LaquaR Consultants CC

P.O. Box 474
Eppindust
Cape Town 7475
South Africa

Cell: +27 (0)73 511 1717
Tel: +27 (0)21 510 6160
Email: lucindafairhurst@gmail.com

Global Climate Change and Adaptation – A Sea-Level Rise Risk Assessment.

PROPOSAL NUMBER:
R030800032
REFERENCE NUMBER:
GLOBAL CLIMATE CHANGE

Prepared For:
The City of Cape Town
Environmental Resource Management Department

CITY OF CAPE TOWN | ISIXEKO SASEKAPA | STAD KAAPSTAD

THIS CITY WORKS FOR YOU

Phase four:
Final Report
Sea-Level Rise Adaptation and risk mitigation measures for the City of Cape Town

Report prepared by
Anton Cartwright (SEI Cape Town) in collaboration with Prof. G. Brundrit and Lucinda Fairhurst

July 2008

STOCKHOLM ENVIRONMENT INSTITUTE

TABLE OF CONTENTS

The City of Cape Town have awarded LaquaR Consultants CC the contract for their Proposal Number: R03-404/06-07

Reference: Global Climate Change

Date: January – July 2008.

An extract from the Terms of Reference of the contract, relevant to this third Phase Three, now follows.

TERMS OF REFERENCE

Global Climate Change: Coastal Climate Change and Adaptation - A Sea-Level Rise Risk Assessment for the City of Cape Town

1. Background and Introduction:

The City of Cape Town administers approximately 307 km of coastline, arguably its single greatest economic and social asset. In October 2003 the City formally adopted a Coastal Zone Management Strategy with the intention of managing and safeguarding the coastal asset for current and future generations.

The City's coast provides a range of social and economic opportunities including recreational and amenity areas, sought after housing and development opportunities as well as core economic attributes. In addition, the City's coast is a dynamic ecological system that supports a wide range of species, ecological systems and ecological services.

Global climate change predictions suggest that amongst others, sea level rise and an increase in the intensity and frequency of storm events may have significant impact on coastlines across the globe. Cape Town with its extensive coastline may be particularly vulnerable to these predicted changes.

2. Motivation and Aim of Project

The aim of the Sea-Level Rise Risk Assessment Project is to:

- Model the predicted sea-level changes in a range of scenario's (time series, incremental climate change, shear events, and storm frequency and intensity).
- Model the form that those changes will take.
- Understand the associated impacts on existing coastal systems, infrastructure and property.
- Provide guidance and implications to future coastal development (to be included in the City's Coastal Development Guidelines).
- Identify high risk areas that are prone to high impact.
- Begin to understand and develop long-term mitigation measures.

The primary objective of this study is therefore:

To model and understand the ramifications of predicted sea-level rise and increased storm events for the City of Cape Town, thereby providing information that may be used for future planning, preparedness and risk mitigation.

3. Project Phases

The project will be undertaken in four distinct phases. Each phase of the project will provide specific outcomes and deliverables. Phase one, two and three have been completed and the reports were submitted in March, May and July 2008, respectively. This report relates to phase four:

Phase 4: Adaptation Measures

- Institute adaptation and management measures to lower the risk profile of the City. This will be achieved through recommendations for priority action to relocate infrastructure and services away from vulnerable areas, and to strengthen protective infrastructure where needed. Illustrative examples will be provided of the adverse impacts of climate change on the coastline of the City of Cape Town, to support recommendations for new coastal development guidelines and to emphasise the negative consequences of non-compliance. Recommendations regarding the integration of adaptation measures with the changed requirements for disaster relief will be made.

- Provide a comprehensive Report Back to the City officials and Departments involved in Phase 2. This will also enable the possible future extension into a participatory approach, with multiple stakeholders, for the discussion of the trade-offs that might arise from the implementation of climate change adaptation measures.

- Review the important economic, social and environmental costs of climate change, as recorded in the Stern Review for the British Government. Here, the importance of early action will be emphasized, and the long-term consequences of deteriorating economic conditions from runaway climate change will be investigated in the context of the City of Cape Town.

1. INTRODUCTION

Phase 3 of this study described and quantified the risk of sea-level rise for the City of Cape Town. This Phase 4 report aims to identify measures that can reduce that risk. It does this by assessing the broad costs and merits of different approaches used to counter the impacts of sea-level rise.

Climate change is affecting mean sea levels and the nature of storm activity in non-linear ways. The best available projections suggest that changes in mean sea-level and storms will be adverse for sea-level rise risks around the City of Cape Town. Future impacts are likely to be exacerbated by the loss of the coast's natural buffering capacity as a result of developments on sand dunes, disruption to the transport of sand by long shore currents and wind, the loss of wetlands and the manipulation of estuaries. The combination of a degraded coastal zone, extreme high tides, changes in sea-levels and altered frequency and intensity of storm events could threaten up to R55 billion worth of tourism, public infrastructure and real estate around the City of Cape Town's coast in the next 25 years. Even the more conservative estimates for the almost inevitable 2.5 meter sea-level rise event that are presented in Phase 3 would involve over R5 billion worth of foregone GGP.

Seen in the context of the City's projected GGP for 2008 of R165 billion, the risk of sea-level rise is clearly significant. The key question arising from Phase 3 involves what to do to reduce and manage this risk. Managing climate change risks has become an increasing part of the global climate change discourse since the December 2006 conference of UNFCCC parties in Nairobi. At that conference it was acknowledged that climate change impacts were already being felt, and that regardless of the success of mitigation efforts, climate change and the ensuing consequences were set to get worse for at least two decades. The inevitability of change and resultant necessity of adaptation is particularly true for sea-level rise. The sea absorbs 80 per cent of the energy that is being added to the global atmosphere by anthropogenic climate change and due to the thermal expansion of the ocean will continue to expand long after atmospheric temperatures have ceased increasing. The resultant risks are, however, not inevitable and can be reduced by timely and well-constructed interventions. In the United Kingdom, for example, it is estimated that appropriate human and institutional responses to sea-level rise and flooding could reduce the associated cost of the phenomenon to that country by 27-fold relative to the business as usual scenario (Foresight, 2007).

- Section 2 of this report outlines current thinking with regards to climate change adaptation.
- Section 3 describes broad approaches for dealing with sea-level rise.
- Section 4 introduces specific options for the City of Cape Town under the headings "no-regrets" options, and "additional" options which include physical, biological and institutional options.
- Section 5 provides a framework for selecting appropriate sea-level rise adaptation measures, while section 6 concludes the Phase 4 report.

2. CLIMATE CHANGE ADAPTATION

Climate adaptation efforts are being driven by the realization that future climate will require social and institutional changes that are unprecedented in terms of current climate variability, and are necessary in order to reduce the risks imposed by climate change. At the African Ministers Conference on the Environment held in June 2008 it was agreed that climate adaptation should not be seen as a "surrogate" for climate change mitigation. Rather climate adaptation was presented as a process that begins with understanding current vulnerability, involves creating capacity to support adaptation planning and implementation and requires learning from experience (UNEP, 2008). Effective climate adaptation will in many instances include mitigations measures.

Text Box 1

Approaches to climate change adaptation

Both discourse and practice with regards to climate change adaptation is evolving rapidly. Some adaptation exercises involve an attempt to predict future climate scenarios and respond with a one-off decision to reduce future vulnerability.

An alternative approach views adaptation as a social-institutional learning process, a series of decisions that result in a pathway of risk evaluation, identifying options, choosing an option, monitoring the outcome and then iterating the process at the next decision node.

This approach which is included in the IPCC's Fourth Assessment Report (2007) and is gaining credibility and support, relates closely to much of the work on "adaptive resources management", and allows decision makers to deal with high levels of uncertainty. In some ways it is a more appropriate paradigm than approaches such as cost-benefit analysis that assume a high ability to predict future risks and outcomes of decisions.

There is a growing awareness that the complex and difficult to predict impacts produced by climate change render it impossible to "climate proof" a community or city. Rather effective climate adaptation is an ongoing process that creates the scope to deal with a wide range of inherently difficult to predict climate contingencies. In the language of United Kingdom Climate Impacts Programme (UKCIP), "The aim is not to be well adapted, but adapting well". Climate adaptation is often most effective when it influences decisions that would have had to be taken anyway, but which can be altered based on an understanding of climate change. Seen as a process, climate adaptation might bring a decision foreword (e.g. plans to install a flood barrage might be expedited due to climate change), result in different decisions to those that would have otherwise taken place (e.g. relocate the site of a planned power sub-station due to sea-level rise risks) or add new options that would not have been considered previously (e.g. invest in estuary rehabilitation instead of estuarine property development as a means of restoring the natural buffer to storm surges).

Climate change adaptation is acknowledged to impose both direct and indirect (via substitution and competitive effects) costs countries. The World Bank has suggested that $10-$40 billion per annum will be required globally for effective adaptation. Oxfam believe this figure to be in the order of $50 billion per annum, while the Stern Review posited an estimate of 5 per cent of country GDP per annum. The burden of these costs is expected to be particularly severe on less developed countries.

In response the UNFCCC has initiated three funds (see Text Box 1) aimed at assisting countries in developing adaptation responses. As a UNFCCC signatory, but not a "least developed country", South Africa qualifies for two of these funds.

Text Box 2

UNFCCC funding for CCA

The Special Climate Change Fund finances concrete adaptation activities, especially projects on water resources management, land management, agriculture, health, infrastructure development, fragile ecosystems such as mountain ecosystems, and coastal area integrated management. The current total for the fund is US$62 million.

The Least Developed Countries Fund is dedicated to least-developed countries. South Africa is not classified as a least developed country but a number of its neighbours are. The fund finances the same activities as the Special Fund for Climate Change. Least-developed countries have access to expedition procedures for the approval of funding to support the implementation of projects in the context of National Adaptation Programmes of Action (NAPAs). The current total for the fund is US$116 million.

The Adaptation Fund is financed through a 2 % share of the profits from the Clean Development Mechanism (CDM) and finances concrete adaptation projects and programmes in developing countries that are signatories of the Kyoto Protocol. This fund is not yet operational, but could be much larger than the SCCF or LDF.

3. ADAPTING TO SEA-LEVEL RISE

The risks generated by sea-level rise should be seen in the context of the suite of risks that climate change is likely to create. It is the combination of climate change risks that is likely to be most damaging to South Africa. More importantly, a number of the potential responses to climate change risk, such as improved institutional coping capacity and better information, will mitigate risk across the spectrum of climate change events. For this reason responses to sea-level rise should be seen in the context of broader climate change adaptation efforts, but this does not remove the need for certain sea-level rise specific measures.

Until recently sea-level rise adaptation measures were focused on the small island states, many of which are highly exposed to the phenomenon. In the light of forecasts that suggest that sea-level rise could be an order of magnitude greater than originally thought by the end of the century, acknowledgement of concern over the problem has become more widespread. Best practice on sea-level rise is clear that the problem is best managed in accordance with the principles of integrated coastal zone management (ICZM). ICZM seeks, over the long-term, to balance environmental, economic, social, cultural and recreational objectives of the coastal zone within the limits set by natural dynamics. Failure to do this runs the risk of unforeseen and perverse consequences that amplify the mal-adaptation risks described in Phase 3.

Present City expenditure on coastal defences will not be sufficient to keep pace with increases in coastal erosion and flooding that are projected under future sea-level rise scenarios. In addition there is a growing acknowledgement within the City of Cape Town (and elsewhere) that many of the infrastructural approaches that have been used to prevent the sea from advancing in the past have proven to be costly to maintain and sometimes ineffective. In addition such efforts, by creating a false sense of security, often come at the expense of more appropriate social and institutional responses[1]. There is, however, considerable inertia in the built environment. Whilst "managed retreats" and a number of the non-infrastructure options that are discussed below are

[1] A review of coastal defences in Britain showed that in 38 % of locations they reduced risk while 18% of the time they actually increased flooding and erosion risk (Foresight, 2007).

increasingly considered more prudent than the "engineering" solutions, the reality is that some settlements and infrastructure cannot be relocated or protected without additional infrastructure. The Thames Barrage, for example, was constructed at huge expense in order to protect the internationally important City of London against the threat of a storm surge up the Thames Estuary.

4. OPTIONS FOR CAPE TOWN

Broadly speaking the sea-level rise options for the City of Cape Town can be classified into (1) "no regrets" options and (2) "additional" options proactively designed to counter sea-level rise and involving some form of trade-off or cost. [2]

4.1 "No regrets" approaches

"No regrets" actions are not directly related to sea-level rise, and would be worth pursuing even of the sea-was not rising due to the systemic benefits that they deliver. Where no regrets steps are taken they assist in the ability to cope with sea-level rise. In most instances they do not require major amounts of additional funding, and do not rule out the possibility of the more targeted interventions discussed in Section 4.2 below. In the context of sea-level rise, no regrets options available to the City of Cape Town include:

i. **Do not reclaim further land:** The City's foreshore, Paardon Eiland and the Sea Point Promenade are the result of ambitious land reclamation projects in the City of Cape Town during the 1930s and 1940s. Reclaimed land around the City of Cape Town is particularly vulnerable due to its proximity to the sea, its exposure to wave action and the fact that it is very often comprised of less stable material (rubble and deposited sand) than

[2] The word "additional" in this context is adopted form the climate mitigation discourse and refers to additional relative to business as usual.

land that rests on its parent material. Against the spectre of sea-level rise further land reclamation should be seen as imprudent, and prevented.

ii. **Do not further degrade wetland and estuaries.** South Africa's wetlands are protected under the RAMSAR Convention and the *National Environmental Management Act* (107, 1998), and the *Integrated Coastal Management Bill* (2006) promotes the idea of a "National Estuarine Management Protocol". Wetlands that are linked to the coast and estuaries serve as a natural buffer against sea-level rise and wave action in particular. Not only are they capable of absorbing large volumes of advancing water, and dissipating wave energy, they also create natural refuge for species that would otherwise be adversely affected by sea-level rise changes. To reduce the size of estuaries, to remove the vegetation that they support or to curtail the flow of water within these estuaries in favour of new housing developments or infrastructure projects is to discount the role that these natural resources play in reducing sea-level rise risk. Similarly polluting these water resources undermines the ability of estuaries, lagoons and wetlands to support biodiversity in the face of other changes such as sea-level rise. Unfortunately a number of the estuaries (Riet River, Black River, Disa River, Eerste River) and lagoons and wetlands (Milnerton Lagoon, Rietvlei, Sandvlei and Noordhoek) have been physically perturbed and polluted beyond any norm for a "natural" state. The key "no-regrets" decision should be to at least not further disrupt these resources.

iii. **Do not further degrade dune cordons:** The sand dunes that appear behind a number of City beaches (Blaauwberg, Milnerton, Hout Bay, parts of Fish Hoek, Strand) provide a natural defence against sea-level rise but are threatened by residents seeking better views of the sea, physical construction on coastal and inland dunes and sand mining. As a matter of precaution, and in compliance with the City's *Coastal Development Guidelines* (February 2008) further removal of sand dunes should be prevented in order to retain the remaining protection that they offer.

iv. **Maintain drains and stormwater systems:** The City has an effective stormwater system capable of discharging high volumes of flood water. Where capacity of the stormwater systems is exceeded, most roads around the City are designed to offer emergency drainage. Sea-level rise in conjunction with heavy rains has the ability to inundate the stormwater system, and frequent sea storms will make maintenance of the system and the roads more difficult. In the future it may be necessary to enhance the system for the changing nature of the threat. In the interim it is essential that the existing system is operating to its potential. Maintaining the system's functionality is already part of the City's flood management strategy, and will take on new significance in the light of sea-level rise.

v. **Integrate sea-level rise scenarios into future planning decisions:** The ability to relocate or adapt existing infrastructure is frequently limited, but the City's population growth, physical expansion and the growth of tourism requires ongoing construction of private and public infrastructure, including roads, energy sub-stations, stormwater drains and housing settlements. The location and nature of planned infrastructure should draw on forecast sea-levels reported in this study. Failure to do this will result in damage that could have otherwise been avoided, and will impose unnecessary costs on individuals and on the City. For example, the location of the planned extension to the Potsdam sub-station and sewerage works should take future sea-level rise (and terrestrial flooding) scenarios into account, as should the current R 4.2 billion upgrade to Cape Town harbour's container terminal.

vi. **Incorporate sea-level rise risks in disaster management strategies:** The need for co-ordinated responses has become something of a cliché in the context of climate change and natural disaster management. The City's disaster relief strategy already includes the risk of sea-surges. It is however imperative that this unit is kept abreast of information on how this risk is developing, and that is it given the opportunity to prepare for the management of this risk and its consequences. This is in keeping with a shift in the disaster management community towards the prevention of disasters rather than recovery from them (Thomalla *et al.*, 2006).

vii. **Decentralisation of strategic infrastructure:** Some of greatest sea-level rise impacts in the City involve damage to strategic infrastructure, sub-stations, sewerage works and roads. South Africa, and the City of Cape Town, is busy with an ambitious infrastructure programme aimed at extending public services to all citizens. In rolling out these services the City has to date relied on energy supplied through a nationally controlled grid, bulkwater supplies, centralised solid waste and sewerage treatment. This approach relies on centrally controlled infrastructure conglomerations such as the national grid and "Vissershok" solid waste disposal. Where this infrastructure is damaged the impact is widespread and the costs are significant, and as such the infrastructure presents a strategic risk. An alternative approach to service delivery would see homes and communities generate and distribute energy locally through a combination of solar panels, solar water heaters, gas and mini-grids, toilets compost human waste on site, houses capture and treat rain water for consumption and solid waste is sorted and recycled locally. Various models and technologies exist to support these decentralised and sustainable communities, but overcoming the costs and the structural and political barriers to their development remains a problem in South Africa. Under a system of decentralised infrastructure it is not possible that an area becomes entirely cut-off from services and it is much less likely that the impacts of a localised sea-level rise event will undermine a large area. This strategic benefit should, in the light of climate change risks to economic infrastructure, be factored into public sector decisions as to how they undertake the ongoing roll-out of services.

viii. **Alleviate poverty and improve living conditions:** Human vulnerability to sea-level rise is, to a certain extent, a function of the ability to mobilize away from the affected area and relocate to new areas, the ability to resettle after losing property or a house, the ability to re-invest after a major loss, the ability to seek shelter in structures capable of withstanding sea-level rise damage, access to the insurance market and the scope for drawing on a well resourced support network. Whilst affluence is not a guarantee against sea-level rise impacts, as with other climate change risks the poor are less able to afford flood insurance, live in less robust houses and are less able to afford repairs. As such the poor are disproportionately vulnerable to sea-level rise and in this sense alleviating poverty and ensuring that people are able to reside in well built and well located houses will assist in creating the type of capacity required to reduce sea-level rise risks. Equally the ability to cope with sea-level rise (and other climate change risks) should feature in the poverty relief efforts of vulnerable communities.

4.2 “Additional” actions

Whilst the no-regrets options outlined above are uncontroversial in their scope and should be (and in many cases are already being) pursued as part of Cape Town’s ongoing development, adaptation to sea-level rise will in some instances require targeted interventions aimed at managing specific aspects of the risk. These interventions involve new investment, new approaches and in most instances some form of trade-off or cost to the City. These interventions are “additional” to business as usual and existing efforts to improve well-being and maintain the environment. In a stylized sense these options can be classified into physical, biological and institutional responses.

4.2.1 Physical options

Hard engineering techniques - seawalls, groynes, detached breakwaters, and revetments - account for over 70 per cent of the protected shoreline in Europe.

- **Sea walls:** Sea walls represent the most common form of coastal protection around the City’s coastline. Paardon Eiland, the Sea Point Promenade, Boulders Beach, sections of Fish Hoek Beach and the Strand foreshore are all protected with sea walls with varying degrees of success. The low sea-wall at Boulders beach prevents wave erosion of the cliff. The Sea Point sea wall has been in place for over 70 years. The wall is set back off a rocky outcrop and is arched sea-ward in order to deflect waves. In spite of these features the paving and terrain that the walls seeks to protect, has to be periodically repaired following high tides and storm surges. There is currently little option but to try and maintain the wall and the adjacent interior adequately. In 2008 the City issued a contract worth R12.5 million for the maintenance of the wall. The reality is that such maintenance jobs are likely to become more frequent and more expensive as sea-levels rise. Beyond the 25 year period adopted in Phase 3 the wall may need to be raised or re-aligned inland. The Strand sea-wall is a construction that protects a road used to access the beach and a mixture of commercial and residential properties. The wall is in a perpetual state of collapse due to wave action and repair efforts are reactionary and increasingly unable to keep up with the rate of erosion. The Strand wall represents a good example of a poorly located and designed physical structure. The best solution to the problems and expenses already being incurred with the Strand sea-wall involves a managed realignment of the coastal edge involving re-establishing a dune cordon as a means of protection for coastal property.

Modern seawalls aim to destroy most of the incident energy, resulting in low reflected waves and much reduced turbulence. The use of “dolosse” or gabions to either construct or protect sea-walls from wave action is also considered good practice. In spite of this a UK study found that sea-walls around that country’s coastline had a 38 per cent chance of improving the situation with regards to sea-level rise, but a simultaneous 18 per cent of unwittingly exacerbating it (Foresight, 2007). In addition sea-walls are often unsightly, and scar the very landscape they are seeking to protect.

Figure 1: An example of a modern seawall on the Isle of Wight, UK.

- **Groynes:** Groynes are wooden, concrete or rock barriers or walls perpendicular to the sea. Groynes do not protect the beach against storm surges but can prevent long-shore drift and erosion. Groynes frequently create dangerous currents, as is the case at Monwabisi on the City's False Bay coastline. At this location the current created by the groyne carries sand offshore at the expense of the beach. Groynes require little maintenance and are effective in preventing long-shore drift. However as a counter to sea-level rise they tend to be ineffective if not detrimental.

- **Barrage and barriers:** Barrages and barriers are used to protect settlements and ports from extreme high tides and storm surges. The famous barrages at Maeslantkering and on the Thames River protect the towns of Rotterdam and London respectively. The Thames Barrage offers protection against North Sea-tidal and storm surge in conjunction with high river levels, and is automatically triggered by forecasts projecting sea-levels of 4.87 metres above the norm. The barrage, which was completed in 1984, is credited with having averted a number of sea-level rise catastrophes. Prior to 1990 the average number of barrage closures was 2 per annum. Since the 1990s the average number of barrage closures has increased to 4 per annum.

  Barrages should be able to open during low risk periods to allow the passing of ships and marine life, and only deployed at high risk times. The problem, however, is that under future sea-level rise scenarios many barriers may have to remain closed most of the time. Barrages are costly to construct and maintain and pose the risk of blocking off what would otherwise be a natural buffer against storm surges (such as an estuary) and thereby displacing tidal surges to adjacent areas. Installing and operating a barrage can only be considered when the value of the protected area is significant, and where detailed studies of the way in which the barrage will alter the storm surge have been completed. Potential barrage sites around the City of Cape Town's coastline include Milnerton Lagoon, The Black River estuary (which is already protected by a weir), sections of the Victoria and Alfred Waterfront, Sandvlei and the adjacent Marina da Gama settlement. If fitted with turbines barrages can be used to generate energy from the passing tides.

- **Raising infrastructure:** A fairly common response to sea-level rise involves simply raising the level of infrastructure. Cape Town docks, for example, would prove difficult to relocate, but could be raised or dredged in order to protect against sea-surges and inundation. Similarly raising the level of roads at Paardon Eiland could reduce the chance of these roads being over-topped by the sea. Problems with raising infrastructure, apart from the cost, include knowing exactly how high the infrastructure needs to be in order to be considered safe (or deciding what is considered safe enough), and the required adjustments to adjacent infrastructure. It is not possible to raise many roads in the City of Cape Town, for example, due to the need to maintain clearance for freight trucks under the many bridges that span coastal roads, most notably in the Paardon Eiland region.

- **Revetments, rock armour, dolosse and gabions:** Revetments, rock armour, dolosse and gabions are among the other physical infrastructure measures used to protect coastlines. They have a limited lifespan, are often damaged in storm conditions and reduce the recreational value of the beach. They are not common along the City's coastline and are not recommended for future protection of the coastline. "Dolosse" – a manufactured form of rock armour - are a South African invention applied internationally to dissipate wave energy. Dolosse are used with some effect at Paardon Eiland and at the Port to protect reclaimed land and the harbour pier from direct wave action.

- **Off-shore reefs:** The use off-shore structures including tyres, sunken ships, dolosse and rocks (usually placed within or just behind the wave zone) has the potential to reduce the amount of energy with which waves impact upon and erode the shore and can contribute to wider beaches. To date most artificial reefs have been constructed to either enhance surfing conditions (Perth, Australia) or in attempt to promote marine life (Florida and South Carolina, United States), but such reefs do not have a good track-record. Reefs tend to alter the near-shore currents in difficult to predict ways, they affect sea-traffic and where they disintegrate (as the reef constructed from used tires in Fort Lauderdale, Florida, did) they can damage existing reefs and coastal vegetation. As Spieler (2002) points out, "Artificial reefs need to be designed to function for specific tasks, at specific sites for specific geographic areas”.

Figure 2: Concrete blocks used off the coast of Australia to create an artificial reef. The rocks have been designed to create refuge for sea-life.

- **Beach nourishment:** Replenishing beaches and dunes with sand - a so called “soft engineering” solution - provides an alternative and often more successful physical approach to reducing sea-level rise risk. Sandy beaches are particularly vulnerable to erosion and retreat. One additional vertical unit of water can cause a 100 fold horizontal retreat (Douglas, et al. 2001) and losses of large sand volumes. Following a storm some sand is replaced naturally, but this can take time, is often interrupted by the following storm and typically results in a net sand loss. As Mather (2007) points out, “Where sand has been removed, sand should be replaced”. Beach nourishment or replenishment involves importing sand and piling sand on top of the existing sand so as to raise the beach. The imported sand must be of a similar quality and particulate size to the existing beach material so it can integrate with the natural processes occurring there, and not inadvertently destabilise the beach. The same process can be followed to restore dune cordon. Where ongoing erosion prevents rehabilitation of the natural dune cordon, sand can be stored within geofabric bags angled back up the erosion slope so as to allow some wave run up over the sloping structure (Mather, 2007). Artificial dunes have a greater chance of succeeding when planted with dune vegetation for additional stability.

Necessary caveats with regards to beach nourishment relate to the sourcing the sand and ensuring sand is of the right texture. Where sand is sourced from adjacent zones those areas may become vulnerable, and where sand is dredged from off-shore it can adversely alter the bathymetry and contribute to greater erosion by increasing the energy with which waves approach the shore. Equally where sand is of a different size or texture it can end up destabilizing the beach. Beach nourishment is necessarily an ongoing process. Sand is required to be recharged every 1 to 10 years.

- **Water pumps:** A number of cities (London in the United Kingdom, Maryland in the United States and Rotterdam in the Netherlands) actively pump sea water from draining systems during times of flooding. This highly reactive approach to managing sea-level rise is expensive and not recommended as anything more than a disaster relief activity.

- **Beach drainage:** Beach drainage or beach-face-dewatering lowers the water table beneath beaches, which causes sand accretion of sand above the drainage system. Typically a piped drainage system is used at the head of the beach to drain into a well that is then electrically pumped empty. The approach, first adopted in 1981, has become increasingly popular in Europe but has also been applied in the United States, Malaysia and Japan.

  The costs of installation and operation per meter of shoreline protection will vary due to the length of the beach, energy costs and pump flow rates but a study undertaken in New Zealand showed costs to be similar to those for beach sand replenishment over the medium term once maintenance costs of the two options are considered (See Appendix B). A potential concern with beach drainage involves its unforeseen consequences on groundwater. Sea-level rise will affect the saline content of groundwater adversely and additional drainage pipes could accelerate this process. See **http://www.griffith.edu.au/conference/ics2007/** and **http://www.shoregro.com** for more information on this as yet untested approach on South African shores.

The physical sea-defences described above are no longer considered "best practice" in efforts to manage sea-level rise, particularly given their propensity to result in unforeseen and adverse consequences, their relatively high cost and the fact that they do not provide absolute guarantees against inundation and storm surges. In spite of this they continue to be used in specific contexts – most notably where it is prohibitively expensive to relocate infrastructure or settlements. In these instances sand and dune replenishment, where possible, tend to provide a more cost effective and sustainable barrier than hard engineering solutions. The key to all physical sea-defences is that they be based on an intimate understanding of near shore process including currents, dune mobility, species migration and wave action. Over the past hundred years the limited knowledge of coastal sediment transport processes at the local government level has often resulted in inappropriate adaptation measures. In many cases, measures may have solved coastal erosion locally but have exacerbated coastal erosion problems at other locations or have generated other environmental or social problems. Failure to understand these elements of the near-shore environment will enhance the chance of physical interventions constituting mal-adaptation (as described in Phase 3) and amplifying risks.

4.2.2 Biological options

Biological responses to sea-level rise are seen as being more natural, less likely to produce adverse consequences and more cost effective than most physical options. The adoption of biological methods is based on the understanding that unperturbed coastal environments offered natural protection against sea-level rise in the past, but have been perturbed by human intervention thereby increasing the risk of future sea-level rise.

In tropical and sub-tropical regions this has seen efforts to restore mangroves that have been stripped by coastal developments or damaged by aquaculture activities (see Figure 3). The Cape Town coast does not have tropical mangroves, but a number of alternative biological sea-level rise measures for the City's coastline are available.

Figure 3: established mangrove plantations on the coast of Fiji seek to restore degraded vegetation and coastal buffers against sea-level rise and storm surges

- **Dune cordons:** Dunes form the natural coastal barrier at many of the City's beaches. Transects taken of the dune profile at Milnerton (see inset Figure 4) indicate that the dune cordon is narrow in places (as little 20 metres). Coastal dunes are being threatened by development, restrictions to the movement of aeolian sand from the Cape Flats that would otherwise replenish these dunes and disrupted tidal transport of marine sand, and the restricting of rivers that used to transport sand with dams and weirs. As such most of the dunes that define the City's beaches are "cut-off" and require human management if they are to retain their function as a buffer to sea-level rise. Examples of where and how this can work include the restoration of the dunes at Hout Bay following the dismantling of the sea-wall on the western side of the beach, and the dunes north of Blaauwberg which have been replanted and fitted with low-impact walk-ways for beachgoers. Where dunes are restored and dune grass is successfully established this vegetation is able to retain wind-swept sand and support the dune.

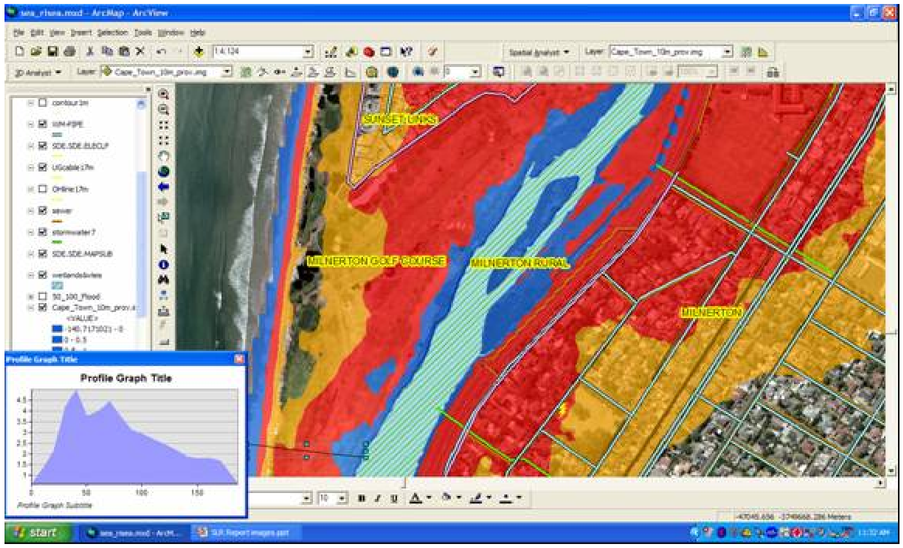

Figure 4: Sea-level rise model for the Milnerton region showing transect of protective dune profile (insert)

- **Estuary and wetland rehabilitation:** Rehabilitating the City's estuaries and wetlands in order for natural vegetation to return to these resources and that they regain their full buffering capacity against storm surges provides a further biological option. Where successful, these areas will also offer refuge for species that would otherwise be adversely affected by sea-level rise. Achieving this would require more than a "no-regrets" prevention of the current degradation and encroachment into these resources. It would require a proactive investment in rehabilitation, an investment that could, in part, be justified by the reduced risk from sea-level rise that would ensue.

- **Kelp beds:** Kelp beds are a feature of the City of Cape Town's coastline. Kelp acts as a significant dissipater of wave energy. Although kelp is variably exposed and covered by low and high tides respectively it has the ability to grow with sea-level rise. Very little is known about changes in the extent of kelp off the South African coast although anecdotal observations from aerial photographs suggest that beds might be expanding (Howard Gold, pers. comms). Kelp is currently harvested under license from Marine and Coastal Management and used in fertilizers.

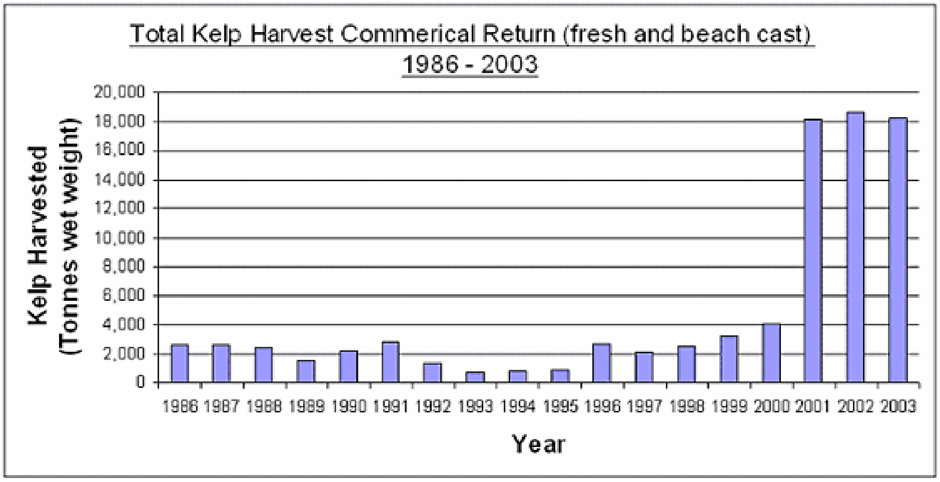

Figure 5: Total kelp harvest commercial return (data sourced from the Seaweed Unit, Marine & Coastal Management, DEA&T [unpublished]).

Kelp beds offer a partial solution to storm surges, and the factors affecting their extent should be better understood. In addition kelp washed up on beaches reduces wave energy, binds individual sand particles thereby contributing to beach structure, and fertilises dune vegetation. It is the practice on Cape beaches to remove kelp from beaches in order to maintain “clean” beaches for tourists and beach-goers. The City’s “beautiful white sandy beaches” where identified as being a major tourist draw card in a 2006 study undertaken by the Western Cape Tourist Board. Unfortunately the removal of kelp in conjunction with the mechanical cleaning of beaches contributes to their destabilisation and vulnerability to erosion.

4.2.3 Institutional responses

Climate change adaptation is increasingly being seen as a social and institutional change process (see section 2 above). Institutional responses do not preclude physical and biological responses;

indeed the success of physical and biological approaches is in many ways dependent on a supportive institutional environment.

Most institutional responses to sea-level rise risk focus on increasing the capacity of people and the environment to cope with problem as a means of reducing risk.

- **Vulnerability mapping:** Identifying vulnerable communities and locations represents the first and important step in any climate adaptation process. This study has identified vulnerable regions of the City's coastline and goes some way toward a vulnerability assessment. We know from Phases 1 and 2 for example that Blaauwberg, Milnerton estuary and Woodbridge Island, Paardon Eiland, Camps Bay, sections of Hout Bay, Fish Hoek, Muizenberg and Strand are potentially exposed. We also know that sandy pocket beaches (such as Llandudno Beach, Sandy Bay Beach and Blaauwberg Beach) are particularly vulnerable to loss of sand during storms. In conjunction with the City's socio-economic profile mapping (see Phase 3 report) this information should be used to identify particularly vulnerable locations and communities and inform response strategies. What we do not yet know is how different locations are variably affected by different types of storms; intuitively the Atlantic Seaboard is more exposed to north-west and south-west storms but more detailed information linking swell and wind direction with coastal impacts at specific locations is required. By applying a vulnerability screen and map (see Table 1 below for potential criteria) it is possible to identify priority areas and communities.

Table 1: Hypothetical screening criteria for sea-level rise exposure

Criterion of vulnerability	high, medium, low	Criterion of vulnerability	high, medium, low	Criterion of vulnerability	high, medium, low
Height above sea-level		Tidal range		Exposure to storm activity	
Subsidence rate at location		Evacuation potential			
Rate of sea-level rise at location		Value of land and infrastructure			
Population density		Mobility of infrastructure			
Socio-economic impact of the		Composition of the coastline			
Exposure to heavy rainfall		State of coastal defences – natural and man-made			

- **Risk communication:** People with different risk aversions will be prepared to take on varying amounts of risk and respond the threat of sea-level rise differently. In order to do this, however, they will require the best available information. Once vulnerable locations and communities have been identified it is incumbent on local authorities to communicate the extent of sea-level rise risk to local residents. There is no single correct response to sea-level rise risks. This is particularly critical for the private developments that are known to be exposed to high seas[3], and others involving yet to be exercised development rights as a result of development rights issued imprudently in the past. Communicating the risk to these property owners and explaining the extent of private and public liability associated

[3] The Coastal Development Guidelines identify The Milnerton Golf Course, the Cutty Sark and Brass Bell restaurants, the White House resort and hotel in Hout Bay and the Sunbird resort south of Gordon's Bay

with the developments will not only shape the extent of future developments but prevent inappropriate demands or claims against the City in the event of a disaster.

Effective communication is also required in the wake of a sea-level rise event in order to prevent mal-adaptation risks. Piece-meal and opportunistic responses to sea-level rise have been identified as contributing to the problems incurred after the 2007 KwaZulu Natal sea-level rise event. In part these actions were the result of uncertainty over who was responsible for the affected areas and private property owners' uncertainty as to which sphere of government would assist them.

- **Apply legislation:** By adopting and enforcing this legislation the City of Cape Town will significantly reduce its exposure to future sea-level rise. The City has produced *Coastal Development Guidelines*[4]. South Africa also has a well thought through *Integrated Coastal Management Bill* that is currently tabled before parliament, which among other things proposes a clearly demarcated coastal buffer zone and national estuarine management protocol. The Bill was preceded by the *White Paper of Sustainable Coastal Development in South Africa* (2000), which drew on South Africa's international commitment to integrated coastal zone management under the United Nation's Agenda 21 and specifically called for the building of institutional and legal capacity to manage the coastal areas.

- **Apply a coastal buffer zone:** In the context of sea-level rise risk coastal set-back zones are, "Frankly just good planning" (Mather, 2007) and can be justified against the required foregone development by their ability to prevent the costs of sea-level rise risk that are presented in Phase 3. The *Coastal Development Guidelines*[5] includes the so-called "blue-line"[6] below which new development should be prevented. The line is a socio-institutional risk management tool that should be seen as dynamic and flexible in the long-term. Where new information on the rate of sea-level rise, or the changed nature of storms shows that

[4] Coastal development guidance for Cape Town's coastline into the future; finding a balance between development, coastal conservation and quality living environments. City of Cape Town 2007.
5 Coastal development guidance for Cape Town's coastline into the future; finding a balance between development, coastal conservation and quality living environments. City of Cape Town 2007.
6 The blue-line is set at roughly a 5 metre contour, adjusted in line with existing coastal developments.

specific locations are more exposed that originally thought, the blue line should be adjusted accordingly. In some instances implementation of legislation and enforcement of a coastal buffer zone will necessitate a managed retreat from impacted areas in order to manage risks. The emphasis in such processes should be on the effective communication and management of such relocations. Where coastal communities relocate the potential for new coastal marshes and wetlands is created and in many instances natural vegetation buffers return. In general coastal realignments represent a low cost option unless compensation and new accommodation has to be provided for affected people.

- **Prevent sand-mining:** Sand-mining on the City's coastline is particularly perverse in terms of sea-level rise. Sand mining removes coastal dunes, destabilizes beaches and increasing the exposure of interior regions. Whilst and mining has supported the activities of the City's construction sector it is illegal. Enforcing sand mining bans would increase the cost of construction for those that have benefited from this activity but reduce the cost of sea-level rise risk.

- **Research and monitoring:** Uncertainties with regards to the manner in which climate change is affecting, and will continue to affect, sea-levels and storm activities around the City's coast remain. Some of this uncertainty is inherent, but some of it is due to a paucity of monitoring and research. The only official measure of sea-level for the City's coastline is from the South African Navy's records in Simon's Bay. This is in spite of the fact that we know sea-levels are rising at different rates at different locations. Projections of the relationship between climate change produced by UCT's Climate Systems Analysis group (CSAG) are indeterminate for north-west and south-west storms - the types of storms that are most likely to inflict damage on the City's coastline. Better information on changing sea-levels and the relationship between climate change and future storms would assist the City in correctly prioritizing sea-level rise risks within the context of the various other risks that it is required to manage. Ideally this research would be integrated with research on the changes in kelp-bed extent and changes in coastal bathymetry, all of which are known to be important to coastal impacts but are currently inadequately understood around the City's coastline.

- **Early warning systems:** The most damaging sea-level rise events are those involving extreme high tides coinciding with storm surges that are approaching land from a higher mean sea-level base. The three elements of a sea-level rise event, mean sea-level, tides and the weather that produces storms, change over very different timescales. They are also subject to very differing levels of predictability. Mean sea-level changes are very difficult to predict due to the inherent uncertainties surrounding climate change, but these changes tend to take place gradually and can be recorded. Tidal flux is entirely predictable, whilst coastal weather and associated swell height can be predicted with some accuracy over a 3 to 5 day period. By combining the information from the predictable elements of a sea-level rise event it is possible to create a reasonably robust system capable of giving coastal inhabitants and businesses 3 days warning of sea-level rise events. Warning allows measures to be taken that can reduce risk such as outward migration, the clearing of storm water drains, the sandbagging of properties and in the specific case of Cape Town, the oil pipeline that runs between the refinery and the port could be filled with sea water to avoid the risk of an oil spill. As suggested by Professor Brundrit, the early warning system could be outsourced by the City of Cape Town by getting a special forecast from South African Weather Service Maritime Weather Office at Cape Town International Airport (Johan Stander 021 934 3296) or could be operated in-house by the City using NOAA Wavewatch III http://polar.ncep.gov/waves/viewer.shtml to obtain specific wave heights, wind speed and direction and combine this with the available tide record.

Text Box 3

Proposed early warning system

Professor Geoff Brundrit, as part of this study, has designed a basic early warning system that could be used or refined for this purpose.

The system would draw on the South African Navy Hydrographic Office's tidal information www.sanho.co.za and the six day weather and wave and wind forecast available from www.weathersa.co.za and http://polar.ncep.gov/waves/viewer.shtml to produce a list of danger days for extreme sea levels, and the times of danger on those days.

A danger day would be defined by the raising of the sea to levels above those brought on by Highest Astronomical Tide – 2.09 metres above mean sea-level. If high tide on the day is HAT – z, then a weather effect exceeding z will result in a total sea level exceeding HAT. The probability of a weather effect exceeding z and resulting in a danger day can be read from a normal distribution table (see Appendix A).

So for 7 April 2008, for example, we know that the high tide occurring at 03h50 would be 9 centimetres below HAT. A normal distribution of the weather effect (z) for example shows that 13.9% of the time a high tide of HAT-9cm will result in seas that exceed HAT due to the weather. By examining the forecast for weather and swell it is possible to say whether the approaching weather and swell is likely to result in a danger day.

If there are several danger days in the month, the probability Ptotal of every danger day being safe in that month is the product of the individual probabilities of the weather effect (z) not reaching the required level on that day. The probability of a least one day going over that limit is then equal to 1-P(total).

- **Insurance market correction:** The insurance markets depend on correct assessments of long-term risks, and yet much of the insurance extended to coastal properties in Cape Town does not factor the risk of sea-level changes into its assessment (Le Roux, pers. comm.[7]). By providing the insurance industry with publicly generated information on the

[7] Andrew le Roux is an actuary with Old Mutual insurance and was consulted for this assignment.

risk of sea-level rise, it is possible that insurance premiums for coastal developments will be raised. This would be adverse for the people and companies seeking to be insured, but in the long run it would guide investment and settlement in these areas and reduce the costs of the liability, some of which is a public liability, in these areas.[8]

5. SELECTING THE MOST APPRORPIATE ADAPTATION MEASURE

The "correct" response to sea-level rise will necessarily be site specific and dependent on geological, social, financial and ecological conditions in the affected areas. Section 4 of this report has identified a number of options available for the management of sea-level rise risk. The more difficult task involves deciding which measures to apply. It is not the role of this study to stipulate the City's responses to sea-level rise, but the study is well placed to identify the types of considerations that should be taken into account in the decisions that will constitute the City's adaptation measures.

5.1 Cost and benefits

Climate change adaptation will impose costs, but the most costly responses to sea-level rise are not necessarily the most effective. Whilst investment in adaptation measures should be justified against the cost of impacts reported in Phase 3, those options that deliver the greatest possibility of protection for the least cost should be deployed first (see Table 2).

[8] The City of Cape Town is not alone in this predicament. In the US, flood insurance maps do not inform current or prospective coastal property owners of erosion risks (Heinz Center, 2000).

5.2 Foregone options

A key consideration in all sea-level rise efforts involves the extent to which a particular option forecloses on the potential alternative options. If climate change adaptation is to be an iterative socio-institutional learning process (SEI, 2008) in which neither the nature of impacts nor the efficacy of responses is perfectly known, then options that permit alternative or additional measures to be taken should, all other things being equal, be favoured over options that rule out alternatives. Early warning systems do not, for example, rule out the potential for constructing a sea-wall or orchestrating a retreat, but the construction of a sea-wall may make a managed retreat less likely in the short term. In this instance the early warning system is more attractive than the sea-wall. Similarly beach replenishment can be reversed or used in conjunction with insurance market measures or better communication, but once a retreat has taken place and infrastructure foregone, it may prove very difficult to recover an area.

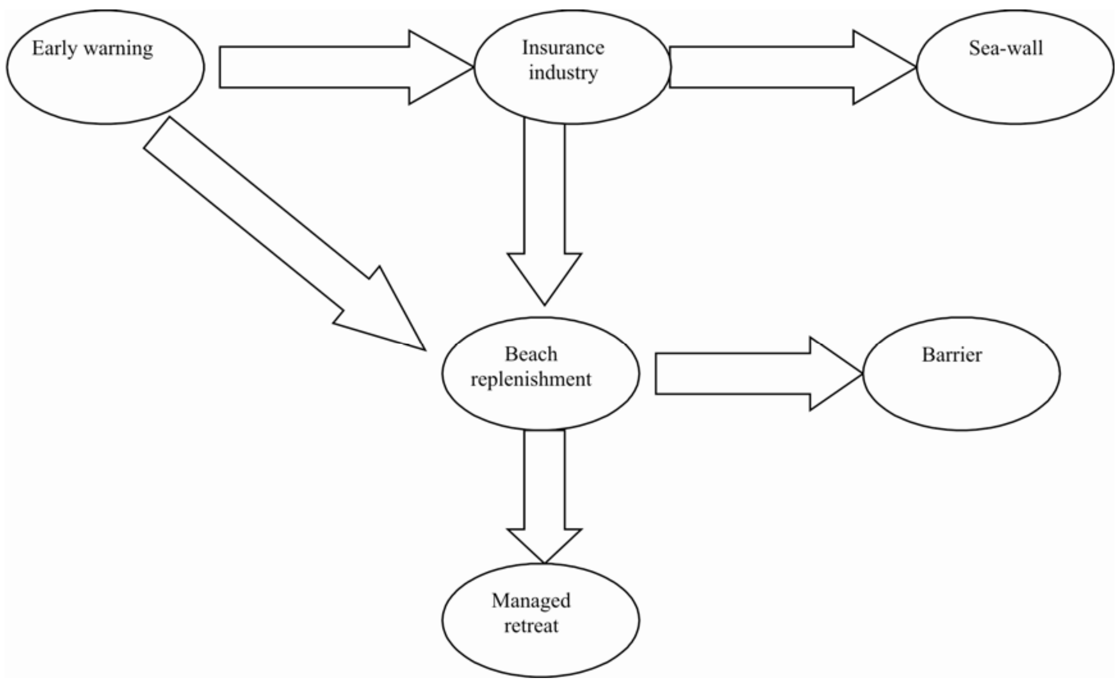

Figure 6: A hypothetical climate adaptation decision-tree, showing the pathway of potential measures and the foreclosure of other measures by certain decisions

5.3 Combined options reduce the most risk

Sea-level rise imposes multifaceted risks that impact via different mechanisms over very different spatial and temporal scales. Very few single interventions (with the possible exception of managed retreat) are able to address all of the risks generated by sea-level rise. For this reason combinations of responses tend to be more effective than any single option (Foresight, 2007). The appropriate combination of adaptation measures will differ depending on circumstances, but as a general approach combined solution should be sought over single interventions.

5.4 Potential for unforeseen consequences

Phase three identified the potential for “mal-adaptation risks” to amplify the net risk of sea-level rise. A number of responses to sea-level rise run the risk of having unforeseen and perverse impacts. Options such as sea-walls barrages and rock armour, which have a track-record of unforeseen impacts should be deployed with more caution than those, such as dune stabilisation and early warning systems, that do not. Particularly where the coastal features such as sediment deposit, storm frequency, bathymetry and biodiversity are not well understood, preference should be given to those options that are less likely to produce unforeseen consequences.

5.5 Capacity to implement

The best sea-level rise options combine integrated institutional responses. The Netherlands for example relies on a sophisticated social and institutional capacity to support its better documented system of dykes and polders. Social and institutional capacity is a function of social cohesion and effective governance. Where this is not present in a particular location, overly ambitious institutional responses may prove inappropriate.

Table 2 depicts the relative cost, benefits, potential for unforeseen consequences and suitability of the adaptation options described above.

Table 2: The relative cost, benefits, potential for unforeseen consequences and suitability of adaptation options.

Option	Cost	Benefits	Potential for adverse consequences	Suitability
Managed retreat	Compensation to property owners, lost public infrastructure, loss of real estate. May result in public liability and can involve protracted negotiation. Weighted average property prices for the City's coastline R1,800 and 2,900 m^2.	The most reliable and long-term solution to sea-level rise. May create new wetland and estuarine habitats.	Relocation of people and infrastructure can generate new social and environmental risks. Foregoes the option of less dramatic measures. Knowing how far to retreat can be difficult.	Widely suitable, especially where local residents agree that they are at risk or where physical structures have failed e.g. Strand, Fish Hoek. Can be considered as part of an enforcement of the "blue-line", particularly in the case of new developments.
Sea-walls	High and ongoing maintenance costs. R 3,000 – R 30,000 per metre.	Can provide effective protection from wave action in particular. Allows continued occupation and business. Walls can be raised and fortified incrementally as the sea rises.	High. Walls can be overtopped, can displace wave energy and cause heightened erosion. Walls create a false sense of security. Restrict public access.	Can be suitable to protect existing infrastructure that is difficult to relocate e.g. Sea Point promenade. Not recommended as part of new planning measures. Can be suitable at the base of cliffs e.g. Boulders Beach.
Groynes	Moderate. An unverified web source cites the cost of groynes to R900 per metre, although clearly some groynes are more expensive than this.	Limited benefits for storm surges and changes in mean sea-level	High. Alters current and sand circulation. Unsightly.	Not suitable.
Rock armour and gabions	Depends on availability of rock. Can be low cost where local rock is available.	Can be used to stabilise sea-cliffs.	Very high. Often increases erosion, unsightly. Rocks in mesh cages frequently break free from their cages.	Not suitable.
Barrages and barriers	Very expensive	Can provide effective protection for settlements and properties that can be easily barricaded e.g. those based on estuaries.	High. In the future barrages may be closed most of the time which will damage ecosystem and restrict movement.	Possibly suitable at Milnerton Lagoon, sections of the water front and Sandvlei where other options have been exhausted.
Raising infrastructure	Expensive especially were supporting infrastructure has to be raised to remain aligned. Costs are roughly $100 million to raise New Orleans levees one foot above normal (Leatherman and Burkett, 2002).	Allows continued functioning of infrastructure and infrastructure networks such as ports and roads.	May be difficult to know how high to raise infrastructure - "how safe is safe enough". Raising roads creates problems under bridges where clearance becomes inadequate.	Suitable to protect ports and certain roads and weirs.

Table 2: The relative cost, benefits, potential for unforeseen consequences and suitability of adaptation options.

Option	Cost	Benefits	Potential for adverse consequences	Suitability
Wetland and estuary rehabilitation	Can be low cost, provided wetlands are not built upon.	Limited impact with regards to sea-level rise, but multiple biodiversity and aesthetic benefits.	Low.	Highly suitable as a first step, wherever wetlands and estuaries exist. Dies not forego the option of more drastic measures at a later stage.
Beach face drainage	Reported to be comparable to beach replenishment.	Results in sand accretion, has achieved satisfactory results in Europe.	May result in saline encroachment into groundwater. High energy costs.	Unproven in the City but may assist in protecting sandy beaches. Not recommended as a first option.
Beach and dune replenishment	Moderate, but ongoing. R 12,000-15,000 per mete of beach)	Can provide highly effective defence.	Low provided sand is suitable in size and harvested from an appropriate source. Requires intimate understanding of near-shore currents and wave action.	Suitable in many sandy beaches along Cape Town' coastline.
Early warning system	Can be very low cost.	Multiple benefits. Allow individuals to respond in line with their risk aversion and exposure. Most effective where options for risk reduction exist e.g. evacuation plan, barrage.	Low, but requires public credibility and clear understanding as to the appropriate response.	Highly suitable. Can be used in conjunction with other options.
Insurance market correction	Very low cost provided research is available.	Many benefits. Over long term can be expected to guide investment in coastal areas.	May result in higher insurance premiums and higher number of uninsured in which case it will burden the poor most. Uninsured may fall back on government support in times of disaster.	High suitable as long as effectively managed.
Effective communication campaigns	Potentially very low cost.	Many benefits. Allows individuals to make own decisions with regards to risk. May absolve government from responsibility.	Limited. May induce over-reaction from public. Could affect a region's competitiveness.	Highly suitable and does not negate the possibility of other measures.

P.O. Box 474
Eppindust
Cape Town 7475
South Africa

Cell: +27 (0)73 511 1717
Tel: +27 (0)21 532 3333
Email: lfairhurst@deat.gov.za

6. CONCLUSION

The physical impact of the sea on the City of Cape Town's coastline is set to increase in the next century as climate change impacts increase. Phase 3 of this study estimates that, depending on the extent of sea-level rise, between R5 billion and R55 billion worth of tourism revenue, public infrastructure and real estate could be threatened by sea-level rise in any given year during the next 25 years. When probabilities are added to these scenarios, the value of the risk over the next 25 years is between R4.9 billion and R20.2 billion.

The risk of sea-level rise could be significantly reduced by pre-emptive measures and planned responses to the problem. This Phase 4 report has outlined a number of measures, their costs and benefits that could be considered to reduce sea-level rise risk for the City of Cape Town. Because sea-level rise generates diverse and multi-dimensional risks, measures that combine approaches will tend to reduce more risk than single intervention approaches.

Where large infrastructure projects are used to reduce sea-level rise risk, it must be acknowledged that these projects are only effective when grounded in an in-depth knowledge of near-shore conditions and the social and institutional infrastructure that is required in order to make these systems functional. As such these engineering solutions have long gestation periods and necessarily should be preceded by the type of research undertaken in this study. The emphasis in this document is on socio-institutional responses to sea-level rise. These responses are not only seen as most appropriate for the City, but are also a prerequisite for any engineered or physical response. Particularly where near-shore processes are not well understood and where the exposed public do not understand the nature of sea-level rise, hard engineering solutions have a greater tendency to amplify risk, often in unforeseen. As such they should be employed as a last resort (see Figure 7).

First resort – no regrets options	**Second resort – “additional” institutional measures**	**Third resort – additional biological measures**	**Last resort – additional physical measures**
▪ No further land reclamation from the sea ▪ No further wetland and estuary degradation ▪ No further dune degradation and development ▪ Maintain storm water infrastructure ▪ Integrate sea-level rise into spatial planning ▪ Incorporate with disaster risk management ▪ Decentralise strategic economic infrastructure and services	▪ Enforce coastal buffer zone – blue line ▪ Early warning system ▪ Correct insurance market failures and under-pricing of sea-level rise risk ▪ Managed retreat where necessary ▪ Social and geographical vulnerability mapping ▪ Risk communication ▪ Apply the requisite legislation ▪ Prevent sand mining of coastal dunes ▪ Additional research into rates of change and causes	▪ Dune stabilisation and planting ▪ Proactive estuary and wetland rehabilitation ▪ Kelp bed protection and ensuring kelp remains on exposed beaches at key times	▪ Beach and dune replenishment ▪ Sea walls ▪ Barrages and barriers ▪ Raising infrastructure ▪ Revetments, dolosse, rock armour ▪ Beach drainage ▪ Off-shore reefs

Figure 7: Stylised sequencing sea-level rise options available to the City of Cape Town in terms of preference and order in which they should be considered.

7. LITERATURE CITED

Adger, N, Hughs, P, Folke, C, Carpenter, S and Rockstrom, J (2005) Social Ecological Resilience to Coastal Disasters. S*cience* Vol. 309. no. 5737, pp. 1036 – 1039.

Berkhout, F., Hertin, J. and Gann, D., 2004: Learning to Adapt: Organisational adaptation to climate change impacts. Tyndall Cantre Working Paper No.47, [10]

Dawson, R (2007) Quantified analysis of the probability of flooding in the Thames Estuary under imaginable worst case sea-level rise scenarios. International Journal of water resource Development and water Disasters. Special Edition.

Demeritt, D. and Langdon, D.: 2004, 'The UK Climate Change Programme and communication with local authorities', Global Environmental Change 14, 325-336.

Douglas, B. C., M. S. Kearney, and S. P. Leatherman. 2001. Sea Level Rise: History and Consequences. San Diego: Academic Press.

Foresight (2007) Foresight: future flooding. Office of Science and Technology, United Kingdom.

Pelling, M. and High, C., 2005: Social learning and adaptation to climate change. Disaster Studies Working Paper No.11, [11]

Pelling, M. and J. Uitto (2001) 'Small Island Developing States: Natural Disaster Vulnerability and Global Change'. Environmental Hazards. 3(2). pp. 49–62.

Spieler, R (2002) Artificial reef research in Broward County 1993-2000. A summary report. http://www.broward.org/environment/dni01209.pdf

Stockholm Environment Institute (2008) http://wikiadapt.org/index.php?title=Main_Page

Thomalla, F., Downing, T.E., Spanger-Siegfried, E., Han, G., and Rockström, J (2006) Reducing Hazard Vulnerability: Towards a Common Approach Between Disaster Risk Reduction and Climate Adaptation. Disasters, 30 (1), 39-48.

APPENDIX A:

Probability of the "weather effect" causing the observed tide to exceed the level of HAT, for a given tide.

High tide below HAT by	Probability of NOT reaching HAT	Probability of exceedance
0 cm	0.500	0.500
1 cm	0.548	0.452
2cm	0.596	0.404
3cm	0.642	0.358
4cm	0.687	0.313
5cm	0.728	0.272
6cm	0.767	0.233
7cm	0.803	0.197
8cm	0.835	0.165
9cm	0.863	0.137
10cm	0.888	0.112
11cm	0.910	0.090
12cm	0.928	0.072
13cm	0.943	0.057
14cm	0.956	0.044
15cm	0.966	0.034
16cm	0.974	0.026
17cm	0.980	0.020
18cm	0.986	0.014
19cm	0.990	0.010

APPENDIX B:

Summary of costs and benefits compiled for Onetangi beach protection, New Zealand. The beach is 1.6 km long.

Option 1: Stabilising wall (sea-wall) at head of beach

Item	Cost	Cost per m of beach
Design of walls	$100,000	
Consents for walls	$100,000	
Timber bollards @ 2m centres	$7,500	
Replacement of wastewater treatment system for toilet block	$75,000	
Dune planting over 1400m based on $275 per linear metre, inclusive of removal of unsuitables, reprofiling dune face, planting and wind fencing top and bottom	$38,500	
Dune toe wall (175m) based on $1,000 per linear metre	$175,000	
Dune toe wall (remaining 350m)	$350,000	
Access ways, assuming two step access ways @ $10,000 each and two sand ladders @ $3000 each	$26,000	
Car park at Third Avenue based on use of grass paver type system @ $30/m^2 for 700m and concrete kerbing	$35,000	
Storm water investigation, looking at Third Avenue detention pond and catchment treatment options	$60,000	
Monitoring over 3 years	$40,000	
Subtotal	$1,007,000	
Contingency (approximately 15 per cent)	$151,000	
TOTAL	NZ $1,158,000	NZ $723.75 (ZAR 4,215 per metre)

Option 2: Beach face dewatering/ drainage

Item	Cost	
Design	$100,000	
Consents	$100,000	
Capital works (pump station/instrumentation, install pipeline and outfall) based on $2,000 per linear metre	$400,000	
Annual operating cost (5 per cent of capital cost) over 3 years	$60,000	
Annual monitoring (per annum), over 3 years	60,000	
Subtotal	$720,000	
Contingency (approximately 25 per cent)	$180,000	
TOTAL FOR BEACH FACE DEWATERING	$900,000	
Land based works from Option 1 including $25,000 design costs and approximately 15 per cent contingency	$354,000	
TOTAL	$1,254,000	NZ $ 783.75 (ZAR 4,564 per metre)

Option 3: Beach replenishment

Item	Near shore sand source (50,000m^3)	Cost per metre of beach	Offshore approved sand source (30,000m^3)	Cost per metre of beach
Design	$100,000		$50,000	
Consents	$200,000		$100,000	
Capital works, $30/m^3 for near shore, $60/m^3 for offshore plus, 15 per cent P&G	$1,725,000		$2,070,000	
Annual maintenance (based on $10/m^3) over 3 years	$450,000		$300,000	
Annual monitoring over 3 years	$40,000		$40,000	
Subtotal	$2,565,000		$2,590,000	
Contingency (around 25 per cent for near-shore, 15 per cent for offshore)	$640,000		$390,000	
TOTAL FOR BEACH REPLENISHMENT	$3,205,000		$2,980,000	
Land based works from Option 1 including $25,000 design costs and approximately 15 per cent contingency	$267,000		$354,000	
TOTAL	NZ $3,472,000	NZ $2,170 (ZAR 12,651)	NZ $4,234,000	NZ $2,646 (ZAR 15,426)