for both erosion and accretion) are apparent depending on when the high and low tide images occur within the CVA analyses. The dynamic nature of the coastline, in particular the interface between the ocean and the land makes coastline change studies very difficult when satellite remote sensing data are used without ancillary data on the tidal state at the image acquisition time.

Figure 10/…

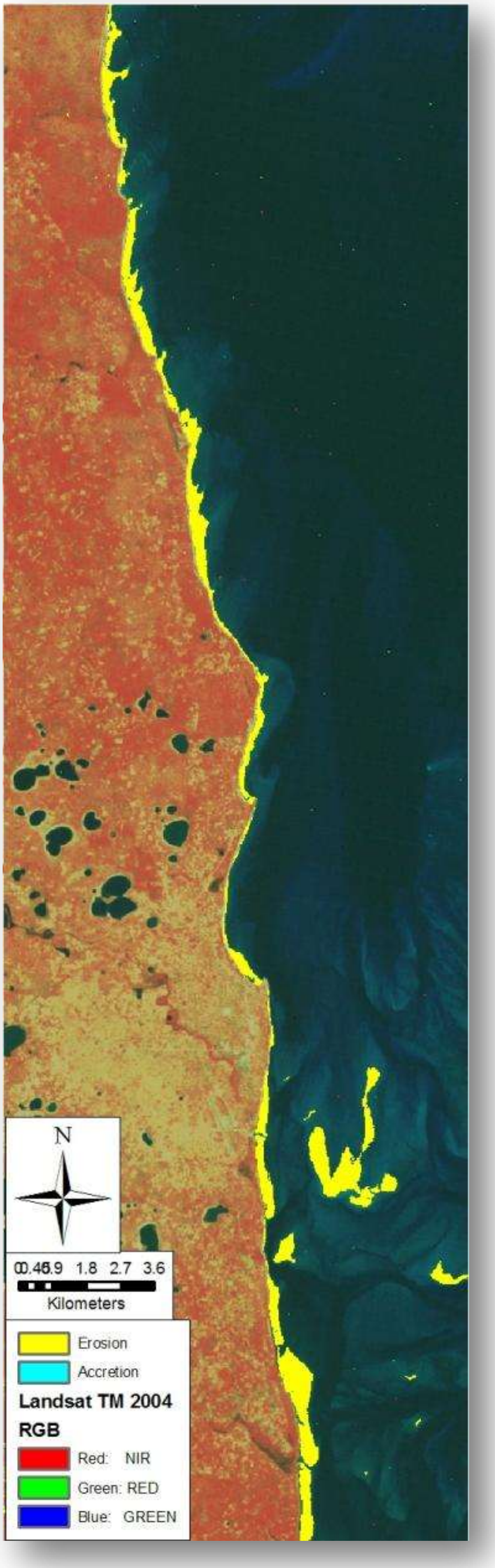

Figure 10 Change Vector Analysis Results (Vilanculos)

2.3 Spectral Change Analysis

Spectral change analysis was only employed for the Maputo study site and was intended as an assessment of an alternative change detection approach. Figure 11 shows the change detection results for the various input images. A, B, C, D report the change detection results for each input image pair mentioned in section 1.2.3. Image A looks at the period between 1986 and 2009 and immediately it is clear that the tidal differences between the images are seen in class 5 (Bare Soil to Water: Blue), the same pattern is seen in image B which covers the 1986 to 1999 period. It is thus easy to deduce that the 1986 scene was captured during a lower tide when compared to the 1999 and 2009 images. The other important class is vegetation to bare soil (class 1). In image A class 1 is seen within the coastal zone both north and south of the city centre, the change from vegetation to bare soil is an indication of land cover change normally associated with vegetation degradation. When found in close proximity to a beach or coastline this could be interpreted as the beach moving inland as a result of coastal erosion, degradation of coastal vegetation (e.g. dunes) or other related processes.

On the other hand bare soil to vegetation change is seen throughout all four image pairs. Typically this type of land cover change is prominent in areas where vegetation has been introduced to replace bare soil or where conservation and or rehabilitation initiatives are successful, or –depending on the vegetation type – simply reflecting vegetation seasonality. In the present analyses class 2 could be associated with accretive processes when found in close proximity to the coastline. All fours scenes return possible accretive processes in close proximity to the coastline. In particular class 2 is prominent in the southern portions of Maputo Bay. Image A, C, and D highlight an additional problem associated with recent imagery within the Landsat archive. In May 2003 Landsat 7 ETM+ experienced a failure of the scan line corrector mechanism on board. This has led to the imagery being distributed with scan line gaps where data is not available. The lines seen in results are due to this missing data. Change results in A, C, and D should therefore be validated using field work and or ancillary aerial photographic data.

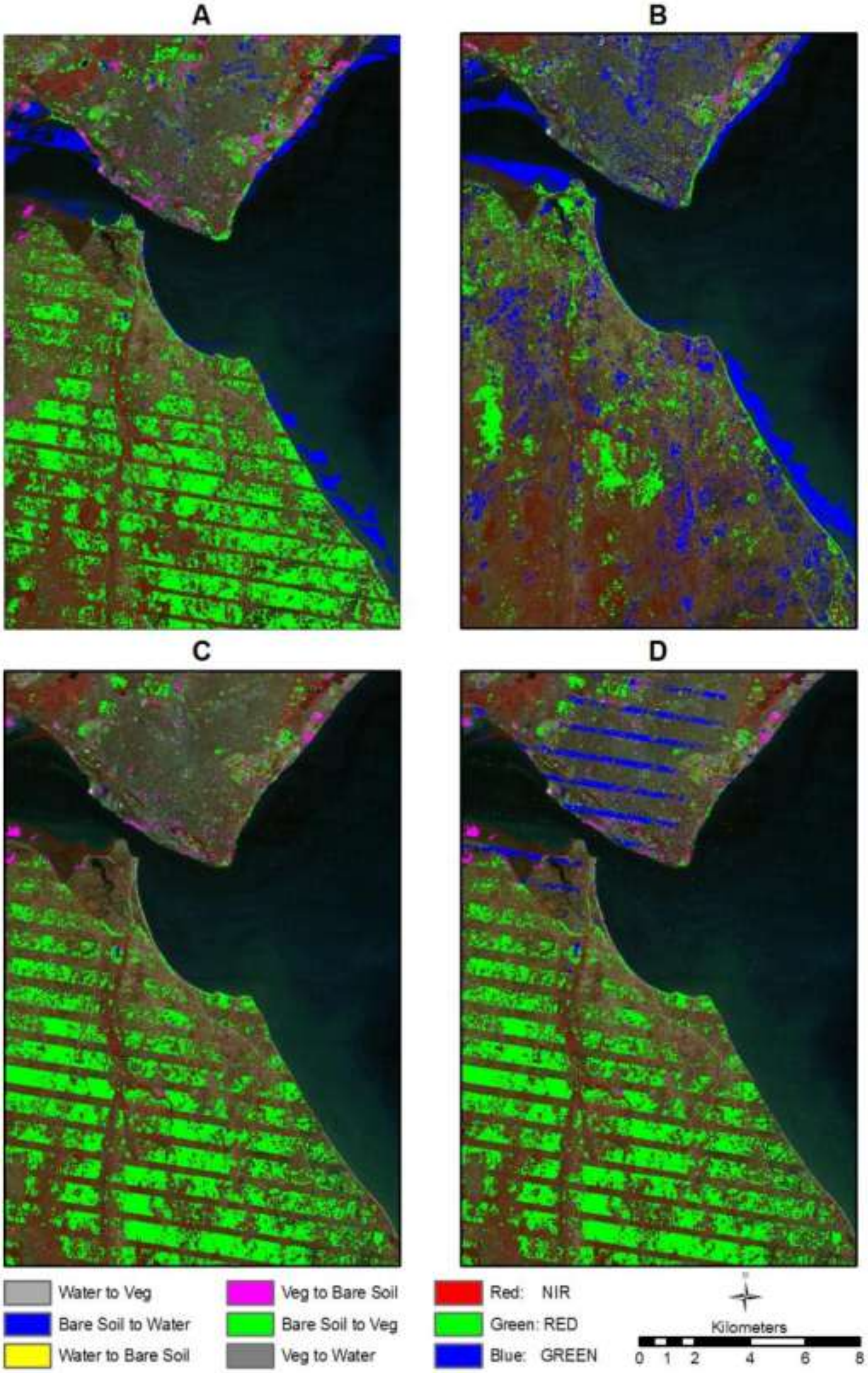

Figure 11 Spectral Change Analyses for Maputo (A: 1986 – 2009; B: 1986 – 1999; C: 1999 – 2003; D: 2003 – 2009)

3.0 DISCUSSION

Methods for assessing coastal morphology and or trends in coastal change have been discussed in this report. Three methods were assessed and reported on with a view to determining the applicability of medium resolution Landsat TM data to coastal change studies. The analyses and report have not sought to identify zones of potential critical change but, instead, report on the applicability of the three methods employed. The experimental design was similar for each of the methods assessed. For each location (Maputo, Beira, Maxixe, and Vilanculos) a number of Landsat TM images were downloaded from either the GLOVIS or SAC archive. Imagery were then pre-processed and analysed.

The experiments were designed to determine which method could accurately map and identify either erosive or accretive processes. The OOIA procedure was by far the most inconclusive of the three. Coastlines extracted using object based analyses were inconsistent and heavily influenced by the nature of the tide at image capture. The approach was also plagued with irregularities when applying the same algorithm to two different images. Band thresholds between images were never the same resulting in time having being spent on updating algorithm parameters. The parameters required adjustment when applying to different locations as well as to different dates in the same location. Thus the idea of creating an OOIA algorithm that can be universally applied to images from the same sensor was not possible. The second (CVA) and third methods (CSA) were however standardised and could be applied to all scenes regardless of data and or location. This was a distinct advantage as it saved the analyst a lot of time in terms of running and assessing the quality of the output. The CVA and CSA methods also compared anniversary date images which were then used to identify trends based on location and frequency of occurrence. Identifying erosive and or accretive processes using the second two methods was far easier as the individual analyses focused on pixel level change as opposed to object level changes (OOIA).

While CVA and SCA were more focussed on identifying change, understanding the nature of that change was far more difficult. The mechanisms which brought about the results mentioned above are complex in nature and refer to the methods themselves, the imagery selected and the nature of the study areas. OOIA is a highly precise approach attempting to select or identify the exact location of the coastline in a temporal set of images collected at different times of the year under varying conditions. The dynamic nature of the coastline means that while the algorithm performs as expected, the location of the coastline is likely to change based on the tidal conditions at the time. In essence the OOIA approach is too precise resulting in highly inaccurate results. The CVA and SCA methods on the other hand did not attempt to locate the actual coastline; rather they sought to identify significant change within the coastal region and attempt to explain that change. The CVA and SCA methods rely on the change in spectra between two image dates and are thus more reliable than a simple vector extracted from a single image date. It should also be noted that the CVA method is more sensitive to trends in coastal change than the OOIA approach in that the final areas identified as erosion or accretion were selected based on the fact that at least two image pairs returned the same results (direction of change vector). Similar analyses could be undertaken for the SCA method; however, for the purposes of this report it was important to illustrate the nature of change between image pairs. Unfortunately, as Sections 2.1 and 2.2 showed while both approaches (CVA & SCA) have their merits they are susceptible to the influence of tidal periodicity. In many cases (depending on which image was captured at either low or high tide) both the accretion and erosive processes identified were not the result of actual erosive or accretive process, but instead, were the result of tidal changes. Retrospectively, a tidal analysis of all image data available for the study would have reduced the impact of tidal ranges but not removed the effects completely.

A historical analysis of change for a coastline as long and complex as the Mozambican is by no means easy. The use of remote sensing data for such a study is the obvious choice. Large scale synoptic observations of the coastline at regular intervals should provide the researcher with enough information to gauge the general state of the coastline (in terms of erosion and or accretion). However, the only data source available for this area is the Landsat archive which, while comprehensive, easily accessible, and free of charge, is limited by the spatial resolution of the sensor. The 30m resolution is far too coarse to identify small scale changes of interest to coastal engineers. For example, in some procedures coastal engineers require data with an accuracy of centimetres and or meters, Landsat accuracy is at best between 30 and 45 metres. It is therefore similar to measuring the width of a human hair using a scholar’s 30cm classroom ruler. Large scale changes (> 60 metres) are obviously detectable along with trends resulting in large scale coastal morphological change, however, engineers involved in this project required accuracies way below what the remote sensing data could provide.

As always projects working in developing countries suffer from a lack of available baseline data. The analysis described in this report could have been conducted using both digital and analogue aerial photography. The Mozambican coastline has been surveyed on several occasions however; this data was not readily available to CSIR researchers. Further, when suitable data were located it was in a format unsuitable for immediate analysis. Bureaucracy also made it very difficult to acquire the high resolution data required for such a study. Additional pre-processing of analogue aerial photography was also time consuming and not an option for the present study. The lack of suitable readily available data for the study makes it very difficult to establish a coastal baseline from which to measure change. An alternative to passive optical monitoring using satellite remote sensing and or aerial photography is the use of high resolution Interferometric synthetic aperture radar (InSAR).

InSAR is used to generate maps of surface elevation as well as deformation using phase signal differentiation in synthetic aperture radar (SAR) images captured at different times of the year. High resolution InSAR such as those flown on the TerraSAR-X system of satellites which can measure ground deformation between two image dates with an accuracy of up to 3m would be suitable for coastal deformation studies. Obviously a historical study using this data is not possible but a reliable monitoring tool could be developed to monitor changes in coastal morphology on an annual basis or every five years.

4.0 CONCLUSION

Satellite remote sensing methods employed during this project returned a wealth of interesting information. It turned out that a historical study of coastal change for the Mozambican coastline requires input data with a higher spatial resolution than the 30m Landsat 5 and 7 (TM and ETM+) data employed. Identifying small scale change using Landsat TM is possible; however, the accuracy of the sensor renders the resulting erosion / accretion maps unhelpful when it comes to assessing the rates of changes and the identification of *zones of potential critical change*. Tidal issues as well as data availability made it difficult to identify large scale changes that could lead to loss of life and damage to infrastructure. Within the context of coastal vulnerability to climate change future studies may well use Landsat TM; however this information should only be used to establish contextual coastal parameters. High resolution satellite data and digital aerial photography along with historical analogue data should be used for more precise studies of climate induced coastal change. Further, it would be prudent for coastal authorities / researchers to explore the use of InSAR data for identifying coastal deformation resulting from erosive processes.

Based on the two most reliable methods used (CVA and SCA), can we briefly summarize the main outcome for Maputo, Beira and Vilankulos?

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APPENDIX 2: THEME 2 MISSION TO INTERACT WITH MUNICIPALITIES

Participants

INGC- Figueiredo Araujo
UEM- Jose Rafael
CSIR- Laurie Barwell

Purpose

- To discuss the preliminary results of the Theme 2 study with relevant municipal officials.
- To reach an understanding on the implications of climate change and the need to influence and incorporate recommendations into current and future plans.
- To comment on current and future infrastructure and structure plans if available. This to be in-situ during the meeting and a follow-up note on relevant aspects were needed.
- To identify existing specialist studies on climate change in order to harmonise recommendations if possible.
- Site investigation of current coastal protection activities and provide observations if relevant.

Structure of interaction (Agenda)

Welcome (Municipality)
Purpose and introduction (INGC)
Technical context (UEM)
Discussion (CSIR)
Way forward (UEM)
Closure (INGC)

Notes of the meetings

Date	**25 August 2011**	**Place** **Maputo**
Municipal representative:		Raul Chilaule
Position:		Head: Environmental Management
Contact details:		+258 826532810
Available plans at meeting	**Current**	General report on coastal protection Maputo City
	Future	Detailed design report and plans not available
Problems	As described in report	
Solutions	As described in report	
Way forward	Obtain detail plans on the infrastructure	
Field observations	Much of Municipal infrastructure is located within high risk area. Many opportunities for PPP exist to support the Municipality in preparing for the impact of CC	
Comments	On hold until detailed plans can be obtained	

Date	**21 September 2011**	**Place** **Matola**
Municipal representative (1):		Abel Ricotze (tel + 258 82 3988720)
Position:		Director of urban and environmental planning
Municipal representative (2):		Aurelio Salomao (tel +258 82 9109930)
Position:		Head planning
Available plans at meeting	**Current**	Structure Plan approved 2010 (digital copy supplied)
	Future	Major waterfront development (no climate change (CC) factors taken into account)
Problems	1. Storm water inundation in wetlands 2. River flooding of low areas in floodplain	
Solutions	Nothing identified	
Way forward	1. The municipal representatives understood the technical concepts and the importance of taking the Theme 2 results seriously. 2. Municipality is aware that their current plans do not consider any climate change factors. 3. The technical level officials at the municipality are now aware of the importance of incorporating the affects of climate change in current and future plans however the higher level decision makers will need to be also convinced in order to effect any changes. 4. Request for another presentation to the Mayor and Council	
Field observations	Some infrastructure is located in the identified vulnerable areas, including e.g. the new tollgate complex. Some commercial infrastructure also at risk (e.g. factories) and infrastructure belonging to the Port of Matola is vulnerable in places.	
Comments	1. Municipal area has not experienced inundations or surges from the sea to date (only river flooding) 2. The planned expansion of the Port of Matola provides an opportunity for future waterfront development as a Private-Public-Participation project which could pay for engineering adaptation actions (as conceptually shown in Theme 2 results). 3. Noted that the new port development project is mainly associated with Maputo so Matola Municipality has not been directly involved or consulted.	

<table>
<tr><th colspan="2">Date 29 August 2011</th><th>Place Inhambane (Tofo)</th></tr>
<tr><td colspan="2">Municipal representative:</td><td>Eugenio Jose</td></tr>
<tr><td colspan="2">Position:</td><td>Head: Infrastructure and Urbanisation</td></tr>
<tr><td colspan="2">Contact details:</td><td>+25 82 4288890</td></tr>
<tr><td rowspan="2">Available plans at meeting</td><td>Current</td><td>Tofo seawall; INGC World Bank climate change study</td></tr>
<tr><td>Future</td><td>Municipal structure plan is large scale and conceptual where three alternatives for future expansion are presented.
Undertaken by Consultants: Arcus Consultants (Maputo). Contact person: Architect Nhachungue +258 823263720</td></tr>
<tr><td>Problems</td><td colspan="2">Listed on the drawing along with photos to illustrate are the following:
1. Destruction of vegetation on primary dune
2. Degradation of natural rock protection
3. Disregard of existing prohibition measures (signage)
4. Vehicular traffic on beaches
5. Lack of toilet facilities (not relevant to Theme 2)
6. Cutting / destruction of mangroves
7. Lack of maintenance to coastal infrastructure
8. Too many buildings in Tofo (relates to spatial planning)
9. Solid waste management (illegal dumping in sensitive areas)
10. Destruction of buildings due to erosion
11. Slumping due to erosion
12. Dunes disappearing</td></tr>
<tr><td>Solutions</td><td colspan="2">No solutions other than seawall at Tofo were presented.</td></tr>
<tr><td>Way forward</td><td colspan="2">Adaptation measures proposed by Theme 2 are relevant to addressing problems. Transfer knowledge to Municipality to enable them to question consultants.</td></tr>
<tr><td>Field observations</td><td colspan="2">Wall design needs to be adjusted to respond to climate change impacts (e.g. sea-level rise (SLR), run-up and wave energy). Major erosion of foredunes north of Nautical Club. Attempts at dune toe protection inadequate.</td></tr>
<tr><td>Comments</td><td colspan="2">1. Municipality is aware that their current plans do not consider any climate change factors.
2. Municipality willing to accept relevant recommended changes to current designs.
3. Municipality is now aware of the importance of incorporating the affects of climate change in current and future plans.
4. There is a need to ensure alignment of recommendations from different studies e.g. World Bank and current Theme 2 studies</td></tr>
</table>

Date	**30 August 2011**	**Place Vilankulo**
Municipal representative (1):		Jeremias Macubele (844651706)
Position:		Head: Administration, Finances & Local Economic Development
Municipal representative (2):		Andre Mavitice (846849560)
Position:		Head: Urban planning, Housing and Environment
Municipal representative (3):		Nelio Nhamutabe (828398320 / 848399390
Position:		Technical: Civil Engineering Construction
Contact details:		(as above)
Available plans at meeting	**Current**	• Old Master Plan (11 yrs old): Three expansion areas. Needs updating (Quote obtained for USD200 000). Did not take CC into consideration. • Plan and design of new Coastal Road, seawall and boat slipway. (Did not consider CC or current coastal processes and wave energy aspects). Commissioned by Ministry of Tourism. Also has Ministry of Public Works & Housing logo on plans. • Mentioned a Solid Waste Management plan (2010).
	Future	• Master Plan needs updating (see above)
Problems	1. Coastal erosion 2. Erosion of sandy steep slopes due to storm water (mainly in town centre) 3. Erosion of sandy steep slopes due to storm water (mainly in town centre) 4. No existing drainage system on paved roads (indirectly linked to Theme 2) 5. Solid waste management (not for Theme 2)	
Solutions	• New Coastal Road design (see above) • Solid waste management plan (not implemented yet – in final stages of approval)	
Way forward	Adaptation measures proposed by Theme 2 are relevant to addressing problems. Transfer knowledge to Municipality to enable them to question consultants.	
Field observations	• Road, wall and slipway design needs to be adjusted to respond to climate change impacts (SLR, run-up, wave energy). • Uncertainty about Datum Level for road design (refer to Consultant for clarification). This is important to allow alignment between Theme 2 study results and Engineering design levels. • Arial Survey of Vilankulo (Oct 2000). Obtain datum level of 'Iron peg in concrete' Vill 1 (739030.72; 7563494.32; WG84 UTM, Zone 36 – M 33 degrees) Height = 12.52 m (not sure if MSL – needs confirmation)	
Comments	1. The municipal representatives understood the technical concepts and the importance of taking the Theme 2 results seriously. 2. Municipality is aware that their current plans do not consider any climate change factors. 3. Municipality willing to accept relevant recommended changes to current designs. 4. Municipality is now aware of the importance of incorporating the affects of climate change in current and future plans. 5. Existing Coastal Protection design study completed and signed off (no further involvement from Consultant possible). Municipality looking for funding to implement, however needs to take CC (Theme 2 recommendations) and Coastal Engineering design practise into consideration before final implementation. 6. There is an opportunity for a Private-Public-Participation project within the Vilankulo Rest Camp area which could pay for engineering coastal protection and beach improvement works (as conceptually shown in Theme 2 results). 7. It is important for INGC (and Theme 2) to interact with Ministry of Tourism as soon as possible.	

Date 31 August 2011		**Place** Quelimane
Municipal representative (1):		Silva Mario (825772876)
Position:		**Head: Planning & Development**
Municipal representative (2):		Santiago Marques (825845440)
Position:		Head: Infrastructure & Housing
Municipal representative (3):		Iria Mvunguabe (827415740)
Position:		Technical: Urbanisation and Construction
Contact details:		As above
Available plans at meeting	**Current**	Outdated structure plan (2002)
	Future	No future plans available
Problems	None presented	
Solutions	None presented	
Way forward	Information and adaptation measures proposed by Theme 2 are relevant to inform and support future structure plan. Transfer knowledge to Municipality to enable them to include CC aspects into the Terms of Reference for future plans.	
Field observations	Work being done on slipway (below HWM – no problem) and the removal of the shipwrecks in Mangrove area (Good). Provides opportunity for re-establishment of mangroves.	
Comments	1. The municipal representatives understood the technical concepts and the importance of taking the Theme 2 results seriously. 2. Municipality not clear on future economic development of Quelimane so cannot plan in accordance. 3. Municipality is now aware of the importance of incorporating the affects of climate change in current and future plans. 4. Potable water supply from groundwater resources (no salinity problems for city water supply). 5. Ideas for future waterfront development (e.g. Brazilians and/or Chinese) provide an opportunity for a Private-Public-Participation project which could pay for engineering adaptation actions (as conceptually shown in Theme 2 results).	

Date 1 September 2011		**Place** Nacala
Municipal representative (1):		Crisanto Paulo (+258 82 859 7423)
Position:		Head: Urban Planning
Municipal representative (2):		Adelino Cobre (+258 84 398 8239)
Position:		Technical: Civil Engineering
Contact details:		(as above)
Available plans at meeting	**Current**	Master Plan recently approved (2011). Did not take CC into consideration.
	Future	Implementation of the Master Plan
Problems	1. Erosion of sandy steep slopes due to storm water (not for Theme 2) 2. Drainage system inadequate (indirectly linked to Theme 2) 3. Informal settlements on steep slopes (not for Theme 2) 4. Lack of capacity (skills etc) and funding to implement Structure Plan (not for Theme 2) 5. The local businesses and entrepreneurs are not volunteering to partner with the municipalities to address the environmental problems. 6. Lack of formal waste site (not for Theme 2) 7. No capacity to control possible pollution from shipping (not for Theme 2)	
Solutions	• Seeking private partnerships to help to fund and solve the problems • Negotiating with World Bank for funding to implement prioritised actions.	

Way forward	• Adaptation measures proposed by Theme 2 are relevant to addressing problems. Transfer knowledge to Municipality to enable them to question consultants. • Results from Theme 2 need to be simplified for presentation and discussion at higher levels within the municipality to ensure take-up as a critical component of the Structure Plan.
Field observations	Municipality not seeing the opportunity to set conditions of approval that include partnering with the developers to improve (and fund) municipal infrastructure.
Comments	1. The municipal representatives understood the technical concepts and the importance of taking the Theme 2 results seriously. 2. Municipality is aware that their current plans do not consider any climate change factors. 3. The technical level officials at the municipality are now aware of the importance of incorporating the affects of climate change in current and future plans however the higher level decision makers will need to be also convinced in order to effect any changes. 4. It is important for INGC to facilitate the dissemination of the results to higher levels of decision making. 5. All ministries commented and signed off on approved Structure Plan. It is therefore important for INGC (and Theme 2) to interact with Ministry of Tourism as soon as possible.

Date 2 September 2011		**Place Pemba**
Municipal representative (1):		Mikas Muianga (+258 826699093)
Position:		Head: Urban Services
Municipal representative (2):		Abel Aluar (+258 826401980)
Position:		Municipal Focal Point Climate Change
Municipal representative (3):		Jose Tavale (+258 82 2581 370)
Position:		Technical representative
Contact details:		(as above)
Available plans at meeting	**Current**	• Outdated Structure Plan (Year unknown). Did not take CC into consideration.
	Future	• None
Problems		1. Sea inundation in Paquite and Chibuabare 2. Critical areas of coastal erosion are Chabane and Ruela 3. Erosion of sandy steep slopes due to storm water (not for Theme 2) 4. Informal settlements in vulnerable areas (not for Theme 2) 5. Sand mining of coastal dunes reducing buffer area 6. Lack of solid waste management (illegal dumping) -(not for Theme 2) 7. Lack of capacity (skills etc) to evaluate and take critical environmental management decisions
Solutions		• No current construction or implementation activities related to Climate Change aspects taking place. • Aware that people in Paquite need to be resettled, but no specific plans were mentioned.
Way forward		• Adaptation measures proposed by Theme 2 are relevant to addressing problems. Need to transfer knowledge to Municipality to enable them to question consultants. • Results from Theme 2 need to be simplified for presentation and discussion at higher levels within the municipality to ensure take-up as a critical component of the Structure Plan.
Field observations		It was mentioned that the Ministry of Tourism has identified an area for future tourism

	development (ARCO-NORTE = Northern Circle). Some infrastructure is located very close to the sea (e.g. on the foredunes) Sand mining site lowering landward side of the foredune and is at risk of being flooded if foredune is eroded away under high sea surges.
Comments	1. The municipal representatives understood the technical concepts and the importance of taking the Theme 2 results seriously. 2. Municipality is aware that their current plans do not consider any climate change factors. 3. The technical level officials at the municipality are now aware of the importance of incorporating the affects of climate change in current and future plans however the higher level decision makers will need to be also convinced in order to effect any changes. 4. It is important for INGC to facilitate the dissemination of the results to higher levels of decision making so-as to get the validation and approval to facilitate implementation in current and future plans.

THEME 2 MISSION TO INTERACT WITH MUNICIPALITY OF BEIRA
20 -22 SEPTEMBER 2011

Participants

INGC- Figueiredo Araujo
UEM- Jose Rafael
CSIR- Andre Theron

Purpose

- To discuss the preliminary results of the Theme 2 study with relevant municipal officials.
- To reach an understanding on the implications of climate change and the need to influence and incorporate recommendations into current and future plans.
- To comment on current and future infrastructure and structure plans if available.
- To identify existing specialist studies on climate change in order to harmonise recommendations if possible.
- Site investigation of current coastal protection activities and provide observations.

Structure of interaction (Agenda)

Welcome (Municipality)
Purpose and introduction (INGC)
Technical context (UEM)
Discussion (CSIR)
Way forward (UEM)
Closure (INGC)

Notes from the meeting

Date	**20 September 2011**	**Place** **BEIRA**
Municipal Representative:		Mario Jose Guina
Position:		Head: Physical Planning
Contact details:		82 43 88 540
Municipal representative:		Augusto Manhoca
Position:		Head: Sanitation
Contact details:		+25 82 56 49 390
Available plans at meeting	**Current**	Strategic Plan approved in February 2010, which has coastal protection as the main subject
	Future	Continuous implementation of the Strategic plan
Problems	The Municipality has identified the following problems: 1. Destruction of vegetation on primary dune 2. Disregard of existing prohibition measures 3. Vehicular traffic on beaches 4. Cutting / destruction of mangroves 5. Lack of maintenance to coastal infrastructure 6. Coastal erosion 7. Destruction of buildings due to erosion 8. Slumping due to erosion 9. Dunes disappearing 10. Informal settlement in risk areas along the coast 11. Inundation	
Solutions	The Municipality has identified the following solutions: Dune protection, dune restoration, 3km of tree planting along the coast, protection of dune vegetation, mangroves protection and restoration, specific areas for vehicular traffic on beach, seawall, groynes.	
Way forward	Adaptation measures proposed by Theme 2 are relevant to addressing problems. Transfer knowledge to Municipality to enable them to question consultants and crosscheck ongoing implementation of adaptation measures.	
Field observations	Opportunities exist for Public-Private-Partnerships to address the identified problems along the coastal interface.	
Comments	1. Municipality´s current strategic does consider climate change factors. 2. Municipality is now more aware of the importance of incorporating the affects of climate change in current and future plans. 3. In 2010 the Municipality created a Disaster Risk Management, Climate Change and Coastal Protection Department. 4. There is a need to ensure alignment of recommendations from different studies and current Theme 2 studies. 5. There is a need to replicate the study to other critical areas, such as the expansion area of Munhava to Ceramica. 6. There is a need of having the final results of the study as soon as possible so that it can be used, bearing in mind that there are already activities being implemented and other to be implemented. 7. Municipality is aware of the need to maximize PPP	

THEME 2 MISSION TO INTERACT WITH MAPUTO PORT EXECUTIVE BOARD DIRECTOR, 25 NOVEMBER 2011

Participants

INGC- Figueiredo Araujo
CSIR- Laurie Barwell

Purpose

- To discuss the preliminary results of the Theme 2 study with relevant municipal officials.
- To reach an understanding on the implications of climate change and the need to influence and incorporate recommendations into current and future plans.
- To comment on current and future infrastructure and structure plans if available. This to be in-situ during the meeting and a follow-up note on relevant aspects were needed.
- To identify existing specialist studies on climate change in order to harmonise recommendations if possible.
- Site investigation of current coastal protection activities and provide observations if relevant.

Structure of interaction (Agenda)

Welcome (CFM)
Purpose and introduction (INGC)
Technical context (UEM)
Discussion (CSIR)
Way forward (UEM)
Closure (INGC)

Notes from the meeting

Date	**25 November 2011**	**Place**	**MAPUTO**
CFM Representative:		Marta E. N. Mapilele	
Position:		Executive Board Director	
Contact details:		e-mail: mmapilele@cfmnet.mz	Tel: 00 258 21 31 33 62
CFM representative:		Antonio Bie	
Position:		Executive Director	
Contact details:		e-mail: antonio.bie@cfm.co.mz	mobile: 00258823273120
CFM representative		Miguel Jose Matabel	
Position:		Inspector General	
Contact details:		e-mail: miquel.matabel@cfmnet.co.mz	mobile: 00258823199460
Available plans at meeting	**Current**	NONE	
	Future	NONE	
Problems	None mentioned		
Solutions	None mentioned		
Way forward	CFM board will share the presentation with the Port technical staff and discuss the results of the study. INGC will be contacted should there be questions or a need for further discussions.		
Field observations	It is important to determine the actual elevation (to MSL) of the current port infrastructure to identify the areas at risk. Major redevelopment plans are underway for a new Waterfront development (including a new Cruise Ship terminal). This offers the opportunity to ensure that CC factors are taken into account in the design.		
Comments	1. CFM's activities and projects do not take climate change issues into consideration; 2. CFM's activities and projects take into consideration environmental impact assessments. There is uncertainty is CC issues are considered in the specialist studies.; 3. CFM is now more aware of the importance of incorporating the affects of climate change into current and future plans. 4. CFM found the study relevant and are willing to use its results and underlined that the study was made at a good time since there are planned activities that did not take climate change issues into account; 5. CFM suggested that INGC should contact the Ministry of Transport and Communication in order to organize a national seminar that would gather public and private stakeholders working with CFM so that everyone could be made aware and agree on how and when to start using the results of the study; 6. CFM’s opinion is that the results of the study should be shared among different institutions within the government and harmonized with other studies, so that the recommendations come from one channel.		

APPENDIX 3: COASTAL PROTECTION: SCOPE OF WORK (PHASE 2)

Key Questions	Work Packages	Deliverables	Assumptions
Q1. Where are the most vulnerable areas along the coast, at the micro level? **Q2. What will these areas look like, with climate change, in future?** **Q3. Which key infrastructure and future investment plans are at risk in these areas?**	WP1. Generate realistic scenarios of future coastal conditions under climate change; WP2. Determine the potential effects of climate change on the sediment transport potential and coastal erosion at Maputo; WP3. Research the potential effects of climate change on wave run-up levels and development set-back lines;	D1.Coastal vulnerability index; [CHAPTER 2] D2. Shoreline change detection at representative points at the key sites(Maputo, Beira, Maxixe, Inhambane and Vilankulos); [APPENDIX 1] D3. Coarse climate change Risk Assessment for Mozambique Coastal Zone; [CHAPTER 6] D4. Description of realistic scenarios of future coastal conditions under climate change for Maputo; [CHAPTER 5] D5. Definition of potential effects of climate change on sediment transport (potential) and coastal erosion for Maputo; [CHAPTER 5] D6. Definition of the potential effects of climate change on wave run-up levels and development set-back lines for Maputo; [CHAPTERS 5 & 6]	A1. Future coastal conditions scenarios limited to factors related to sediment transport potential, coastal erosion, wave run-up and development set-back lines only; A2. Evaluation based on available information only (no detailed field measurements to be undertaken); A3. Short site visit to Maputo to verify the aspects related to vulnerability index;

Key Questions	Work Packages	Deliverables	Assumptions
For the identified 10 key sites: **Q4. What shoreline management strategies are most appropriate (Do Nothing; Hold the existing line; Advance the existing line; Retreat)?**	WP4. Determine the potential effects of climate change on the sediment transport potential and coastal erosion at the key sites; WP5. Based on the output of WPs 1, 2, 3 and 4, the 10 key sites will be analysed using available information (specific specialist field investigations are beyond the scope of this study); WP6. A portfolio of relevant and practical coastal protection (adaptation and mitigation) measures will be defined using input from coastal engineering practice and experience from the Expert Reference Team following specific site evaluations (Field visits);	D7. Definition of potential effects of climate change on sediment transport (potential) and coastal erosion at the key sites; [CHAPTER 5] D8. Definition of the potential effects of climate change on wave run-up levels and development set-back lines at the key sites; [CHAPTERS 5 & 6] D9. Shoreline management strategies defined for the 10km shoreline at each of the 10 key sites; [CHAPTER 8]	A4. Short site visit to the key sites to verify the aspects related to vulnerability index and to identify possible protection / adaptation options; A5. Input on projected future climate change scenarios required from Theme 8 (Extremes) A6. Detailed engineering design, e.g. hydraulic stability analyses or structural dimensioning, is not appropriate at this stage.
Q5. What structural coastal protection measures are needed to compensate for the potential effects of climate change?	WP7. Appropriate management approaches will be identified from published best practice and as advised by the Expert Reference Team following the site visits;	D10. Conceptual designs, including functioning and location/general layout, where appropriate. Rough (ball-park) cost estimate provided. [CHAPTER 7] D11. Type of management / maintenance actions / approach identified for each of the conceptual protection measures. Rough (ball-park) cost estimate provided. [CHAPTER 8]	A7. Site specific designs and construction specifications would be done under a final phase or directly with construction. A8. The scope of the deliverable is limited to a write-up of possible adaptation / mitigation options for coastal protection at the 10 key sites.

Key Questions	Work Packages	Deliverables	Assumptions
Q6. What should be the strategic framework on which all coastal structures and sea defences can be evaluated? **Q7. What recommendations are in order for planned investments along the coast, with emphasis on Beira and Maputo?**	WP8. Desk-top study to define appropriate evaluation criteria. WP9. Take into consideration opportunities and constraints with respect to investment possibilities at Beira and Maputo.	D12. Evaluation criteria appropriate for strategically evaluating proposed coastal structures and sea defences; [CHAPTER 7] D13. Generally for the various types of coastline and specifically related to identified developmental / investment opportunities at Maputo and Beira; [CHAPTER 7]	A9. Criteria will be limited to appropriate coastal defence mechanisms and approaches. A10. Interaction with Themes 3 and 4 required. A11. Evaluation based on information to be provided by Mozambican stakeholders;
Q8. What should go into a coastal zone information system?	WP10. Identify relevant spatial and non-spatial information that can be made available via a proposed coastal zone information system; WP11. Providing collected data and information in the required format to feed into a communication system provided under Theme 1 as far as possible.	D14. Metadata of various information sets available. [ON CD] D15. Data and information gathered and developed under Theme 2 will be made available for communication via the relevant communication system provided via Theme 1. [ON CD]	A12. It is assumed that a content management system via a suitable portal system will be made available.
Q9. What input can be provided for an integrated coastal management policy?	WP12. Appropriate ICM policy relevant information will be identified from published best practice and as advised by the Expert Reference Team	D16. Input relevant to Coastal Protection under Climate Change provided for integration into an integrated coastal management policy for Mozambique; [CHAPTER 10]	A13. The input will be limited to the scope of Theme 2 only. Development or writing of a ICM Policy document is beyond the scope of the contract.