THE RISKS, MANAGEMENT AND ADAPTATION TO SEA LEVEL RISE AND COASTAL EROSION ALONG THE SOUTHERN AND EASTERN AFRICAN COASTLINE.

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Submitted in fulfillment of the academic requirements for the degree of Doctor of Philosophy in Environmental Science in the School of Environmental Science, University of KwaZulu-Natal, Durban.

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Abstract

Sea level rise and coastal erosion are two processes which may result in major problems for coastal cities around the world. This is particularly true for Southern and Eastern African cities as they struggle to meet their developmental challenges in addition to sea level rise and coastal erosion. This thesis focuses on three main areas, the analysis of the rates of sea level from tide gauges in the region, the extent of wave run-up on the beach and the development of a simple technical and management framework that managers can apply to assess coastal hazards.

The rates of sea level rise in the region vary, Zanzibar, Tanzania reflects a falling sea level at -3.64 ± 1.62 mm per year while the highest rate of sea level rise at Diego Garcia, British Indian Ocean Territories is $+4.35 \pm 7.61$ mm per year. The rate of sea level rise are dependent on the complex interactions of vertical crustal movements, barometric pressure changes, and the warm Agulhas and cooler Benguela currents.

Wave run-up is an indicator of the hazard zone. A number of international wave run-up models were assessed for use in this region and were found to be unsuitable. A new wave run-up model was developed which uses the bathymetric profile as opposed to the beach slope in predicting wave run-up. This model uses the equation $\frac{R_x}{H_0} = C\ S^{2/3}$, where R_x is the wave run-up height above Still Water Level, H_0 is the significant wave height at the closure depth, C is dimensionless coefficient where median values are described by $C \simeq 7.5$, S is a representative nearshore slope ($S = (h_c/x_h)$). h_c is the closure depth and x_h the horizontal distance from the waters edge to the closure depth.

An assessment of the impacts of sea level rise and wave run-up was undertaken based on a detailed case study of the Durban coastline. The results were incorporated into a standalone freeware viewer tool enabling this information to be accessible to planners, decision makers and the general public. The research has identified several types of shoreline that are vulnerable to coastal erosion, sea level rise and extreme wave events. Recommendations as to what adaptation measures could be undertaken for the different beach types are proposed. With this information coastal

managers and decision makers charged with managing shorelines can take the first step in understanding and adapting into the future.

Preface

The experimental work described in this dissertation was carried out in the School of Environmental Sciences, University of KwaZulu-Natal, Durban, from April 2006 to May 2011, under the supervision of Professor‘s Gerald G. Garland and Derek D. Stretch.

These studies represent original work by the author and have not otherwise been submitted in any form for any degree or diploma to any tertiary institution. Where use has been made of the work of others it is duly acknowledged in the text.

Declaration 1 - Plagiarism

I, Andrew Alan Mather declare that:

1. The research reported in this thesis, except where otherwise indicated, is my original research.

2. This thesis has not been submitted for any degree or examination at any other university.

3. This thesis does not contain other persons data, graphs or other information, unless specifically acknowledged as being sourced from other persons.

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a. Their words have been re-written but the general information attributed to them has been referenced

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5. This thesis does not contain text, graphics or tables copied from the Internet, unless specifically acknowledged, and the source being detailed in the thesis and in the Reference section.

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Declaration 2

Details of contributions to publications that form part and/or include research presented in this thesis.

Published peer reviewed journal papers

Publication 1
Mather, A.A. 2007. Linear and nonlinear sea-level changes at Durban, South Africa, *South African Journal of Science*, 103, 11/12, 509-512.

Publication 2
Mather, A.A. 2008. Coastal erosion and sea-level rise: Are municipalities prepared?, *IMIESA, March 2008*, 49-71.

Awarded third best paper published in the 2008 *IMIESA* journal.

Publication 3
Mather, A.A. 2008. Sea-level rise and its likely financial impacts, *Journal of the Institute of Municipal Finance Officers*, Vol. 8, Number 3, 8-9.

Publication 4
Mather, A.A. 2008. Coastal zone planning and management: The new rules. *E-proceedings of the Planning Africa 2008 Conference: Shaping the future*, Sandton, Johannesburg, South Africa. 16 pp.

Publication 5
Mather, A.A., Garland, G.G. and Stretch, D.D. 2009. Southern African sea-levels: corrections, influences and trends. *African Journal of Marine Science*, 31(2),145-156.

Publication 6
Mather, A.A., D.D. Stretch and Garland, G.G. 2011. Predicting Extreme wave run-up on natural beaches for Coastal Planning and Management, *Coastal Engineering Journal*, Vol. 53, No. 2, 87-109.

I was solely responsible for the conceptualisation, research and preparation of this paper. I collected the data, undertook the analysis, formulated and wrote the paper. D Stretch provided technical comments on the final draft.

Submitted peer reviewed journal papers

Publication 7
Mather, A.A. 2011. A Southern African perspective on flooding by sea level rise and coastal erosion: A case study of the Durban coastline, *Water*, Special Issue-Flood Risk Management, (Eds: B. Jonkman and R. Dawson) (in review).

Published peer reviewed conference papers

Publication 8
Garland, G.G. and Mather, A.A. 2007. Recent Sea level Change in Durban and Implications for management, *Proceedings of MEDCOAST*, Alexandria, Egypt.

I was responsible for the data analysis, evaluation and conclusions. G. Garland packaged the research into a conference paper.

Publication 9
Mather, A.A. 2007. Coastal erosion and sea-level rise: Are municipalities ready for this?, *71st Conference of the Institute of Municipal Engineers*, Durban, South Africa.

Awarded best written conference paper.

Publication 10
Mather, A.A. 2008. The Integrated Coastal Management Act: The new rules, *Proceedings of the South African Planning Institute Conference*, Johannesburg, South Africa.

Publication 11
Mather, A.A. 2008. Sea-level rise for the East coast of Southern Africa. *COPEDEC VII*, Dubai, UAE.

Publication 12
Mather, A.A. 2010. Stormy sea ahead: Planning for sea level rise. *Proceedings of the South African Planning Institute conference*, Durban, South Africa.

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I was solely responsible for the conceptualisation and preparation of this paper. I collected the data, undertook the analysis, formulated and wrote the paper. G. Garland provided editorial comments on the final draft.

Chapters in books

Publication 14
Cilliers, L. and Mather, A.A. 2009. Case study of the KZN storm in 2007. *In: Intergovernmental Oceanographic Commission: Hazard awareness and risk mitigation in ICAM*, Manual and Guide No. 50.

I was responsible for the portion of the paper dealing with the storm event. L. Cilliers supplemented my contribution and edited the document.

Publication 15
Mather, A.A. 2011. Sea level rise and its anticipated impacts along the east coast of South Africa. *In: Observations on Environmental change in South Africa*, (Ed: L. Zietsman), SAEON, SUN Media, Stellenbosch.

Publication 16
Mather, A.A., Roberts, D. and Tooley, G.A. 2011. Adaptation in practice: Durban, South Africa. *In: Resilient Cities 2010*, Springer.

I was responsible for the complilation of this paper with D. Roberts and G. Tooley providing editorial comments and suggestions.

Other publications

Publication 17
Mather, A.A. 2008. Coastal erosion, *In: Geohazards the risks beneath our feet*, (Ed: S. Frost-Killian) Quest, Volume 4 (2), 28-33.

Publication 18
Mather, A.A. 2009. The impacts of sea level rise on the eThekwini coastline and possible adaptation responses, *Durban Climate Change Summit*, Durban, South Africa.

Publication 19
Mather A.A. and Roberts, D. 2009. *A Climate smart city. Implications for climate change variability on African Water Resources*, Cambridge University, England.

I was responsible for the preparation of this publication. D. Roberts provided editorial input.

Publication 20
Stretch, D.D., Mather, A.A. and Taylor, R. 2009. *Region climate change impacts in South Africa: Estuaries and coastal systems. Implications for climate change*

variability on African Water Resources, Cambridge University, England.

Publication 21
Goschen, W.S., Mather, A.A. and Theron, A.K. 2009. Sea-level rise: trends, impacts and mitigation for South Africa Phase I: Qualitative overview and analysis, *In: South African Second National Communication under the United Nations Framework Convention on Climate Change for the Intergovernmental Panel on Climate Change (IPCC): South Africa Country Report.*

I was the main technical author of this publication as it was based on my two publications 1 and 5 above. W. Goschen acted as editor and corresponding author and A. Theron provided additional technical input and editorial input.

Publication 22
Mather, A.A. 2010. Responding to Climate change: Municipal adaptation plans, *Proceedings of the International Association of Ville and Ports*, Buenos Aires, Argentina.

Publication 23
Mather, A.A. 2011. Sea level rise and coastal erosion adaptation: Coastal Development Set Back lines. *Climate Change Impacts, Adaptation and Mitigation in the Western Indian Ocean (WIO) region: Solutions to the Crisis conference*, Grand Baie, Mauritius.

Publication 24
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Signed...

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The path I have trodden over the last five years has taken me on a never ending journey of discovery. This journey has at times brought with it elation when things went well and the research efforts yielded exciting results. But along with the elation, has come the inevitable disappointments. Yet through all this the lasting impression as I reflect back is the enriching experience that this has been and the many friendships that I have been made and strengthen along the way.

To my dear wife Tina and daughters Lara and Samantha whom have suffered in silence, well most of the time anyway, while I toiled away during the evenings and on weekends. Many is the time we sacrificed outing's to the beach, waterskiing and visits to family and friends. After this is over I will be making it up to you.

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'*I have never examined a Doctoral thesis with so much published material... This work stands out as an excellent example of detailed scientific research that has direct relevance for contemporary society as it struggles to adjust to the threats posed by climate change and sea level rise. Mr Mather has made a contribution of regional, national and global importance. The thesis is impressive in its breadth. It tackles difficult scientific questions and then go on to assess the relevance of the findings for society in the way in which it managed the coast. In bridging the science-society gap, Mr Mather has achieved something that proves very difficult for researchers worldwide...Overall, this thesis is a major contributor to the subject* '.

Professor Andrew Cooper.

Prologue to Chapter One

In recent times climate change and sea level rise have become household words as the awareness of these terms reach more and more people. However, most people have a difficult time understanding the likely effects of climate change and particularly sea level rise and so it is important that research in this area provides the tools in which to show the likely effects of sea level rise.

The most important questions to address are the issues of whether sea levels are changing and if so in which direction, by how much and what will be the impacts. Sea level rise and its impacts on the shoreline is perceived to be a complex issue, due to the spatial and temporal uncertainties associated with it. However, it is the threat of sea level rise which will need to be faced and mitigated if humankind are to adapt to the changes.

Chapter 1

GENERAL INTRODUCTION

‘*The maps of the world will have to be redrawn*’
Sir David King, U.K science advisor.

1.1 The need for sea-level change information

Over the last few decades, there has been increased awareness globally of the effects of climate change brought about by human impacts on our planet. Not a day goes by when we are not reminded that the continuation of our consumptive lifestyle is leading to a changing climate, can lead to negative consequences for all. It is increasingly clear that man has become an agent of change.

The effects on the Earths climate are expected to vary between different regions of the world; however, scientists are predicting increasing temperatures in most parts of the planet (IPCC, 2007). The changes affect the amounts and spatial variability of rainfall, which will cause droughts in some areas and floods in others. This change will lead to issues relating to food security as crops fail (Parry *et al.*, 2004). Biodiversity challenges will arise as alien invasive species moving in to new areas competing with the indigenous flora and fauna and pushing them towards extinction (Hampe and Petit, 2005). Increasing spatial distribution of vector carrying animals, which spread diseases, for example, malaria-carrying mosquitoes moving into areas previously too cool for them to survive will occur (Martens *et al.*, 1995). The raised temperature will cause ice and glaciers to melt and will heat up the oceans causing thermal expansion of the seawater leading to rising sea-levels (Allison *et al.*, 2011). These rising sea-levels will in turn change the coastline as we currently know it (Murray *et al.*, 2007).

Rising sea-levels will impact directly on coastal cities, towns and human communities, many of which have built a lifestyle around the coast and rely on the sea for income and depend on the sea to provide food for their families. Urban settlements have expanded rapidly over the last thirty years, most particularly in the developing countries (Rakodi and Treloar, 1997). The worlds sandy coastline is estimated to be in the order of 170 000 kms (34%) with numerous urban settlements dotted along this ribbon of sand (Hardisty, 1994). The United Nations has indicated that over half of the worlds population lives within 60 kilometers of the coast and that this will rise to three quarters by the year 2020 (UN, 1993). This is not surprising, as people are drawn to this rich and unique landscape where the sea meets the land.

Ports and harbours have long played a key role in the logistical transport network for nations to trade. The majority of international imports and exports are moved by sea transport because this method of transport is, compared to road, rail and air transport, by far the cheapest. This makes the long-term viability of ports and harbours a key element in a countrys economic survival into the next century (Rodrigue, 2006). Port and harbour development is hugely expensive and the developers of this infrastructure expect to use it for extended periods of up to a century. Rising sea-levels therefore are a potential threat to the viability of world ports and must be planned carefully based on full information about potential sea-level changes (Gallivan *et al.*, 2009).

The direct spend of global foreign tourism was estimated at US$ 681.5 billion in 2005 with direct spending in South Africa accounting for R53.4 billion (Tourism KZN, 2007). Visiting the beach by foreign tourists was ranked as the fifth after shopping, nightlife, social activities and visiting natural attractions (Tourism KZN, 2007). For the domestic tourism market, the beaches form the most important tourism attraction with 73% of all domestic visitors visiting the beaches (Tourism KZN, 2007). The southern and eastern coast of Africa provides an ideal location for these facilities with its sunny climate, sand beaches and warm Indian Ocean. Rising sea-levels may lead to reduced beach widths, damaged tourism infrastructure, and could be the single biggest factor in the shrinkage and/or collapse of the beach tourism industry (Watkiss *et al.*, 2005).

Beach loss is not always an indicator of rising sea-levels. Beaches can accrete under rising sea-levels as additional sediment becomes available for these beaches to widen. However, it is the sandy beaches which have considerable urban development backing them that gives rise to the most concern. Beach and shoreline erosion can lead to the loss of valuable public and private land and property. Private land owners are often the most negatively affected as many have invested large sums of money purchasing prime and expensive seaside properties to live out their retirement years. The options for the affected property owners to protect their properties are limited and difficult in an environment where little is known of the likely quantum and rate of shoreline regression. Where man decides to fortify the shoreline to reduce erosion damage and protect the land and property, the costs associated with this will negatively affect economies (Stallworthy, 2006).

Sea-level rise and its impact on the shoreline is perceived to be a complex issue, due to the spatial and temporal uncertainties associated with it. This invariably affect the manner in which people engage with the issue and how sea-level change is managed internationally, regionally and locally. The International Panel on Climate Change (IPCC, 2001) has highlighted research and policy insight at the sub-national (regional) scale as an important and unexplored geographic and political arena for analysing the impacts of, and responses to sea-level rise. The implicit assumption is that the experience of regional and local scale sea-level rise impacts makes the issue real for stakeholders in a way that a global scale impact would not do. The injunction to think globally and act locally has become common currency in debates about sea-level rise. As such, the role of national, provincial and local government in taking action and implementing laws, policies and strategies to deal with sea-level rise is crucial (Glavovic, 2006).

Historical sea-level changes have been widely documented and understood (Morner, 1971; Tanner, 1992; Church *et al.*, 2001; Levitus *et al.*, 2005; Ishii *et al.*, 2006; Church and White, 2011 (see Figure 1.1) but the predictions of the extent of the rate of sea-level rise into the future have remained a contentious and debatable issue (Morner *et al.*, 2004; Tol *et al.*, 2006).Thus, there is a critical need, not only to understand sea-level change and its impacts around the world, but more particularly the situation as it pertains to Southern and Eastern African coastal cities in the near absence of research of this nature.

In addition to the concerns of rising sea-levels is the possibility of increased storminess. Any increase in the wave climate will result in additional wave energy along the shoreline. This additional wave energy will result in enhanced coastal processes including erosional impacts in the cross- and long-shore directions. The change in wave climate could also result in higher than current extreme wave events. These extreme wave events generate significant wave run-up upon the shore. The quantum of wave run-up at any beach locality is an important variable to determine as it provides some indication of coastal vulnerability to coastal erosion during storm events and the risk to any landward located infrastructure. In other words rising sea-levels combined with increased wave heights will allow wave run-up to exceed currently wave run-up levels. This increase alters the risk profile of infrastructure located at the back of the beach.

1.2 Problem Definition

The quantum of recent sea-level change for Southern and Eastern Africa is unknown and unequivocal evidence for whether sea-levels are rising or falling over the last few decades is yet to be presented. The changes that may occur along our coast when shorelines adjust to these impacts becomes even more uncertain in the absence of this knowledge. Clearly, such knowledge is necessary to determine what steps society should take to plan for sea-level change. What is clear is that shoreline response and wave run up models which are largely empirical in nature, are not easily transplanted into a new region without some understanding of their dynamics and applicability to the new location. Calculating/estimating the extent of beach loss is crucial, so that impacts can be correctly understood, and adaptation measures designed, as there are significant social, environmental and economic ramifications. Several beach

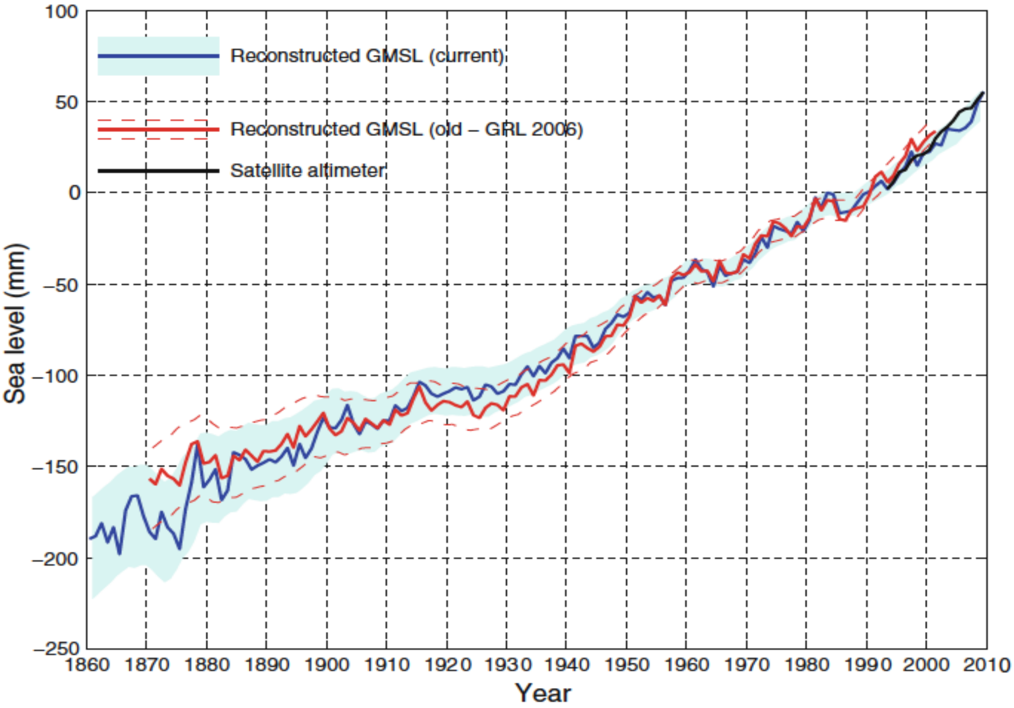

Figure 1.1: Global sea-level rise from 1860 to 2009 (Church and White, 2011).

response and wave run up models are in use globally but none have been evaluated or tested for their applicability to the South African shoreline. The identification of an acceptable model (or development of a new local model if none is applicable) will be invaluable for Southern Africa, providing managers and planners with a means of predicting the extent of the wave hazard zone and potential shoreline changes in their regions.

1.3 Questions, aims and actions

The research poses 4 questions:

1. Have there been changes of sea-level over the last fifty years along the Southern and Eastern African coastline?
2. If so what is the rate and direction of sea-level change?
3. What factors are influencing these sea-level changes?
4. How should these future sea-level changes be managed?

Within this, the 5 overarching aims of the study are:

1. To determine the most accurate measured rates of sea-level change along the Southern and Eastern African coastline
2. To predict future changes in sea-level for the remainder of this century
3. To develop a management model to allow society to anticipate these physical changes
4. To explain why this study is of relevance in the global sea-level rise context
5. To assess constraints to the management of shoreline change

These aims will be achieved by the following 10 actions:

1. To analyse all available tidal gauge records for all suitable gauge stations on the Southern and Eastern African coastline
2. To determine the most reliable and accurate tide gauge data
3. To compute sea-level trends along the Southern and Eastern African coastline
4. To determine which factors are influencing this change and to what extent they aggravate or mitigate sea-level change
5. From these results develop scenarios of sea-level change in the region for the remainder of this century
6. Through a review of management models of wave run up and shoreline change develop a model suitable for use in the region
7. To determine sites within the region which are most vulnerable to shoreline changes in the future
8. To review the legal framework for coastal management

9. To assess the capacity of local government to manage sea-level rise and coastal erosion
10. To set the results within the global context

1.4 Research Philosophy and Approach

The work comprises a synthesis of data published by the author and from unpublished sources. These data were used to determine current trends of sea-level rise, future sea-levels, extreme wave run-up and beach regression. The work includes for the first time a locally developed research into extreme wave run-up and delineation of the wave hazard zone. This has been used to determine the High Water Mark (HWM), as defined by the Integrated Coastal Management Act 2008, providing the tools to demarcate the inland extent of the coastal zone. This in turn provides management information for the sustainable management of the coast. An in-depth discussion on research methodology is presented in Chapter 3.

1.5 Motivation for the research

1.5.1 Introduction

Southern and Eastern African coastal areas have experienced an unprecedented rate of development. For example in South Africa eco-estates and golf courses have become the preferred developer's choice. Development activity has resulted in the KwaZulu-Natal coastline developing from 28% in 1994 to over 50% by 2006. Climate change is now an accepted reality and in this context, it is vital that we plan ahead. sea-level rise poses the biggest challenge for management of our shoreline in the coming decades. It has become clear that if ever there has been a time for better management of the coast and coastal developments, it is now. This change in the planning landscape has taken the form of a new piece of legislation, the Integrated Coastal Management (ICM) Act, which was promulgated in 2009. This new Act superceded the Sea Shores Act of 1935, which is currently the oldest environmental legislation still left on the Statue Book. This long overdue piece of legislation will bring in sweeping changes and bring South Africa up to international best practice in coastal zone management.

'*Africa's long and beautiful coasts and the abundance of marine resources can contribute to providing economic, food and environmental security for the continent. These coastal and marine resources, like the rest of Africa's environment resources, cannot continue to be exploited in a manner that does not benefit Africa and her people. This is a paradox of a people dying from hunger, starvation and poverty when they are potentially so rich and well endowed.*'

President Nelson Mandela, 1998.

Climate change and more specifically sea-level rise (Mather, 2007a) is going to be a challenge for all countries which have access to the coast. In order to manage the effects of sea-level rise it is important that an enabling environment is created in which these issues and problems can be properly and sensibly considered. The key success factors, which need to be considered in the management of sea-level rise and coastal erosion, include providing the political, social, financial and legal frameworks in which these issues can be addressed. This thesis will focus only on the legal and planning framework required by the South African Integrated Coastal Management Act (ICM, 2009) as the other Southern and Eastern African countries are currently overhauling their legislation in this area. South Africa, in the last decade, has been slowly revamping the coastal management legislation. In the early 1990's it was recognized that the current Seashore Act of 1935 was no longer an appropriate tool to manage the complex coastal environment. The Draft Green Paper (DEAT, 1998) and Draft White Paper for Sustainable Coastal Development in South Africa (DEAT, 1999) were the products of an extensive process of public participation and reflected the interests and aims of a broad range of coastal stakeholders (Glavovic, 2000).

In April 2000, the finalized White Paper for Sustainable Coastal Development in South Africa was published (DEAT, 2000). At that time, hopes were high that within a few years a completely new Act would emerge from this process, which would repeal the Seashore Act of 1935, currently the oldest environmental law on the Statue Books. Unfortunately, this was not to be and the process towards a new Act has been slow and difficult. The proposed Bill titled the National Environmental Management: Integrated Coastal Management Bill (ICM, 2007) was finally introduced into the National Assembly in the second half of 2007. The ICM Act was finally promulgated into law in December 2009.

The ICM Act makes the planning of the coastal zone a legal requirement for planning entities that are located on the coast. New planning concepts and instruments such as Coastal Management Plans, Estuary Management Plans, Development Setback Lines and Shoreline Management Plans are introduced in this Act. Some of the new concepts are controversial, for example a moving High Water Mark which when it moves inland results in the associated loss of private land to the state, already dubbed *"what the sea erodes, the State claims"*. This new planning landscape is undoubtedly going to be challenging and requires planners working within the coastal zone to add new tools to their toolbox.

1.5.2 Integrated Coastal Management Act (2009)

The Act covers a wide range of inputs relating to the management of the coast. The most important elements from a coastal management and planning viewpoint are the following:

Coastal boundaries
Special Management Areas
Establishment of a Coastal Set Back Line
The Management of Estuaries
Coastal Zoning Schemes
Establishment of Coastal Management Programmes
Shoreline Management Plans

Each of these key areas is described briefly below.

1.5.2.1 Definition of the coastal zone

The geographical extent of a coastal zone is always a debatable subject amongst coastal professionals; the Act has defined the Coastal Zone as:

> *"the area comprising coastal public property, the coastal protection zone, coastal access land and coastal protected areas, the seashore, coastal waters and the exclusive economic zone and includes any aspect of the environment on, in, under and above such area"*
> (ICM, 2009).

Simply put the coastal zone is the area bounded on the seaward side by a line running along the shoreline 200 nautical miles (± 370 kms) out to sea. The inland boundary is defined as 100 metres inland of the High Water Mark (HWM) in areas zoned under a land development plan and 1 kilometre inland of the HWM in areas with no land development plans. This includes all state and privately owned land in this area. The exception is protected areas where the protected area boundary takes priority. What is important about this definition is that the coastal zone is mainly water (99.75%). However, from a land use planning point of view the relatively narrow (0.25%) land portion of the coastal zone (from the HWM to the edge of the coastal buffer zone) is critical to the overall sustainability of the coastal zone. It is therefore important to identify the boundary between the wet portion (sea) and dry portion (land), commonly referred to as the High Water Mark (HWM).

1.5.2.2 High Water Mark (HWM)

Dating back to the mid 1800's, the HWM had been used to define all seaward cadastral boundaries along our shoreline. Until recently these boundaries have been viewed as static but the pressing issue of a rising sea-level has brought home the reality that the HWM in the 21^{st} Century is likely to be very different to that of the past and needs to be managed differently. The Act introduces the concept of a moving HWM, which principally is to ensure that a sufficient buffer exists along our shoreline to minimize damage and loss to land and property located in the coastal buffer zone. The Act states that if the HWM moves inland and remains in this new position for a period of at least two years then a process of resurveying the new HMW may be initiated. The current private landowner will have his seaward boundary changed resulting in a reduced property size. The land lost by the private landowner will revert to the state with no compensation.

1.5.2.3 Special Management Areas (SMA)

The Act provides for declaring an area that is partially or wholly within the coastal zone as a special management area. Specific environmental, cultural or socio-economic reasons must exist for such a declaration to be made. In addition, the Act requires that appropriate measures should be put in place to manage a SMA.

1.5.2.4 Coastal setback lines

The Minister will now be empowered to establish a coastal setback line, which will protect coastal property, contribute to improved public safety and preserve the aesthetic values of the coastal zone. The Minister will prohibit or restrict the building, erection, alteration, or extension of structures that are wholly or partly seaward of this line. Local authorities that are located along the coast will be required to delineate the coastal setback line on all maps and zoning schemes so that the public can determine the position of this line relative to their cadastral boundaries. Furthermore, it is a requirement that the Registrar of Deeds endorse this coastal setback line in all relevant deeds.

1.5.2.5 Estuary Management Plans

Estuaries, which for many years have been poorly managed, are also in line for a dedicated intervention. The Act requires that Estuary Management Plan's (EMP's) be drawn up for every estuary along the coast. Each EMP must conform to the National Estuarine Management Protocol that will be developed. Estuary Management Plan's must form an integral part of a Provincial and/or Municipal Coastal Management Programme.

1.5.2.6 Coastal zoning schemes

Coastal zoning schemes facilitate the management of human activities within the coastal zone. These are prepared by authorities responsible for coastal areas. These are layered in order of precedence for example the coastal zone scheme approved by the Minister takes precedence over one approved by the manager of a coastal protected area and in turn over the zoning scheme approved by a municipality. Municipalities may adopt a coastal zoning scheme and enforce this as part of a land use scheme.

1.5.2.7 National, Provincial and Municipal Coastal Management Programmes (CMP's)

National CMP
The Act introduces a requirement for a national Coastal Management programme, which must be completed within four years of the commencement of the Act by the government authorities. It must be a policy directive for the integrated, coordinated and uniform approach to Coastal Management by all role players including organs of state in all spheres of government, non-governmental organisations, the private sector and local communities.

The National CMP must contain

A national vision for Coastal Management including the sustainable use of coastal resources

National Coastal Management objectives

Priorities and strategies to achieve these objectives

Performance indicators to measure progress

A set of norms and standards for the management of the Coastal Zone

A framework for co-operative government

Provincial CMP
The Act requires that, within four years of the commencement of the ICM Act, a Provincial CMP be completed. It must be consistent with the National CMP and National Estuarine Management Protocol. Similar to the National CMP the Provincial CMP must also contain Estuary Management plans for estuaries.

Municipal CMP
The Act also requires Coastal Municipalities, within four years of the commencement of the ICM Act, to adopt a CMP. The Municipal CMP's may be prepared and adopted as part of an Integrated Development Plan (IDP) and Spatial Development Framework (SDF), which can be adopted in accordance with the Municipal Systems Act. However, Municipal CMPs may also be prepared as stand alone plans. All these CMP's must be reviewed within 5 years in order that all plans are consistent across spheres and with all other statutory plans (i.e. IDP's).

1.5.2.8 Shoreline Management Plans

Shoreline Management Plans are plans developed to manage the change in the shoreline position resulting from sea-level rise and coastal erosion. These plans are tailored to specific stretches of coastline and have the following management outcomes:

Do nothing
Advance the line
Hold the line
Retreat

These plans are developed in advance of possible shoreline changes and they are informed by projected sea-level rise, coastal erosion rates as well as social and economic considerations. For example, a well developed beachfront has a significant economic impact and as a consequence municipalities will be more likely to adopt a defence strategy rather then a retreat strategy, at least in the short term. These Shoreline Management Plans are a requirement of the new Act.

1.6 Discussion

The ICM Act is undoubtedly long overdue and has strong powers to re-energize the management of our coastal zone in a manner which is relevant to our local situation and in line with international best practice. The components of the Act have been well structured and endeavour to address the concerns of all stakeholders. Perhaps the only concern is the time frames given to undertake the major elements of this Act. The National, Provincial and Municipal governments have been given four years to undertake and adopt a layered and consistent set of CMP's for the country. Each sphere working in isolation would be hard pressed to source budget, implement and adopt an agreed plan in this timeframe. This time squeeze will require a move away from the National top-driven approach to a concurrent cooperative roll-out at all three levels of the proposed Act if deadlines are to be met. With this in mind the various interventions already undertaken in the spirit of the new Act need to be shared so that we can benefit from work already completed and experience gained.

Coastal Management in the eThekwini Municipality is presented here as a possible model for other local authorities. The eThekwini Municipality has always had an active role in coastal management and has recognized the importance of better management of its coastline (Nijhoff, 1935; Smith, 1941; Kinmont, 1955; Barnett, 1982; Campbell *et al.*, 1985; Barnett, 1999; Mather *et al.*, 2003; Mather, 2007a, b). Early in 2003, arising from local government restructuring, a dedicated strategic coastal and catchment management resource was established. This has allowed the municipality to advance the concepts in the ICM Act and as a result it is recommended that each municipality provide a dedicated resource like this to manage

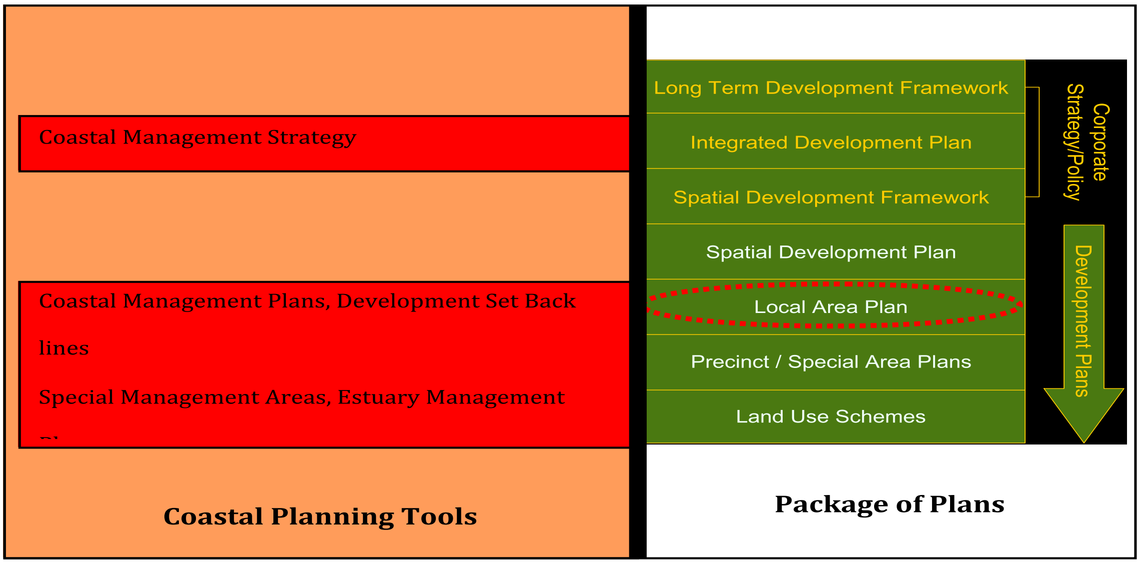

Figure 1.2: Relationship between eThekwini Package of Plans and Coastal Tools.

the roll out of this new Act. One of the first tasks was to develop a draft Coastal Zone Management Strategy that incorporated the elements of the ICM Act. The draft eThekwini Coastal Management Strategy and the draft Kwazulu Natal Coastal Management Policy (DAEA, 2004) were completed in 2004 but could not be adopted because of delays with the promulgation of the ICM Act. Notwithstanding this, the eThekwini Municipality embarked on preparing Development Set Back Lines and Coastal Management Plans for portions of its coastline.

1.6.1 Package of Plans

The eThekwini Municipality has developed a ‘package of plans’ approach to managing urban development. In order to integrate coastal management into the city development planning new coastal planning instruments have been developed in conjunction with city plans, especially at Local Area Plan (LAP) and Land Use Management (LUMS) level (refer Figure 1.2).

It is important that these are integrated into existing planning legislative requirements to ensure that they are addressed correctly and are monitored for progress towards each goal. To enable the proper integration of this Act with broader city planning it is recommended that all coastal management plans be embedded into statutory frameworks like the IDP to ensure it is given proper consideration and to ensure that this will be monitored for progress.

Figure 1.3: Development setback lines, eThekwini (shown in red) and the provisional KZN (shown in green) at Eastmoor Crescent, La Lucia, Durban.

1.6.2 Development Set Back Lines

Within eThekwini, the Development Set Back and Coastal Erosion Lines have been prepared by coastal engineering consultants. A study of the extent of historical shoreline variation is first analyzed and then factors such as long-term sea-level rise and storm erosion envelopes are factored in, yielding a potential coastal erosion line. An environmental buffer is added to this to ensure that after an erosion event sufficient natural vegetation remains to re-colonize the eroded portion. The inland boundary of the environmental buffer forms the Development Set Back Line. This line is used to control the placement of buildings and structures on a coastal site. Currently in the eThekwini Municipality no new private development is permitted seaward of this line. The Development Set Back Line is being incorporated into our Local Area Plans (LAP's). This line (shown in red) can be seen in Figure 1.3.

Within the Province of KwaZulu-Natal the Development Control lines developed by the eThekwini Municipality were the only lines in existence at the time of the March 2007 coastal erosion event when a significant sea storm created havoc along the KZN coastline (Smith *et al.*, 2007; Mather, 2007b; Mather and Vella, 2007). Arising out of the post storm assessments the author presented a proposed Development Setback line which could be used as a first approximation for the KZN coastline. This was based on the extent of shoreline damage along the 100 kms of eThekwini Municipality coastline. This line (green line in Figure 1.3) was subsequently adopted as an interim coastal set back line until the formal scientific coastal set back line can be establish. This formal scientific coastal set back line will be legally enforced upon the adoption of the ICM Act (Breetzke *et al.*, 2008).

The concept of a setback line is fundamental to the future management of the shoreline. This will enable the better placement of developments along the shoreline. It is the first line of urban management which if well handled will reduce the extent of physical damage to development located within/close to the danger zone. The longer it takes to implementation these controls the larger the problem of managed retreat will be.

1.6.3 Coastal Management Plans

Coastal Management Plans (CMP's) have been developed for three stretches (approximately 75%) of the eThekwini Municipality coastline. These CMP's are primarily to manage the impacts of human activities on the coastline. The key elements of CMP's are described below based on FutureWorks (2007):

Coastal Roles refers to the functions that the various sections of the coast perform and have been described in terms of their strategic, economic, social and environmental significance.

Coastal Features refers to the natural features of a coastal area, for example coastal waters, coastal dunes, rocky shores, estuaries, dune forests, grasslands.

Coastal Facilities are manmade infrastructure and / or improvements in the coastal area, for example recreational, transport, commercial, waste management and stormwater management facilities.

Coastal Activities are human activities that take place in the coastal area for example recreation, residential and marine resource harvesting.

Risks and Impacts are either inherent natural threats (e.g. sea-level rise and coastal erosion) or introduced threats posed by facilities (e.g. pollution from waste management facilities) and activities (e.g. recreation driving in sensitive areas) that may compromise the sustainability of coastal ecosystems, opportunities for future economic growth and / or the quality of life for human communities within the study area.

Development refers to the physical establishment of infrastructure or facilities that may be required to ensure effective coastal management. It may also include activities or programmes that empower (i.e. develop) people and communities to contribute to and / or benefit from coastal management.

Strategic Management refers to both short and long term planning and / or control activities necessary to ensure sustainable coastal ecosystems and human settlements.

Operational Management refers to the day-to-day management activities that ensure sustainable coastal ecosystems and human settlements.

The CMP process involved the following phases:

Phase One: Assessment of the Study Area's Precincts in terms of Coastal Risks, Features, Facilities, Activities and Management (see Figure 1.4).

Phase Two: Development of Coastal Vision, and inputs of coastal zonings and controls into the LAP and LUMS.

Phase Three: Formulation of Development and Management Strategies for the coastal zone.

Figure 1.4 shows a section of coastline which has had a risk assessment undertaken and this shows the particular types of risk such as beach erosion, sea-level rise and land instability associated with this area. This risk assessment is typically the first step to formulating responses to the identified risks. Throughout the preparation and implementation of the CMP's within the eThekwini Municipality there has been ongoing consultation with internal and external stakeholders. This process yielded a precinct-based list of key coastal management activities that need to be undertaken to achieve the vision by the various role-players i.e. Provincial, NGO's, municipal departments and other stakeholders.

1.7 Conclusion

The changes that have been introduced in the ICM Act will change the South African coastal planning and management landscape. It will bring with it a fair share of new challenges and concepts for the built environment professionals working in the coastal zone. Foremost from a public point of view is the controversial 'moving High Water Mark' and its implications for existing land ownership, land rights and property values. Changes in property boundaries and therefore property sizes have far-reaching implications for zoning, development rights and development management. The challenge for the public bodies involved in coastal planning and management is the requirement for various interventions to be in place in a relatively short period of four years. While this may be feasible for large capacitated municipalities to deliver, it will be much more difficult for smaller municipalities to comply unless there is cooperation and sharing between all parties involved.

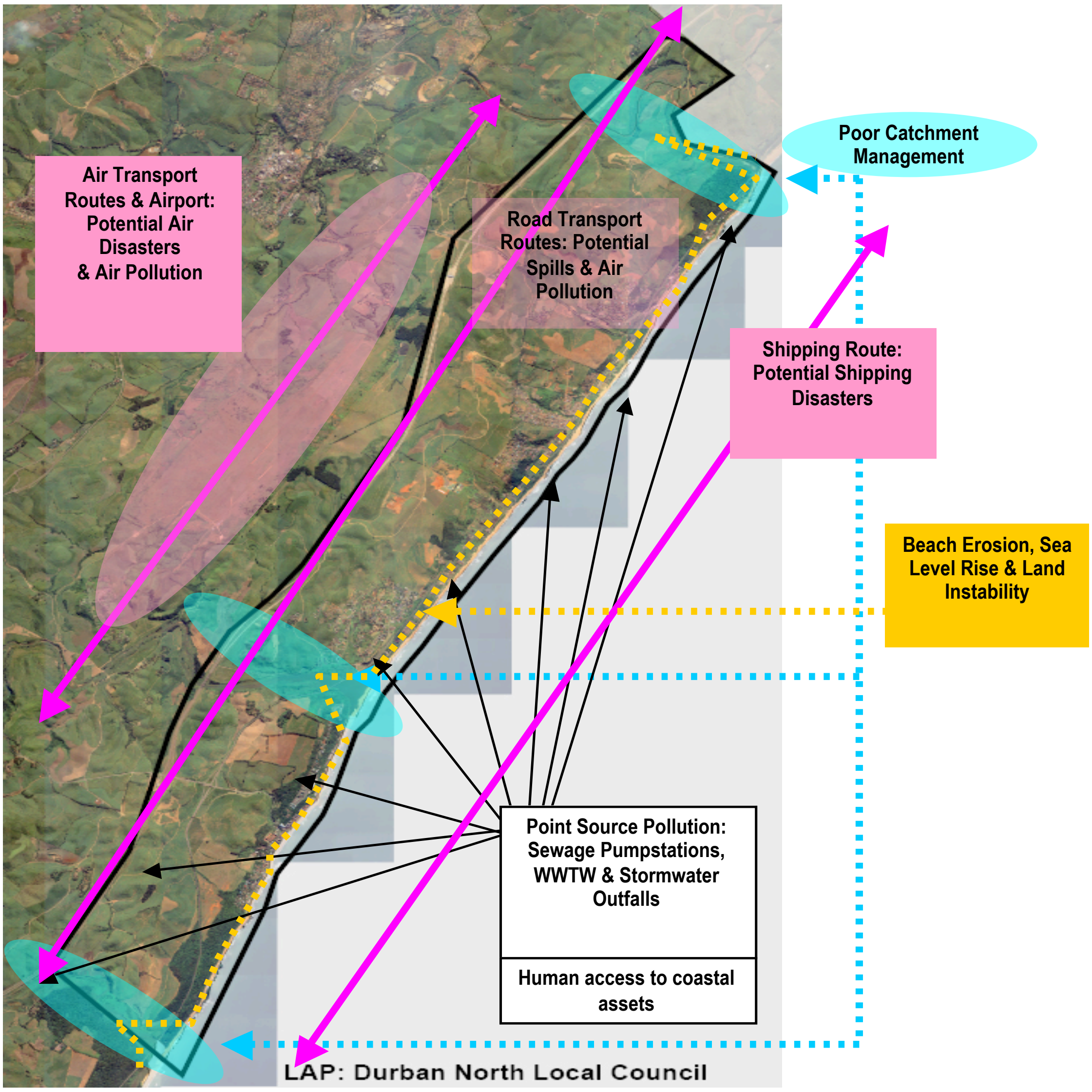

Figure 1.4: Schematic depiction of coastal risks for the Ohlanga to Tongati coastline, eThekwini Municipality (FutureWorks, 2007).

Nevertheless, this Act provides us with an opportunity to overhaul the current outdated coastal management framework and to plan and manage coastal development in a more integrated and focused manner. With the passage of time the legal and planning framework will be put in place to enable the proper management of the shoreline in the face of sea-level rise and coastal erosion. Apart from the scientific input required to generate future scenarios, it is clear that financial resources and political support will also be required to complement and support this Act and the instruments it introduces to enable the better management of our coastline. Without these additional factors the management of the coast will be less than optimal.

1.8 Outline of the Thesis

This thesis has been broken up into chapters dealing with various components of the research. Apart from Chapters 1, 2, 3 and 11, the remaining Chapters 4 to 10 are written in the form of linked yet stand alone papers with dedicated references as briefly described below. As the thesis is comprised of separate stand alone papers some information from previous chapters is repeated to provide the context of each subsequent paper.

Chapter 2 provides a literature review of the main subject areas to be explored in the thesis.

Chapter 3 discusses the data and research methodology to be used.

Chapter 4 deals with the Durban tide gauge analysis.

Chapter 5 deals with the detailed analysis of the South African and Namibia tide gauge stations and provides for corrections to the data, factors which influence sea-levels at each station and 'relative' and 'eustatic' sea-level trends.

Chapter 6 discusses sea-level rise along the Southern and Eastern African coastline.

Chapter 7 covers the development and validation of a wave run up model for use in the region. Comparisons between this model and selected global wave run up models are undertaken.

Chapter 8 provides a perspective on planning for sea-level rise and includes an overview of the legal and planning environment of coastal management with particular reference to South Africa's new Integrated Coastal Management Act.

Chapter 9 covers the preparedness, capacity and response capability of local, provincial and national government to the impacts of sea-level rise and coastal erosion.

Chapter 10 provides a Southern African perspective on flooding and coastal erosion and focuses on the Durban coastline as an example for the region.

Chapter 11 provides the conclusion to this thesis and indicates direction for future work in this field.

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Epilogue to Chapter 1

In this chapter the scene has been set for the research including the key questions, goals and objectives. In Chapter 2 a literature review of the available literature on the subject will be undertaken.

Prologue to Chapter 2

In the introductory Chapter the thesis topic was introduced to the reader. In this Chapter the relevant literature will be discussed.

Chapter 2

LITERATURE REVIEW

2.1 Introduction

Sea-level rise and its associated impacts are perceived as complex issues, due to the spatial and temporal uncertainties and consequences associated with it and these invariably affect the manner in which people engage with the issue and how it is managed internationally, regionally and locally (Barnett, 1990; Matthews, 1990; Barron and Thompson, 1990; Cazenave *et al.*, 1998; Kay and Alder, 1999; Church *et al.*, 2008a, b). The Intergovernmental Panel on Climate Change (IPCC) has highlighted research and policy insight at the sub-national (regional) scale as an important and unexplored geographic and political arena for analysing the impacts of, and responses to sea-level rise. The implicit assumption is that the experience of regional and local scale sea-level rise impacts makes the issue real for stakeholders in a way that a global scale impact would not do. The injunction to think globally and act locally has become common currency in debates about sea-level rise. Recent work has started to downscale global impacts down to regional levels including developing countries (Dasgupta *et al.*, 2009) and port cities (Nicholls *et al.*, 2008). The role of national, provincial and local government in taking action and implementing laws, policies and strategies to deal with sea-level rise and its impacts is crucial (Glavovic, pers com 2009).

Four areas of research are relevant to the research presented in this thesis: sea-level change research, sea-level change projections, extreme wave run-up and beach/shoreline response to sea-level rise.

2.2 Historical sea-level research

A variety of natural factors acting on the earths surface has caused sea-levels to vary in time and space(Church *et al.*, 2001; Bindoff *et al.*, 2007). These factors include solar and lunar tides (Pugh, 2004), waves and winds (Pugh, 1987), crustal movements (Baker, 1993; Pirazzolli *et al.*, 1994; Davis and Mitrovica, 1996) and atmospheric conditions (Dickman, 1988; Hoar and Wilson, 1994; Wunsch and Stammer, 1997; Proshutinsky *et al.*, 2004) both at a local, regional and global scale. Anthropogenic factors have also played their part. These anthropogenic influences include warming (Warrick *et al.*, 1996; Bindoff and McDougall, 2000), glacier and ice sheet melt (Zwally *et al.*, 1983; Dyurgerov and Meier, 1997; Arendt *et al.*, 2002; Munk, 2003; Arrigo and Thomas, 2004; Vaughan, 2005; Joughin, 2006; Jenkins and Holland, 2007; Meier *et al.*, 2007) and surface and ground water storage (Gornitz, 2000; Ngo-Duc *et al.*, 2005; Chao *et al.*, 2008). Given these interconnected and independent influences, research on historical sea-level change has been an ongoing process (Nicholls and Tol, 2006).

2.2.1 Worldwide sea-level change

The calculation of recent historical sea-level trends started as simple linear regression analysis of tide gauge data to the present time where tide and satellite data are used to determine linear and non-linear trends. These results have shown ever increasing rates of sea-level rise over the 19^{th} and 20^{th} century. Early indications are that this trend will continue and accelerate throughout the 21^{st}century, notwithstanding any human interventions to reduce it's impact on the planet.

2.2.1.1 Linear sea-level rise regression trends

Early research into sea-level changes can be traced back to the works undertaken by Gutenberg (1941), Polli (1952), Cailleux (1952), Valentin (1952), Lisitzin (1958) and Fairbridge and Krebs (1962), Kalinin and Klige (1978). These researchers found that global linear sea-level rise was between +1.1 to +1.5 mm per year. Emery and Aubrey (1980) found a considerably higher figure of +3.0 mm per year. From 1980, the number of sea-level trends published in the literature increased considerably, and includes the work of Gornitz *et al.* (1982), Barnett (1983, 1984), Pirazzolli (1986, 1993, 1996), Gornitz and Liebedeff (1987). In 1988, the Intergovernmental

Panel on Climate Change (IPCC) was established. This initiative intensified sea-level research (Peltier and Tushingham, 1989; Pirazzolli, 1991; Trupin and Wahr, 1990; Peltier and Tushingham 1991; Douglas, 1991).

This then culminated in the single largest study of sea-level rise by Emery and Aubrey (1991) who examined 517 stations over the period between 1807 to 1986 and perhaps providing the most globally representative sea-level change study to date. They found that there was a large amount of variability of the observed sea-level change at stations. Some of this can be explained by the location of the gauge site, for example located on a subsiding river delta, while others by post glacial rebound. What was evident from their research was that while regional differences are evident they are independent of vertical crustal movement and subsidence. This conclusion means that other forces are responsible for rising global sea-levels. It also implies that it would be incorrect to adopt a global sea-level change figure directly to a region. Despite reducing the 517 gauges down to only 36 which they described as from ‘stable coasts’, the results were the same.

They concluded that they could not find any justification in selecting a few long term station results to be indicative of regional or global average sea-level changes. They found that the trends in relative sea-level change were strongly dependent on the number of tide gauges used in the analysis. And finally they concluded that the Permanent Service for Mean sea-level (PSMSL) was the most useful data set available, but issues of non-uniformity in sampling limit its usefulness in determining long term trends, especially in the period pre-1930.

Later, Nakiboglu and Lambeck (1991), Shennan and Woodworth (1992), Douglas (1992, 1995), Gröger and Plag (1993), Gornitz (1995), Mitrovitch and Davis (1995), Peltier (1996), Davis and Mitrovitch (1996), Peltier and Jiang (1997), Douglas (1997), Viliblic (1997) all provided linear sea-level trends using tide gauge data which indicate a positive global sea-level trend.

In 1992 the use of satellite altimetry data in providing measurements of sea-level heights were made possible by the deployment of a satellite network making it possible to use these data for sea-level trending and analysis. Up until this time the spatial coverage of tide gauge data was heavily biased towards the northern hemisphere (Douglas and Peltier, 2002). This has sparked off some debate as to the validity of the results from these global tide gauge studies particularly as to whether these results are truly representative of the global situation (Park, 2007). Some authors have continued to use the traditional data from tide gauges whilst acknowledging its shortfalls in spatial coverage, but this coverage is slowly improving with time as the tide gauge network expands (Woodworth, 1991). Satellite altimetry has however provided an effective way to address the spatial inadequacies of the data and provides data from all ocean regions (Cazenave, 2009). The use of satellite observations come with their own set of calibration problems and provided the error corrections are adequately addressed, e.g. satellite orbital shift that can be of a similar magnitude to sea-level rise, they are capable of reliable results (Mitchum, 2000).

The first satellite altimeter study by Nerem (1995) and updated by Nerem *et al.* (1997) produced a linear rate of sea-level rise of +2.1 ± 1.2 mm per year (1993-1997). Since the advent of satellite altimeter data, authors have chosen to use the new satellite altimeter exclusively obtaining a better spatial coverage and arguably better representative data (Cazanave *et al.*, 1998; Nerem, 1999; Cabanes *et al.*, 2001; Nerem and Mitchum, 2001; Johansson, 2002; Cazenave and Nerem, 2004; Lieuliette *et al.*, 2004). While others have continued using tide gauge data (Lambeck *et al.*, 1998; Peltier, 2001; Proshutinsky *et al.*, 2001; Lambeck, 2002; Hunter *et al.*, 2003; Church *et al.*, 2004) or combining the satellite and tide gauge data (Woodworth, 1999; Church *et al.*, 2001; White, Church and Gregory, 2004; Bindoff *et al.*, 2007 and Leuliette and Miller, 2009). Recent global satellite sea-level trends +2.4 ± 1.1mm per year (Jason-1) and +2.7 ± 1.5 mm per year (Envisat) are in good agreement with sea-level trends derived from upper ocean steric sea-level measurements using AGRO floats, ocean mass calculations using GRACE gravity observations and tide gauge measurements (Berge-Nguyen *et al.*, 2008; Leuliette and Miller, 2009).

2.2.1.2 Non-linear sea-level trends

Non-linear sea-level trend analysis has been a recent approach that aims to elucidate both average trends and the rate of change of these trends, although there have been previous attempts to determine a non-linear sea-level relationship (Woodworth, 1990). Success in determining a non-linear relationship was first achieved by Church and White (2006) who were able to demonstrate a statistically significant acceleration in sea-levels. Since then several authors (Jevrejeva *et al.*, 2006; Jevrejeva, 2008; Woodworth *et al.*, 2009) have determined an acceleration in sea-levels. Recent work by Siddall *et al.* (2009) using data going back over the last 22 000 years have supported the non-linear relationship view with the development of a hysteresis model of sea-level changes over this time. They were able to clearly demonstrate the tipping points which triggered rapidly rising or falling sea-levels. However this rapid change is regarded ‘physically untenable’ since the Earth is currently at the maximum high stand of this interglacial period (Pfeffer *et al.*, 2008). This places important limitations on the future system response and will be addressed in the discussion on future sea-level change predictions in Section 2.3.

So far, global sea-level change has been discussed, but the focus of this study is on Southern and Eastern Africa. The Southern and Eastern African location is typified by a large open face to the southern oceans and two distinctly different coastlines. The western coastline is influenced by the colder Benguela current while along the eastern coastline the warmer Agulhas current dominates. This variation in conditions is relatively unusual as colder upwelling systems are not commonplace, occuring in only 5 locations globally (Hutching *et al.*, 2009). However, it is intuitive that the absolute rates of global, regional and local sea-levels are likely to be different and are likely to vary in greater magnitude as the size of the study area decreases reflecting the local physical variations. Holgate and Woodworth (2004) held the view that sea-levels along the global coastline were rising faster then the global open ocean sea-level trend. Recent altimeter results however appear to contest this, implying that global, regional and local sea-level trends are rising at the same rate (Prandi *et al.*, 2009).

2.2.2 Southern and Eastern African sea-level change

In stark contrast to the global situation, very little research on sea-level trends in Southern and Eastern Africa has been conducted. Southern and Eastern African sea-level data has been collected since the 1950's but is of variable quality with many gaps and much noise. The author was only able to find research undertaken in the 1980's and 1990's that is now nearly two decades old. The earliest studies by Merry (1980, 1990) found that there were no trends in sea-level around the South African coastline, however his data covered the period from 1960 to 1975, arguably too short to be useful in determining any trends (Woodworth *et al.*, 2007). This was followed by Brundrit (1984), who used a larger dataset to highlight the long-term inter-annual variability of sea-level on the West coast of South Africa and Namibia, and De Cuevas *et al.* (1986) who analysed low frequency fluctuations in sea-levels.

Further extension of the work of Brundrit (1984) by Brundrit *et al.* (1987) found that high sea events propagate polewards from the equatorial Atlantic. Hughes *et al.* (1991) examined changes on the West and Cape coast of South Africa. Hughes and Brundrit (1992) developed an index to assess the vulnerability of the South African coastline to sea-level rise. They observed that coastlines are most susceptible to extreme storm and flood events. Hughes (1992) used estimates of sea-level rise to determine the impacts of sea-level rise on selected locations along the South African coastline, for example the sea-level rise impacts for the City of Durban (Hughes and Brundrit, 1990). Thereafter, Brundrit (1995) examined the South African tide gauges at Lüderitz, Port Nolloth, Simon's Town and Mossel Bay. He determined a trend for the west coast of $+1.2 \pm 0.4$ mm per year but was unable to determine trends along the southern or eastern coasts of South Africa. No new research has been undertaken along the Southern African coastline since 1995. Historical research into sea-level changes are based on a single research project by Ramsay and Cooper (2002) for South Africa. Ramsay and Cooper derived a sea level change curve from present time to approximately 200 000 years before present (see Figure 2.1).

2.2.3 Gaps in sea-level change research

In reviewing the global, Southern and Eastern African sea-level change research, two major omissions in the current research are evident. The first issue is the question of geographical coverage of sea-level change trends. So far global sea-level change analysis has been biased towards the northern hemisphere although as the

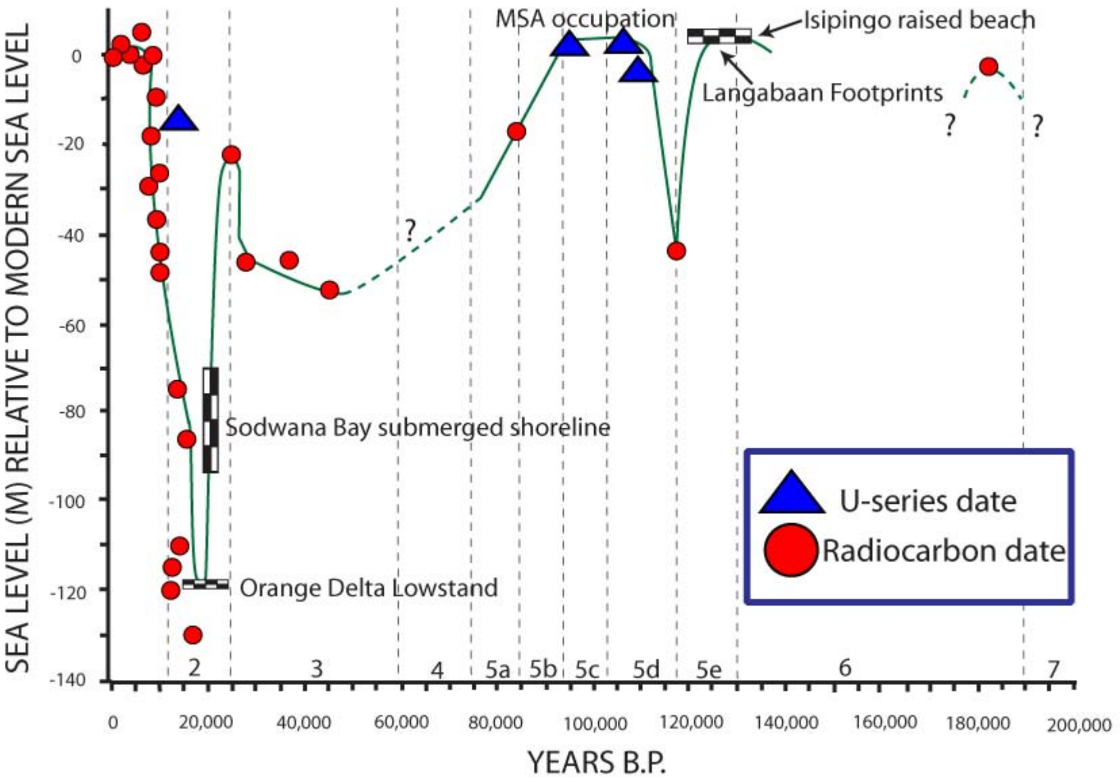

Figure 2.1: Sea-level curve for past 200 000 years based on available sea-level indicators from the South African coast and shelf. Undated former shorelines are shown as shaded blocks in their inferred chronological position (after Ramsay and Cooper (2002)).

satellite altimeter data accumulates this distortion will reduce. The second issue is the accuracy of tide gauge data. While satellite altimeter data continues to build, much can be done to improve the reliability of historical data from the existing Southern and Eastern African tide gauges. Some of this data has been set aside because of questions concerning the integrity of the data (Woodworth *et al.*, 2007) and furthermore, the reliability of the data has been influenced by the lack of tide gauge reference datum restricting the compilation of multiple year records across different datum (Woodworth *et al.*, 2007). The failure to have reliable tide gauge data in turn reduces the accuracy of satellite radar altimetry as tide gauges are the main tool used to calibrate satellite radar altimetry (Mitchum, 2000; Aman and Testut, 2003).

In the Southern and Eastern African context the gaps in data and knowledge are focused around a gauge network which is underfunded and poorly maintained (Woodworth *et al.*, 2007). In South Africa, the situation is better in that there exists a relatively good spatial distribution of tide gauge stations around the coast at most coastal cities. However, the largest current gap in knowledge is the understanding of the historical rates of sea-level rise in the region. Apart form the relative sea-level rise changes little is known about the 'eustatic' sea-level rise around the horn of Africa, which requires an understanding of many of the local physical variations along this stretch of coastline, for example Warm Agulhas currents on the east coast and cooler Benguela current on the west coast. These gaps in knowledge present the opportunity to:

(1) undertake an analysis of the available tide gauge data in this region and determine the most accurate tide gauge data and

(2) quantify the extent of sea-level change from these data. Undertaking this work will provide additional southern hemisphere sites for satellite altimetry calibration supporting the accuracy of future sea-level analysis.

Moreover, this work will expand the global database of corrected and reliable tide gauge stations enabling improved accuracy of any future global sea-level trends from tide gauge analysis.

2.3 Sea-level rise predictions

Over the past several decades, driven by the concerns about the impacts of global warming, many researchers and organisations and individuals, such as the Intergovernmental Panel on Climate Change (IPCC) and others, have sought to understand mans influence on global sea-levels (IPCC, 1990, 1996, 2001; Bindoff *et al.*, 2007). Part of this research has been focused on the current and future rate of sea-level rise (Church *et al.*, 2001). Models have been used to provide some indication of future sea-levels. The most well known models are the Coupled Global Climate Models (CGCM's) (Horton *et al.*, 2008) and the Ocean General Circulation Models (OGCM's) (Thompson *et al.*, 2008). These models provide a range of predictions based on different rates in anthropogenic processes such as CO_2 emissions. The most widely referenced predictions of sea-level rise is the work of the Intergovernmental Panel on Climate Change (IPCC) which updates this work every 4 years or so.

2.3.1 Global sea-level rise predictions

Global sea-levels are rising primarily because of an increase in the quantity of water in the oceans and thermal expansion of the ocean from increasing temperatures. These increases are due to warming (Warrick *et al.*, 1996; Bindoff and McDougall, 2000), glacier and ice sheet melt (Dyurgerov and Meier, 1997; Krabill *et al.*, 2004; Box *et al.*, 2006; Shepherd and Wingham, 2007; Oerlemans, 2007; Rignot *et al.*, 2008; Steffan *et al.*, 2008; Bahr *et al.*, 2009; Willmes *et al.*, 2009). These are mitigated by surface and ground water storage (Gornitz, 2000; Ngo-Duc *et al.*, 2005; Chao *et al.*, 2008).

sea-levels vary in time and space because of a complex variety of natural factors acting on the Earths surface (Church *et al.*, 2001; Bindoff *et al.*, 2007), including solar and lunar tides (Pugh, 2004), waves and winds (Pugh, 1987), crustal movements (Baker, 1993; Pirazzolli *et al.*, 1994; Davis and Mitrovica, 1996) and atmospheric conditions (Dickman, 1988; Hoar and Wilson, 1994; Wunsch and Stammer, 1997), Proshutinsky *et al.*, 2004), at both local and regional scales. These natural factors interact with anthropogenic factors making it difficult to predict with some degree of certainty the future sea-level at a specified location, with any degree of certainty.

Global sea-levels have been found to be rising at different rates over the last 22 000 years since the Last Glacial Maximum (Fairbanks, 1989; Harvey and Nichols, 2008; Siddall *et al.*, 2009) and are likely to increase further if temperatures continue to rise (IPCC, 2007; Rahmstorf, 2007; Siddall *et al.*, 2009). Several authors including the IPCC have developed methods to provide input into the possible amount of sea-level change that can be expected (Hunter, 2008). Church and White (2006) were the first to put forward evidence of an acceleration in global sea-levels using tide gauge data. They were able to define a quadratic equation in which the historical trend from global tide gauge records was explained. This quadratic equation was used to provide a projection of global sea-level change based on a extrapolation of the observed historical sea-level change.

Rahmstorf (2007) developed a semi empirical relationship between global temperature and global sea-level and using this relationship was able to provide future sea-levels for various temperature increase scenarios ranging from 0.5 m to 1.4 m above the 1990 levels using the IPCC 2001 results. His approach was critisied by Holgate *et al.* (2007) for data clustering and using predicted trends based on one-half of the data. Similarly Schmit *et al.* (2007) questioned the approach of Rahmstorf, particularly the issue of trend subtractions and nonsense correlations. Rahmstorf (2007b) rebuttal addressed these issues to the extent that one of the critics, S. Jevrejeva, went on to apply a similar approach (Jevrejeva, 2008). Jevrejeva *et al.* (2008a, b) utilised a longer sea-level record to that of Church and White (2006) taking the record back to 1700 AD. They determined the acceleration in sea-level change and projected a sea-level change of 34 cms for the 21^{st} Century. Two months after this was published, Jevrejeva (2008) presented her analysis of the last 2000 years of temperature and sea-level data at the European Geosciences Union annual conference in Vienna, Austria and predicted a range of 0.8 m to 1.5 m of sea-level rise by 2100.

Rahmstorf's temperature/sea-level rise relationship approach had now gained some momentum. Horton *et al.* (2008) applied Rahmstorf's approach to the latest CGCM's results (IPCC, 2007) effectively producing an update of Rahmstorf (2007). Horton and his coworkers derived projections for three of the Special Report on Emissions Scenario's (SRES) scenarios (B1, A1B and A2). Their results using the IPCC Fourth Assessment Report (FAR) show that the projections are slight less then those of Rahmstorf (2007). The results of Horton *et al.* (2008) were given for the mean and then the range across the 11 CGCM's used as follows. For the B1 scenario 0.60 m (0.54 to 0.75 m), A1B scenario 0.74 m (0.62 to 0.88 m) and A2 scenario 0.77 m (0.68 to 0.89 m) by 2100.

Rahmstorf's results were 0.70 m (B1), 0.79 m (B2), 0.84 m (A1B), 0.84 m (A1T), 0.87 m (A2) and 1.01 m (A1F1) by 2100. These results are higher than the predictions given in the IPCC FAR which could be the result of the omission of carbon-cycle feedbacks, model simulations which exclude physical processes and the historical relationship between temperature and sea-level becoming invalid as climate change alters the ice-albedo and other climate change feedbacks. Horton *et al.* (2008) conclude that perhaps other more complex semi-empirical models, including delayed sea-level response to surface air temperature forcing were required.

Siddall *et al.* (2009) approached the relationship of temperature and sea-levels by examining the relationship over the period since the Last Glacial Maximum. They proposed a hysteresis cycle of sea-levels based on the rapid historical transition of sea-levels between the Last Glacial Maximum and the interglacial periods observed by Clark and Lingle (1979), North (1984), Petit *et al.* (1999), Clark *et al.* (2004), Pollard and DeConto (2005). Historical temperature and sea-level data were combined into a heating hysteresis cycle only although the authors acknowledge that the cooling cycle is likely to be less responsive to drops in temperature because of lags in the formation of ice and will in all likelihood be a different curve.

Siddall and his coworkers, using temperature projections from the IPCC scenarios, predicted a range of sea-level rise values ranging from 0.07 to 0.82 m for the year 2100. This range is slightly wider then the IPCC (2007) predictions of 0.18 to 0.59 m but compare well with the IPCC (2007) prediction if ice melt (0.09 to 0.17 m) is included. Recent sea-levels have been tracking the upper most bands of the IPCC 2001 projections over the period 1990 to 2005 perhaps indicating that the IPCC projections are too conservative (Rahmstorf *et al.*, 2007). On the other hand recent research into the physical process of ice melt appear to limit the maximum possible ice melt, therein limiting the projected sea-level rise to less then 2 m by 2100 (Pfeffer *et al.*, 2009).

2.3.2 Southern and Eastern African sea-level rise predictions

No detailed research on the possible future range of sea-level has been undertaken to date in the region. Several authors have used estimates of possible sea-level rise in their research. Hughes (1992) used the then IPCC estimate of 1 m of sea-level rise to determine the impacts on selected locations along the South Africa coastline. Similarly, Cooper (1991, 1995 a, b) used the same estimates of potential sea-level to determine impacts and vulnerabilities of sea-level rise along the east coast of South Africa. Recently Brundrit (2008) has provided the City of Cape Town with a projected increase in sea-levels of 150 mm between 2008 and 2020.

2.3.3 Gaps in sea-level rise predictions

While much is known in the context of global sea-level rise predictions it is also clear that the range of the likely amounts of sea-level are dependent on numerous and interconnected influences. Human emissions are a key element of this uncertainty and without certainty in the likely route to be followed by individual emission reduction programs in the different countries, it is difficult to choose the most likely scenarios. Perhaps the most logical approach is to keep a range of possible scenarios in mind when considering the future state. In the Southern and Eastern African context, limited information is available on the historical trends in sea-level and no projections into the future have been attempted. The most obvious and largest gaps in knowledge on sea-level rise predictions is the lack of regional sea-level rise predictions and given the uncertainty, the range of reasonable sea-level change scenarios which should be used. This process, while difficult due to the data sparseness, is becoming an urgent priority for planning. This gap in knowledge will be addressed in Chapter 10.

2.4 Extreme wave run-up

The process involved as a wave travels from deep water inshore to the beach is complex. However, it is known that as waves approach a shoreline the waves interact with the bathymetry of the ocean floor. This can cause a change in wave direction depending on the incident wave angle to the coastline, shoaling and refraction.

Svendsen *et al.* (1978) and Short (1999) have identified four hydrodynamic sections along a sloping beach; firstly a pre-breaking or shoaling section where waves steepness increases until the wave breaks, secondly an outer surf zone where the highest waves in the distribution break, thirdly the inner surf zone section where waves transform into surges or bores and finally the wave run-up section which is of particular interest here.

A drop in water level occurs at the start of the surf zone (wave 'set-down') and rises (wave 'set-up') approaching the shoreline (Longuet-Higgins and Stewart, 1963; Bowen *et al.*, 1968; Nielsen 1988). The surf zone accounts for the majority of the wave energy loss (Stockdon, 2006). When the wave reaches the beach, the remaining energy is converted to potential energy in the form of run-up on the slope of the beach (Hunt, 1959; Stockdon *et al.*, 2006). The energy within the waves running up the beach provides the energy to rework the beach slope, erode the toe of any dunes (Ruggiero *et al.*, 2004; Sallenger, 2000) and attack any manmade structures in its path. The extent of extreme wave run-up (see Figure 2.2) is critical in determining the area of coastline that will be adversely affected by extreme wave attack, as Hughes and Brundrit (1992) have already identified this as the most vulnerable scenario.

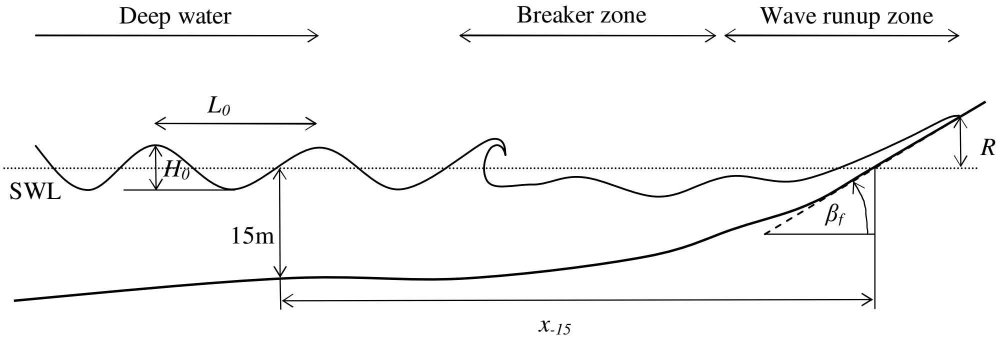

Figure 2.2: Sketch showing wave run-up on a sloping beach (Mather *et al.*, 2009).

2.4.1 Global research on wave run-up

Earlier work on wave run-up was confined to regular monochromatic waves in the laboratory (Miche, 1951). Hunt (1959), using breaking regular waves derived an empirical relationship for run-up based on beach slope, incident wave height and wave steepness. This was reworked into its non-dimensional form by Battjes (1974a) using the Iribarren number ξ_0, named by Battjes (1974b), after C.R. Iribarren (Iribarren and Nogales, 1949). Walton *et al.* (1989) modified the Hunt (1959) equation when the application was extended to steep slopes (slopes 1/10 to vertical) by replacing tan β with sin β in the Iribarren number ξ_0. The Walton *et al.* (1989) formula, often referred to as the modified Hunt formula, was verified by laboratory data from the studies of Saville (1956) and Savage (1958).

Mase (1989) produced predictive equations based on laboratory results for irregular run-up on smooth, plane, impermeable, continuous and gentle slopes ranging from 1/5 (11.3°) to 1/30 (1.9°). These equations provided run-up elevations based on varying amounts of statistical exceedance i.e. run-up exceeded by 2% of the run-up crests. Hedges and Mase (2004) revised Hunt's equation further by incorporating wave set-up into the original equation. Analysis of irregular wave run-up on natural beaches was undertaken by Holman and Sallenger (1985), who analysed 154 wave run-up time series and found that the wave run-up R was proportional to the Iribarren number ξ_0.

Holman (1986), using the data gathered from the CERC Field Research Facility at Duck, USA for deep water waves ranging between 0.4 and 4.0 m with wave periods between 6 and 16 seconds, was able to provide the relationship between $R_{2\%}$ wave run-up heights $R_{2\%}$, offshore wave height H_s and the Iribarren number ξ_0. Douglass (1992) analysed Holman's (1986) field measurements and decided that the beach slope was not an important parameter in predicting wave run-up on natural beaches. Douglass (1992) eliminated beach slope from the relationship giving maximum wave run-up R_{max} to be dependent on the offshore wave height and peak spectral period T_p.

Nielsen and Hanslow (1991) undertook field studies along the Australian coastline on beaches with irregular waves where the significant wave height varied between 0.53 and 3.76 m, wave periods between 6.4 to 11.5 seconds, beach slopes varying between 0.02 and 0.19 and beach sand grain size d_{50} between 0.18 and 0.8 mm. Their study concluded that wave run-up $R_{2\%} = cL_{zwm}$ where c is an empirical factor.

Hughes (2004), working with wave momentum flux parameters derived a relationship for maximum wave run-up using the depth integrated wave momentum flux across a unit area and the beach slope β_f. This equation has application only to offshore breakwaters where the structure is out of the breaker zone (Hughes pers. comm). Stockdon *et al.* (2006) examined data from beaches in the USA and the Netherlands and derived their formula for the elevation of the 2% exceedance run-up level $R_{2\%}$ as being dependent on wave height H_0, wave length L_0 and beach slope β_f.

As shown above predictive models of wave run-up have traditionally focused on the beach foreshore slope β_f as the key determinant of wave run-up R in studies using regular waves (Mishe,1951; Hunt, 1959; Battjes, 1974b; Waldon *et al.*, 1989; Mase, 1989 and Hedges and Mase, 2004) and irregular waves (Holman and Sallenger, 1985; Guza and Thornton, 1989; Nielsen and Hanslow, 1991; Ahrens and Seeling, 1996; Sallenger, 2000; Hughes, 2004 and Stockdon *et al.*, 2006). The only exception has been the work put forward by Douglass (1992) who used the wave height H_0 and wave length L_0 to determine wave run-up.

2.4.2 Southern and Eastern African research on wave run-up

To date there has not been any published literature on wave run-up published in the Southern and Eastern African region.

2.4.3 Gaps in research on wave run-up

Two obvious gaps in knowledge exist in research on normal and extreme wave run-up. Firstly almost all the global wave run-up models have been developed for wave heights not exceeding 4 m. No researcher has to date considered extreme wave run-up for wave heights in the 8 to 10 m range. This is surprising given the large wave conditions often experienced at several other locations around the world, including Southern and Eastern Africa. Secondly, this provides an opportunity to test the international models in the Southern and Eastern African context and to determine a suitable model for use within the region. This model is the first step in determining the risk or hazard zone, which will inform better management of the shoreline. This will be explored in Chapter 7.

2.5 Beach response

Beach response under rising sea-levels is a hotly debated subject (Fitzgerald *et al.*, 2008) which is neatly summarised by the IPCC (2001) in their Working Group II-Impacts, Adaption and Vulnerability, (Chapter 6, pg 357) who noted that:-

> *"Previous discussions of shoreline response to climate change have considered the well-known simple relations between sea-level rise and shoreline retreat of Bruun (1962). This two-dimensional model assumes maintenance of an equilibrium nearshore profile in the cross-shore direction as sea-level rises. Some papers have supported this approach for long-term shoreline adjustment (Mimura and Nobuoka, 1996; Leatherman et al., 2000); others have suggested various refinements (Komar, 1983, 1998a). Although the model's basic assumptions are rarely satisfied in the real world (Bruun, 1988; Eitner, 1996; Trenhaile, 1997), its heuristic appeal and simplicity have led to extensive use in coastal vulnerability assessments for estimating shoreline retreat under rising sea-levels, with varying degrees of qualification (Richmond et al., 1997; Lanfredi et al., 1998; Stewart et al., 1998). Erroneous results can be expected in many situations, particularly where equilibrium profile development is inhibited, such as by the presence of reefs or rock outcrops in the nearshore (Riggs et al., 1995). Moreover, Kaplin and Selivanov (1995) have argued that the applicability of the Bruun Rule, based on an equilibrium approach, will diminish under possible future acceleration of sea-level rise "*
>
> (IPCC 2001)

One of the main issues raised is the concerns about questionable results when the

Bruun's model is used in areas which are not able to adjust naturally to their equilibrium profile, or where reefs and rocky outcrops interfere with a normal sandy beach response. One of the features of the Southern and Eastern African coastline is the long stretches of sand beaches backed by relatively intact sandy dune cordons. Whilst there are rocky areas these are limited in extent and there is no intention to run the Bruun's model at these rocky locations. Beach response to wave run up is also an issue particularly if the incidence of large wave events are realized. These wave events with their increased energy is likely to reduce the width of sandy beaches over time in conjunction with beach retreat associated with raising sea levels given all other influences and factors remain constant.

2.5.1 Global beach response research

Beach research can be traced back to the studies of Cornaglia (1889) but the first major text on shoreline development amongst other subjects was that by Johnson (1919). In England, Ward (1922) and Steers (1964, 1973) published research on beaches. Shepard (1948, 1963) continued this work supported by the research of Guilcher (1958) and Williams (1960). King (1972) published the first dedicated text on beaches, which importantly covered the processes of beach and coastal development at geomorphological and geological scale. These were followed by major texts written by Bascom (1964), Wiegel (1964), Zenkovich (1967) Fairbridge (1968) and Bird (1968). Into the 1970's two complimentary studies by Meyer (1972), who focused on the mathematical approach to understanding wave processes and Komar (1976), who focused on understanding beach processes. Schwartz (1982) published the first encyclopedia on beaches and this was followed by several texts on the dynamic and changing nature of beaches by Kaufman and Pilkey (1979), Neal *et al.* (1984), Carter (1988) and Pilkey and Dixon (1996) to name a few.

The 1980 to 1990 period saw an increase in research (Bird, 1979, 1981, 1983, 1985; Bird and Paskoff, 1979) with some specialisation in the beach morphodynamics field with specialisation in research into specific geographical areas (McCann, 1980; Thom, 1984; Short,1993, 1996), on coastal geomorphology (Pethick,1984; Hardistry, 1990), coastal management (Nordstrom, 1992; Bird, 1996; Clark, 1997) and beach ecology (McLachlan, 1983; Brown and McLachlan, 1990). Despite this research, the response of the beach shoreface is not well understood. Some authors question whether the concept of equilibrium profiles is valid (Pilkey *et al.*, 1993) while others support this concept (Moore,1982). Shoreface changes take place over a range of time scales ranging from days to millennia. This has lead to ambiguity in the science of shorefaces as to date no systematic approach has been adopted (Short, 1999). In understanding the shoreface behaviour, a time horizon of several decades is required. This time horizon has been formally termed Large Scale Coastal Behaviour (LSCB) (Terwindt and Battjes,1991; De Vriend, 1991, 1992 a, b; Cowell and Thom,1994).

LSCB has used the concept of shoreface translation in response to sea-level rise (Bruun, 1954, 1962, 1983, 1988; Carter 1988) and/or sediment changes (Curray, 1964; Hands, 1983; Everts, 1987; Niedorada *et al.*, 1985; Swift *et al.*, 1991 and Dubois,1995, 1997). A fair degree of criticism has been leveled against the shoreface translation concept because of the 'depth of closure' concept. Depth of closure is defined as the depth at which a set amount or less is observed between successive profiles. Bruun (1962) used 0.2 m while Hallermeier (1981) used 0.3 m. This depth of closure varies with the duration between successive profiles i.e. annual cutoff depths are deeper then quarterly cutoff depths (Niedoroda *et al.*, 1985).

Stive and De Vriend (1995) described this upper shoreface as the 'active zone' signaling that this area was the most mobile. Predictions of the shape and form of the shoreface and the processes involved in the shaping of this profile has interested many researchers, for example Bascom (1951, 1954), Inman and Bagnold (1963), Goodnight and Russell (1963), Kemp and Plinstone (1968), McClean and Kirk (1969), Goda (1974), Sunamura (1984), Sallenger and Holman (1985), Hughes and Borgman, (1987), Dean (1987, 1990), Dean (1977), Work and Dean (1991), Dean (1991), Komar and McDougal (1994), Hardisty (1994), Raubenheimer and Guza (1996), Sorensen (1997), Cowell *et al.* (1999), Larson *et al.* (1999), Leatherman *et al.* (1997), Dubois (2001), Reeve, Chadwick and Fleming (2004). The focus of this research is on the upper shoreface regressing inland under rising sea-levels.

Despite the concerns by some researchers that the beach response cannot be modeled statistically, for example (Pilkey and Cooper, 2006) and should be modeled qualitatively (Cooper and Pilkey, 2004), Cooper (pers. comm. 2009) has accepted that the range of alternative approaches are limited. Adding to these uncertainties in modeling are the uncertainties of the climate change predictions (Reilly *et al.*, 2007). This has lead to heated debate around the accuracy of the predicted shoreline changes (Cowell and Thom, 2006; Cowell *et al.*, 2006; Pilkey and Cooper, 2006; Cooper and Pilkey, 2007) and the inability of the model to explain the past responses (List *et al.*, 1997). The Bruun model is based on a set of assumptions which are difficult to justify in most situations and as a result there are inherent uncertainties in the results. Despite this and recognizing the limitations, the Bruun rule will be used in the analysis in this thesis, since this will provide a first order approximation of shoreline retreat sufficient to determine associated impacts.

2.5.2 Southern and Eastern African beach response

No research on beach response models has taken place in Southern and Eastern Africa. However, some work has been done on developing an index to assess South Africa's vulnerability to sea-level rise (Hughes and Brundrit, 1992). Hughes and Brundrit (1990), Hughes (1991, 1992), Hughes *et al.* (1993) applied this to selected areas along the South African coast and used the Bruun rule to regress the shoreline. This work is now dated and was limited to specific location along the coast. Theron (1994) reviewed sea-level rise impacts and the use of the Bruun rule and followed this up with research on the analysis of potential impacts in the Southern African region (Theron, 2007). This study was undertaken at a country level and was understandably constrained by the lack of in depth case studies.

Over the last three years, several studies into the impacts of sea-level rise are underway or have been undertaken in the region. Harris (2008) examined the impacts of sea-level rise and storms on the beach ecology along the KwaZulu-Natal coast of South Africa. The City of Cape Town initiated a series of studies into sea-level rise impacts for their coastline (Brundrit, 2008; Fairhurst, 2008 and Cartwright, 2008). Work on sea-level rise impacts has commenced in Namibia and Mozambique (Theron, pers comm. 2009). Several other municipalities are considering similar projects.

2.5.3 Gaps in Southern and Eastern African beach response research

While there is work underway in the region, the approach adopted varies between the researchers. Each researcher favours a different methodology using different combinations of sea-level rise and storm impacts. There is a need to adopt a uniform approach to modeling sea-level rise impacts so that comparable evaluations at regional and national scales can be undertaken. This gap in knowledge is an opportunity to provide specific research into developing a comparative evaluation of the risks and vulnerability for the entire region. This is an important element given the scare resources available competing for allocation. From this, a cogent adaptation plan can be developed by each municipality to implement.

In order to achieve this an approach which will be able to predict the range of sea-level rise and coastal storm impacts with the minimum amount of data collection and consulting time is clearly the goal. Not only must it be easy to undertake but it must also be easy to replicate across the region and to train others to undertake the roll out of the methodology. This is discussed in detail in Chapter 10.

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Epilogue to Chapter 2

The review of the literature has found that there is a significant amount of research at a global level in all areas of sea level rise, sea level projections, wave run-up and beach response. What is very clear is that when it comes to the Southern and Eastern African research the gaps in research are significant. Research on sea level rise in South African is now over 20 years old and did not provide a full coverage of the coastline, while the rest of the region is virtually unresearched. There are many authors working on global sea level rise projections using a variety of different methods however little work has been done in the study area. Similarly the research on beach responses is well represented at the global level by work in first world countries but completely absent from the African continent.

Prologue to Chapter 3

This Chapter sets out the data and research methodology that will be used in this thesis. The Chapter discusses the data that will be collected and used in this study. A number of different data sets had to be accessed to provide the input information for the research Chapters 4 to 10.

Chapter 3

DATA AND RESEARCH METHODOLOGY

3.1 Introduction and Research Methodology

Climate change has become one of the biggest challenges for modern society in recent times. A large amount of research is directed towards understanding the extent of anthropogenic influences on our climate by many research organisations around the world. Of particular relevance here is the impact that rising sea-levels will have on the coastline and specifically what this could mean for the Southern African coastline. It was previously noted that little local research into the effects of sea-level change has been undertaken to date in this region and this research has been structured to begin to address this shortfall. The proposed thesis is to address a series of research questions which will provide new knowledge which can be applied in the global coastal planning, management and engineering fields but more especially in this region.

sea-levels are subject to a range of forcing which have effects ranging from minutes to several decades. Gravitational effects from the moon and sun provide a diurnal tide range, which is modified by local effects such as wind, barometric pressure, storm surge and the bathymetry of the near shore area. The majority of these influences can to some extent be effectively removed from the record by using long term data. If there are trends in some variables such as barometric pressure and land movements these will still be evident in the data trends. These will need to be removed to determine the underlying 'eustatic' sea-level trends. Storm wave run-up has been a major contributor to the erosion of sandy shorelines. The amount of wave run-up is determined by the amount of energy available in the wave when it reaches the shoreline. This concept will be explored later in the form of a new wave run-up model based on the bathymetric profile of the coastline.

3.2 Data

In this section, data used in this study are outlined, together with a brief discussion of the methodologies used to describe the characteristics of the data. Data used in this thesis was collected from a variety of published and unpublished sources within South Africa and internationally.

3.2.1 Sea-level data

sea-level data are recorded at most coastal cities and ports in the region. While there is a single tide gauge at each location, various versions of these data were available. For this study these data were sourced from the three known sources. The first source of sea-level data is held by the South African Navys Hydrographic office based in Simons Town, South Africa. They are responsible for the collection, analysis and distribution of these sea-level data and predicted tide levels for the South African tide gauge network. They were also responsible for the Namibian tide gauge network until 1998. The South African Navy makes their data available on request.

The second source of sea-level data is held by the Permanent Service for Mean Sea Level (PSMSL) based in Liverpool, United Kingdom. They are responsible for the collection, publication, analysis and interpretation of sea-level data from almost 2000 tide gauge stations from around the world, including most of the tide gauge sites in this region. The PSMSL receives these tide gauge data from the respective national authorities in each country. The PSMSL keeps two types of tide gauge data. The PSMSL 'Metric' (or total) data which consists of monthly and annual means from each station-year is recorded against a common datum. The metric data however does not necessarily correct for datum differences between consecutive station-years. The other type of sea-level data held by the PSMSL is the 'Revised Local Reference'or ' RLR'data. These data are also available as monthly and annual means. These data has been analysed by the PSMSL after receipt from the national authorities and can be used for the basis of analyses of secular changes in sea-level as datum changes have been removed and all years are set to a single datum. The PSMSL make these data available through the Proudman Oceanographic Laboratory website www.pol.ac.uk.

The third source of sea-level data is held by the British Oceanographic Data Centre (BODC) based in Liverpool, United Kingdom. The South African Navy tide gauge data, obtained by the University of Cape Town was passed on to the University of Hawaii as part of the Joint Archive for Sea Level (JASL), which comprises of the Tropical Ocean Global Atmosphere (TOGA) and the National Oceanographic Data Centre (NODC). Thereafter these data were passed on to the BODC. During this process additional analysis is undertaken prior to publication by the BODC. After 1987 the South African Navy has supplied these data directly to the BODC. These data is available as mean hourly tide levels. The BODC makes data available through their website www.bodc.ac.uk.

The instrument types used to collect these tide data have been float and stilling well gauges, SRD acoustic tide gauges and more recently some of these sites have been upgraded to Kalesto radar gauges. The South African Navy intends replacing all existing tide gauges with the Kalesto radar gauge as finances permit. This will enable fast and more accurate data collection and analysis without extensive human data correction needed. The maintenance of the tide gauges are the responsibility of the national authorities. sea-level data was obtained from the BODC and the South African Navy as hourly means while the PSMSL data, in the RLR format, was obtained as monthly and annual means.

The South African sea-level data will be assessed for difference between the three data sets with the view to determining which these data can be used with confidence to determine long term trends. The first operation was to calculate the mean monthly sea-levels for the SAN and BODC data. The first step was to eliminate each incomplete day of these data from the analysis as proposed by Pugh (1987). Failure to remove this will bias the data as incomplete tide cycles will remain in the data.

The next step was to calculate the mean monthly and mean annual sea-levels for the SAN and BODC. Once this was completed the comparisons between the SAN, BODC and PSMSL can be undertaken. This process of data comparisons highlighted the differences between each and through this process enabled some corrections to be applied to these data. The final stage was to compute linear and non-linear trends using these acceptable data. This is dealt with in much greater detail in Chapters 4 and 5. The rest of the region outside of South africa and Namibia has very little data but what data exists was made available on the PSMSL website. The analysis of these data was undertaken in Chapter 6.

3.2.2 Barometric pressure data

Barometric pressure data for the South African and Namibian stations are available from the South African Weather Office. Data is recorded at Automatic Weather Stations (AWS) mainly located at airport sites. The data is available as hourly means, minimums, maximums and daily means. The data is available on request. Data from 1970 to 2008 was obtained for use in this study. Barometric pressure data, combined with sea-level data, was used to determine the ‘proxy inverted barometer’ relationship between these two data. This relationship will be used to correct the sea-level trends by the removal of the barometric pressure trends form the individual stations. This analysis will be undertaken using monthly and annual means.

3.2.3 Wave data

Wave climate data for the South African ports is available from the Council for Scientific and Industrial Research (CSIR) based in Stellenbosch, South Africa. This data is collected, analysised and interpreted by the CSIR on behalf of the Transnet National Ports Authority (TNPA). The data is available in various time formats and is available on request. The data is collected using both Acoustic Doppler Current Profilers (ADCP) and wave rider buoys. Fetch length were determined from naval charts and using typical cyclone wind speed the fetch and duration limited wave heights were determined for the coastline in question. Voluntary Observing Ships (VOS) wave data is obtainable from the Ship Observations Team (SOT) of the Joint World Meteorological Organisation (WMO)/ Intergovernmental Oceanographic Commission (IOC) Technical Commission for Oceanography and Marine Meteorology (JCOMM) at www.bom.gov.au/jcomm/vos/ and this data was used to validate extreme wave heights calculated around the Southern and Eastern African coastline. The offshore wave heights were used as input in the hazard model developed in Chapter 10.

3.2.4 Wave run-up data

Wave run-up swash/debris mark data was collected using two methods:

(1) wave run-up heights indicated by debris washed up the beach were measured in the field using land surveyors at selected locations and

(2) the use of aerial photography to identify the position of the beach scarp position and using a Digital Terrain Model converting these positions to heights above mean sea-level.

The levels were obtained by the surveyors using theodolites to an accuracy of 0.001 m. Wave run-up marks where collected only along the South African coastline for logistical reasons. The areas where data was collected was along the eThekwini and Kwadukuza Municipality coastline after the March 2007 storm event and for the Cape Town Metropolitan coastline after the September 2008 storm event. These wave run-up data where provided in a WGS84 projection for analysis and importation into GIS. Wave runup data was to be analysed for different types and slopes of the coastline and near shore. These were used as input into the wave run-up model developed in Chapter 7.

3.2.5 Beach slope data

Beach slopes data was confined to the South African coastline and were measured using both ground surveys and aerial photography analysis. Beach slopes were analysed for different types and slopes of the visible beach to determine the wave run-up predicted by current wave run-up models. These will be used as input into the wave run-up model developed in Chapter 7.

3.2.6 Vertical crustal movement data

Vertical crustal movements are to be obtained from three sources. The Peltier ICE-5G model results which can be downloaded from the PSMSL website (www.pol.ac.uk) for both the VM2 and VM4 models. At some of the South African tide gauge sites the Hartebeesthoek Radio Astronomy Observatory (HartRAU) near Pretoria has installed Global Positioning System (GPS) receivers which receive satellite signals from a constellation of twenty-four satellites. Data of daily receiver positions in the x, y and z planes are available on request and summaries/trends are available on the NASA Jet propulsion Laboratory web site http://slideshow.jpl.nasa.gov/mbh/series.html. The third source of data is held by Systeme D'Observation du Niveau des Eaux Littorales (SONEL) and was downloaded from their web site at www.sonel.org. The SONEL data was available for the Eastern African region.

Ground movements can be used to remove the land movement from the sea-level change trend to compare relative sea-level and eustatic sea-level changes.. The vertical movement was simply be deducted from the sea-level trends to determine a value for the sea-level change relative to the geoid. This will also be used to compare local results with sea-level trends from global satellite observations in Chapter 4, 5 and 6.

3.2.7 Aerial photography

Aerial photography was used in the wave run-up model development and in the hazard model in Chapters 7 and 10. Aerial photography which has been rectified and geo-referenced was obtained for selected locations in the study area. There are several available sources, the Surveyor General office in Pietermaritzburg, KwaZulu-Natal, various air survey companies based in South Africa and the local municipalities. The most accurate and recently flown aerial photography for the KwaZulu-Natal province is held by the Oceanographic Research Institute on behalf of the province and that held by the eThekwini Municipality in Durban for their coastline. The eThekwini Municipality coastal aerial photography has been flown at a high resolution every year since 2006. This series of high resolution photography is imminent suitable for analysis using aerial photography techniques. Aerial photography was obtained from the eThekwini Municipality and imported into a Geographical Information System.

3.2.8 Bathymetry data

Bathymetry profiles were obtained from Admiralty/Naval charts produced by the national authorities. The South African Navy‘s Hydrographic Office surveys, charts and produces a comprehensive range of charts for the South African coastline. These are easily obtainable from local yachting supply companies. Naval charts were obtained for the areas of interest and the -15m contour was digitised from the paper prints and warped to compensate for any paper shrinkage against a number of other fixed and known topographic features and land survey points on the mapping. These were then imported into a Geographical Information System as a shape file. This was used in Chapter 7 in which a new wave run-up model was developed as well as Chapter 10 which address the extent of wave run-up hazards now and with future sea-level rise.

3.2.9 State of municipal readyness data

The approach taken here was to conduct a survey questionnaire of different groups working in the coastal management field. The scope was limited to South Africa for logistical reasons but as one of the more developed countries in the region arguably it would reflect the most aware and proactive countries. The different groups can be segmented into those in government, which can be further split into those who work for national, provincial and local government. The next group is those who work for non-governmental bodies and consultants. These were chosen as they are familiar with the capacity or lack thereof of municipal government to respond. Members of the general public were excluded from the survey as it was felt that they are unlikely to know the specific details of what government is undertaking.

Each respondent was emailed a set of questions with simple yes/no/don't know answers. Individual responses will be recorded under their specific grouping. The distribution of returns from this survey was heavily biased towards the municipal and non-governmental/consultant groups. Only 3 out of the thirty-one returns were from provincial government and a nil return was received from the national government level. This may be a reflection of the number of people working at the different levels. South Africa has thirty-nine coastal local authorities, 4 coastal provinces and a single national department. The majority of the samples were from individuals working at the local level on coastal management issues and it is accepted that they have a good understanding of the issues facing local municipal government. The results of this analysis are detailed in Chapter 9.

3.3 Data limitations

Generally, the data obtained was of an acceptable standard for this research without significant pre and post analysis. The only exception to this was the tide gauge data, which appears to have problems with reliability and accuracy. The reason for the inaccuracy is detailed as follows. The South African Navy installed 'float actuated Kent' type gauges as early as 1958. By the middle of the 1980's the installed Tide gauge network was overdue for complete replacement. In conjunction with the Council for Scientific and Industrial Research (CSIR), a modern acoustic type gauge was developed and deployed in 1990. Eight gauges were deployed in South Africa and Namibia and unfortunately were a complete failure. These gauges were erratic, extremely difficult to tune and were grossly inaccurate resulting in the fact that most data collected over this period was unusable.

These gauges were finally abandoned between 1996 and 1998. Replacement gauges of the SRD type were installed in 1996 but these too were found to be unsatisfactory and after additional work and modifications the data only just achieved an acceptable standard. In parallel the South African Navy have installed Kalesto radar tide gauges and are in the process of rolling this out to all tide gauge location as funds permit. The installed Kalesto tide gauges have performed well to date. With these data limitation in mind the analysis of tide gauge data needs to be done carefully given that there are periods of questionable data which if not properly dealt with could distort the results. Little is known about the other tide gauge stations in the region however as the PSMSL undertakes additional control checks to data supplied by the respective countries it was assumed that if the PSMSL RLR database was used for this study then the data can be assumed to be reasonably reliable.

3.4 Summary

This Chapter builds on the literature review in that it outlines the data requirements for the study, the sources of the data and the proposed analysis, which was used for these data. This sets the scene for the detailed analyses that address the research questions posed at the beginning of this thesis.

Epilogue to Chapter 3

The various data sets required for this study have been discussed and the limitations of the data highlighted where it was a known issue. In the next Chapter the first of the regions tide gauges that of Durban will be examined.

The records of tidal observations from Durban, South Africa are examined for accuracy for use in design calculations and other long-term trend analysis such as sea-level rise. Tidal datasets for Durban were accessed from the South African Navy's Hydrographical Office, the British Oceanographic Data Centre and the Permanent Service for Mean Sea Level. This investigation yielded several anomalies and errors in all the datasets, which would significantly affect their validity in subsequent analyses. The anomalies are identified and a recommendation is given to address them. A set of revised tidal data are proposed, which can be used with better confidence in tidal calculations and in predicting longer-term trends for Durban tide levels.

Prologue to Chapter 4

The first step in understanding sea-level change is to analyse the existing tide gauges in the region. The east coast of South Africa has had little recent sea-level research undertaken so the first location chosen was Durban as the largest port city on the east coast. Previous research by Cooper (1991) quoting Hughes (pers. comm.) had indicated no significant trends in sea-level. Cooper (1991) noted that the lack of an upward trend could be due to possible instrument error, land movement and/or other factors which he was not able to determine at the time. More recent work by the CSIR (2006) as part of research into climate change for the eThekwini Municipality found an upward trend of +4.5 mm per year.

Given this large discrepancy in sea-level trends what was needed was a determination of the most accurate evaluation of the tidal data and the determination of recent historical sea-level changes at Durban. The purpose of Chapter 4 is then to analyse the tidal records for Durban with the aim of determining the most accurate measurements of sea-level change. This chapter will then start to address the thesis questions of whether sea-level has been changing along the south east coast of Africa and to determine the rate and direction of sea-level change. The first part of Chapter 4 deals with the data evaluation of the different data available for Durban, the data errors and corrections required and lastly to produce a revised and corrected tide record for Durban which can be confidently used for planning and design purposes. The second part of Chapter 4 deals with the analysis of this revised data set and the determination of linear and nonlinear sea-level trends.

This Chapter includes the thematically linked, published journal paper, which appeared as a peer reviewed research letter titled:

Mather, A.A. 2007. Linear and nonlinear sea-level changes at Durban, South Africa, *South African Journal of Science*, 103, Vol. 11/12, November/December 2007, 509-512.

The original journal publication has been reproduced in full with the permission of the Editor of the South African Journal of Science. The original journal publication is included in the Appendix.

Chapter 4

DURBAN TIDE GAUGE ANALYSIS

4.1 Rising or falling sea levels: Durban's tidal record examined

4.1.1 Introduction

4.1.1.1 The need for accurate tidal records

The importance of a reliable and complete tidal record is critical for a variety of purposes. Coastal and port engineers desire a correct record of tide influences in order to provide the proper selection of design criteria for maritime structures and port infrastructure. Coastal managers and planners need a dependable record to define areas that require special zonation and/or special building controls. These include the demarcation of the High Water Mark, which is now required in terms of the Environmental Impact Assessment Regulations 2006, potential erosion areas, and development set back lines along the coastline. Coastal policy makers and planners require a tide dataset that can be analysed to provide trends for the prediction of sea level change in the region. In the light of concerns about global climate change, tidal records are becoming important indicators in monitoring the impacts of climate change around the world and can provide vital information to researchers in their efforts to assess the rate of change, the likely impacts of these changes and to give valuable input into future predictions (Proshutinsky *et al.*, 2001). An accurate tidal record is of great importance in this field of work as changes are normally in the order of millimeters per year (Pugh, 1987).

4.1.1.2 Predicting sea level change from tidal gauge records

Prediction of sea level change by Douglas (1991) from tide gauges around the world, using a record period of at least 50 years, showed that half recorded rising sea levels and half showing receding sea levels. Most of the worlds tide gauges are located at the edge of continental plates, on river deltas or along coasts that are subject to post glacial rebound. This makes it difficult to isolate the relative sea-level change, although several authors have attempted to do so. Emery and Aubrey (1991) evaluated 587 gauges longer than 10 years from around the world and identified only 36 gauge records as originating from stable coastlines, of which three where from the south-western coast of South Africa. However no records of significant length were from the east coast of South Africa, even though it may be considered as geologically stable.

4.1.2 Aims and Objectives of the study

This Chapter describes an analysis and some noteworthy observations of the tidal record for Durban, South Africa. The South African Navy's Hydrographic Office has been recording tide data for all major South African ports including Durban. For Durban, the unprocessed data, in the form of hourly recordings measured in Chart Datum (CD) (Table 4.1 and Table 4.2) from a single tidal gauge between 1970 and 2003, was processed by three different organisations, namely the British Oceanographic Data Centre (BODC), the South African Navys Hydrographic Office, and the Permanent Service for Mean Sea Level (PMSL), the latter two sets being identical.

BODC publishes tide gauge data received from the University of Hawaii after re-analysis of the original Durban data received from the University of Cape Town. All these organisations make the processed data available for planning and research organisations and it is these data sets, which form the basis for this paper. All the Durban datasets contain gaps and in some instances have complete years missing. Although the published data sets are drawn from the same unprocessed gauge records, they contain clear differences. The objectives of this study are to analyse and evaluate the accuracy of the Durban tide record, to correct wherever errors in data have occurred and to produce a corrected and definitive tidal record, which can be used with confidence in determining sea level changes.

4.1.3 Materials and methods

Analysis of a single 35-year dataset with readings taken every hour equates to a considerable amount of data, which needs careful evaluation. The Intergovernmental Oceanographic Commission (1985) provides several methods for analyzing such data, which are briefly discussed below.

4.1.3.1 Arithmetic mean values

This approach is to simply average all the month records to produce a value for that month. This applies only when there are no gaps in the data. If this is applied

Table 4.1: Schedule of South African Navy tidal data set for Durban.

Year	**Period of data**
1970	30 September to 31 December
1971	1 January to 31 December
1972	1 January to 31 December
1973	1 January to 31 December
1974	1 January to 30 December
1975	27 January to 31 December
1976	1 January to 13 December
1977	3 January to 31 December
1978	1 January to 31 December
1979	1 January to 31 December
1980	1 January to 31 December
1981	1 January to 31 December
1982	1 January to 31 December
1983	1 January to 31 December
1984	1 January to 23 December
1985	16 July to 31 December
1986	1 January to 30 December
1987	6 January to 31 December
1988	1 January to 31 December
1989	3 January to 31 December
1990	1 January to 31 December
1991	1 January to 31 December
1992	1 January to 31 December
1993	1 January to 31 December
1994	1 January to 31 December
1995	9 January to 31 December
1996	2 January to 19 December
1997	22 May to 31 December
1998	No data
1999	No data
2000	No data
2001	No data
2002	No data
2003	No data
2004	No data
2005	No data
2006	No data

Table 4.2: Schedule of BODC data.

Year	**Period of data**
1970	1 October to 31 December
1971	1 January to 31 December
1972	1 January to 31 December
1973	1 January to 31 December
1974	1 January to 28 December
1975	27 January to 31 December
1976	1 January to 15 December
1977	3 January to 31 December
1978	1 January to 31 December
1979	1 January to 31 December
1980	1 January to 31 December
1981	1 January to 31 December
1982	1 January to 31 December
1983	1 January to 31 December
1984	1 January to 31 December
1985	No data
1986	1 January to 30 December
1987	6 January to 31 December
1988	1 January to 20 December
1989	3 January to 31 December
1990	No data
1991	1 January to 31 December
1992	1 January to 20 December
1993	1 January to 19 February
1994	1 January to 23 December
1995	9 January to 31 December
1996	2 January to 19 December
1997	22 April to 31 December
1998	No data
1999	No data
2000	14 February to 13 November
2001	11 February to 31 December
2002	1 January to 31 December
2003	1 January to 31 December
2004	No data
2005	No data
2006	No data

to data with gaps the incomplete tidal cycles in the record biases the data. This method has limited applicability given the data gaps in the Durban record and is not considered in further analyses.

Another approach (Pugh, 1987) is a modified form of the above, which entails the following steps:

(i) For any day that has incomplete hourly data records, the days recordings are removed from the data calculations ;

(ii) For each month (less the days eliminated above), a mean monthly tidal level value is calculated, eliminating the effect of low and high tides.

4.1.3.2 Low-pass filtered mean values

In order to eliminate the tidal aliasing inherent in the arithmetic mean value approach, the application of a low-pass filter can be applied which gives a smoothed daily noon value, which can then be averaged out over the month in question. There are several filters available designed for this purpose such as the Doodson filters, which uses 19, 72 and 168 hour periods (Doodson and Warburg, 1941). Tidal filters are discussed in detail by Godin (1972), Thompson (1983) and Dijkzeul (1984).

Because of the simplicity and ease of application the arithmetic method was chosen here. It is important to note that, whereas the approach may seem to be simplistic it has been shown to provide a good correlation with more sophisticated analysis when used to provide weighted mean monthly values to calculate annual values (Pugh, 1987). To quote from Pugh (1987) on the accuracy

"This method is used by many authorities because it requires little mathematical insight, yet produces values close to that obtained by more elaborate tide-elimination techniques (Rossiter, 1958). The maximum contribution, due to aliasing of tidal changes, to a 30-day monthly mean-sea level is 0.055 per cent of the M_2 *amplitude, 0.267 per cent of the* K_1 *amplitude, and 0.401 per cent of the* O_1 *amplitude. Over a 365-day year the maximum* M_2 *error is 0.035 per cent. The* S_2 *component will of course average to zero over any period of complete day's".*

Where M_2 is the principal semidiurnal lunar tide component, K_1 is the principal solar and lunar declination component, O_1 is the principal lunar declination component and S_2 is the principal semidiurnal solar tide component in the tide harmonic equation.

Recorded tide data is most often measured against a Chart Datum by marine surveyors, which simply put is where the zero datum (Vertical axis = 0 m) is equal to the lowest possible tide level (often referred to as the Lowest Astronomical Tide (LAT) which occurs once every 18,6 years) (South African Navy 2006). To correct this to a datum which can be used by land surveyors it is necessary to correct these tide recordings to the corresponding Land Leveling Datum (LLD) and confusingly referred to as Mean Sea Level (MSL)). These conversions are calculated and published by the Hydrographic Office of the South African Navy.

4.1.4 Results

The tidal record for Durban provided by the South African Navy (SAN), after its data screening process, was examined for each year. The record was converted from Chart Datum to Mean Sea Level using the published offsets and then mean monthly values of tide levels were calculated (Figure 4.1).

Evident from the time series are four distinctly different sections in the tidal record. From 1970 to the end of 1991, the profile is typical, containing a seasonal and interannual signal, but confined to a band of about 300 mm between mean monthly maxima and minima.

The second period, between the beginning of 1992 and the mid-2002, is characterised by a sudden drop in mean levels, which then over the period between middle of 1992 rises rapidly at about 0.5 m per decade to a maximum mean level in the middle of 2002.

The third period is between the middle of 2002 and the beginning of 2003, which shows a similar steep drop.

The fourth period from the start of 2003, is comparable with the first period (1970-1991). This apparent shift in the centre of the record between 1992 and 2002 suggests that the Tidal Datum has shifted or that calculation errors had entered the tidal records.

To further examine these differences in the SAN dataset the BODC tidal record for Durban was accessed to ascertain the extent of these differences. It is important to note that, where there is only one set of original data from the tide gauge in Durban, the BODC reanalyses this data using its own resources and produces a second data set for Durban. The same method used by as Pugh (1987) was then applied to the BODC dataset and is shown in Figure 4.2.

The BODC data varies from the SAN data and contains six distinctly different sections. From 1970 to the mid-1987, there is a fairly typical profile, which contains an expected seasonal and interannual signal that is confined to a band of about 300 mm between mean monthly maxima and minima. The second period, between the middle of 1987 and the end of 1987, is characterised by a sudden drop in mean levels. The third period, between 1988 and mid-1992, is characterised by a typical tidal

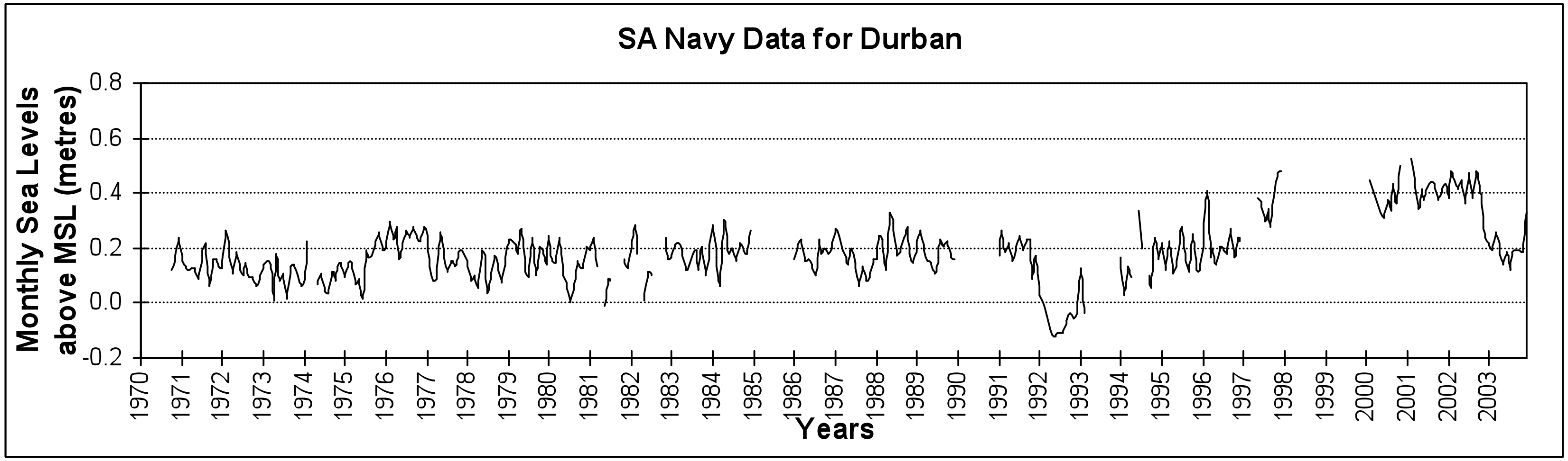

Figure 4.1: Mean monthly tide values for Durban using SA Navy data.

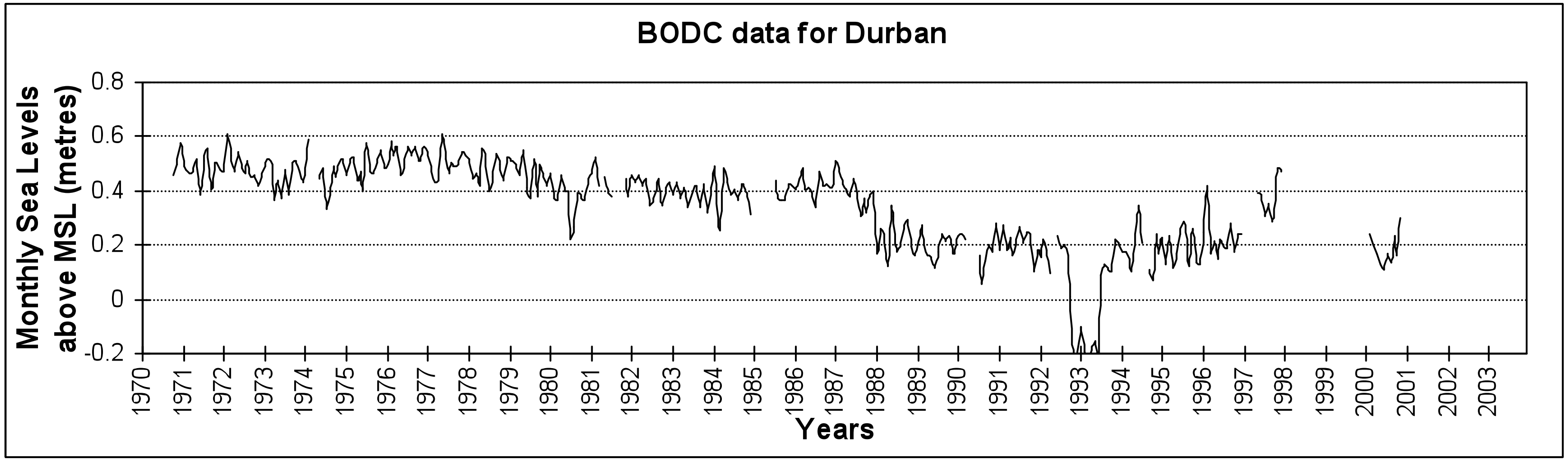

Figure 4.2: Mean monthly tide values for Durban using BODC data.

sequence. The fourth period, between mid-1992 and mid-1993 shows a sudden drop in levels which rises again rapidly to the start of 1994. The fifth period, between 1994 and the end of 1997 shows a typical tidal sequence, whereas the sixth period, in 1997 shows an elevated section. The seventh period in 2000 shows a return to a level comparable with the third (1998 to mid-1992) and fifth periods (1994 and end 1997) respectively. The two datasets are clearly different (Figure 4.3) except for the periods 1988-1992 and mid 1994-1998.For better understanding the differences the datasets have been broken into shorter periods.

Period: 1970-end of 1987 The BODC data follows a similar profile to the South African Navy (SAN) data, but at a higher level, which indicates a datum shift in the BODC records. The BODC dataset is approximately 340mm above the SAN data in 1970 and then slowly reduces to a difference of approximately 240 mm in 1987. It is commonly known that the mean level (ML) for Durban is in the order of +0.2 m MSL (Theron, pers. comm. 2006), so it is clear that the BODC data is incorrect because the mean monthly levels are centered around +0.5 m MSL. Thus the BODC data for this period can be discarded as unsuitable for data analysis. The SAN data yields no erroneous results for this period except for 1981 and 1982. For these years, the hourly records are identical for each time step throughout the year and appear to be duplication, which is most likely to be human reporting errors (Farre, pers. comm. 2006). This appears to be a simple case of data mismanagement. The subsequent datasets obtained from the SAN for 1981 were confirmed to be correct and the problems with this data have now been addressed and therefore future releases of this data will be correct.

Period: 1988-end of 1991 Both the BODC and the SAN records correlate extremely well (Figure 4.4) throughout this period and therefore either set are suitable for use.

Period: 1992-end of 1993 Both datasets show different profiles, with each showing rapid drops at different times. To investigate if the data were valid, SAN datasets for Richards Bay (160 kms north of Durban) and East London (450 kms south of Durban) were examined for any similar trends (Figure 4.5). It is important to note that the tidal series is reduced to the same datum in Figure 4.3. The Richards Bay and East London datasets show similar profile trends, with a relatively normal band of variation around the +0.2 m MSL level and most importantly a horizontal trend. The marked drop in mean monthly levels apparent in the Durban profiles (Figure 4.6) are not shown for either Richards Bay or East London (Figure 4.5). Thus, it is concluded that neither the BODC nor SAN datasets are useful for Durban for the years 1992 and 1993 for data analysis.

Period: 1994-end of 1996 This period yields a very good correlation between the BODC and SAN tidal data (Figure 4.6) and thus these datasets can be used with

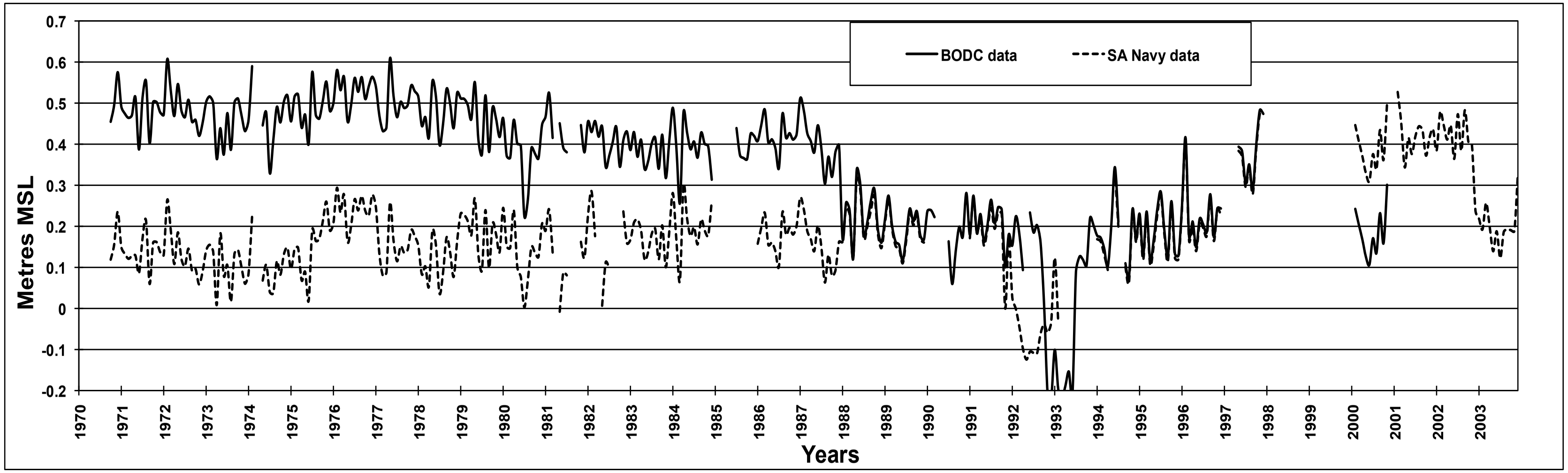

Figure 4.3: Mean monthly tide values for Durban using BODC and SA Navy data.

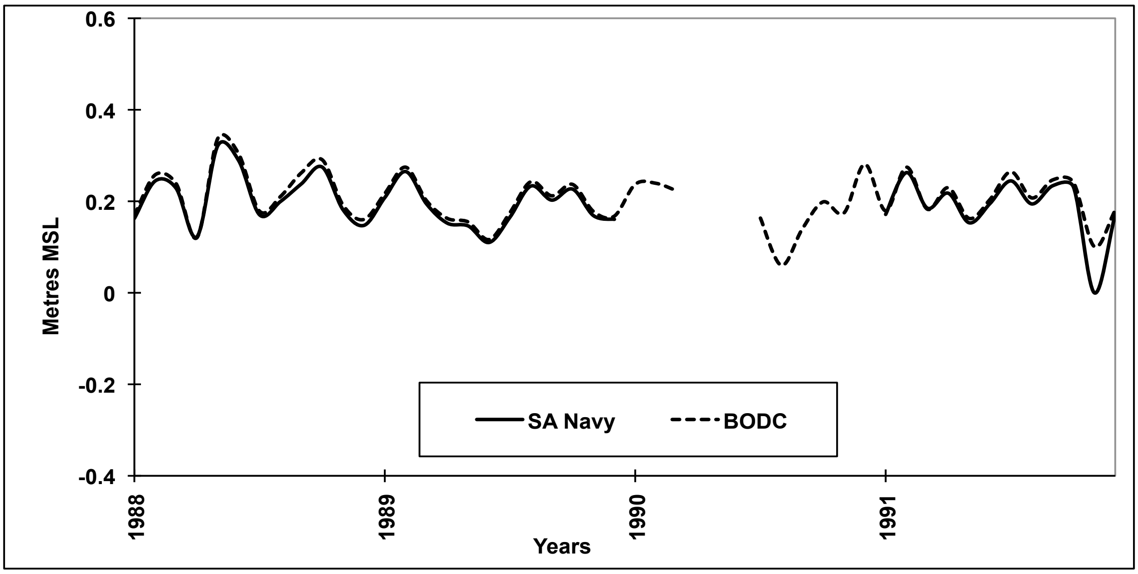

Figure 4.4: Mean monthly tide values between 1988 and the end of 1991 using BODC and SA Navy data.

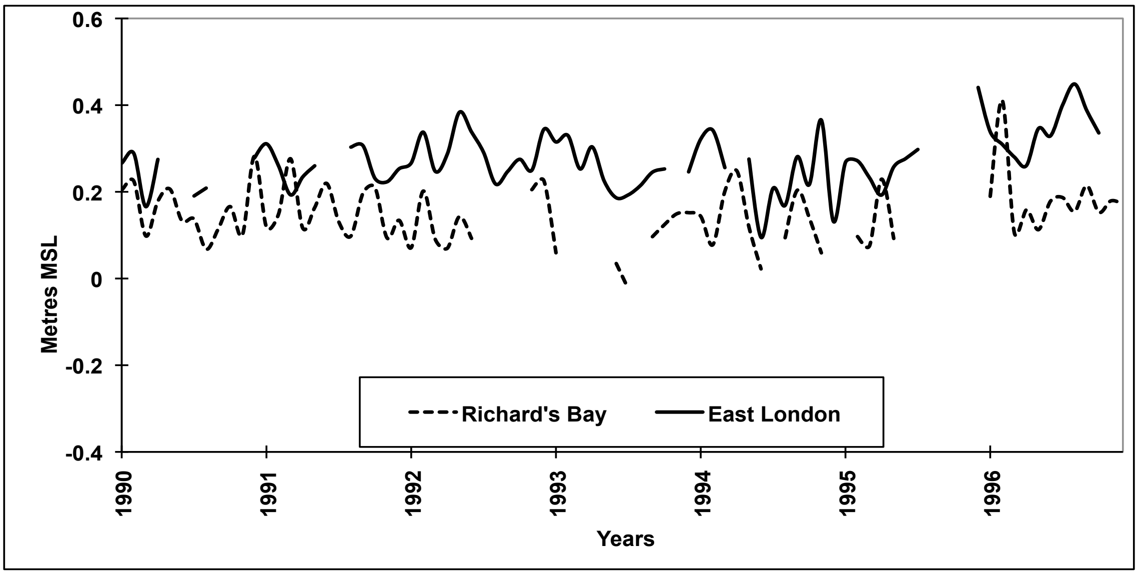

Figure 4.5: Mean monthly tide values between 1990 and 1997 for Richards Bay and East London using SA Navy data.

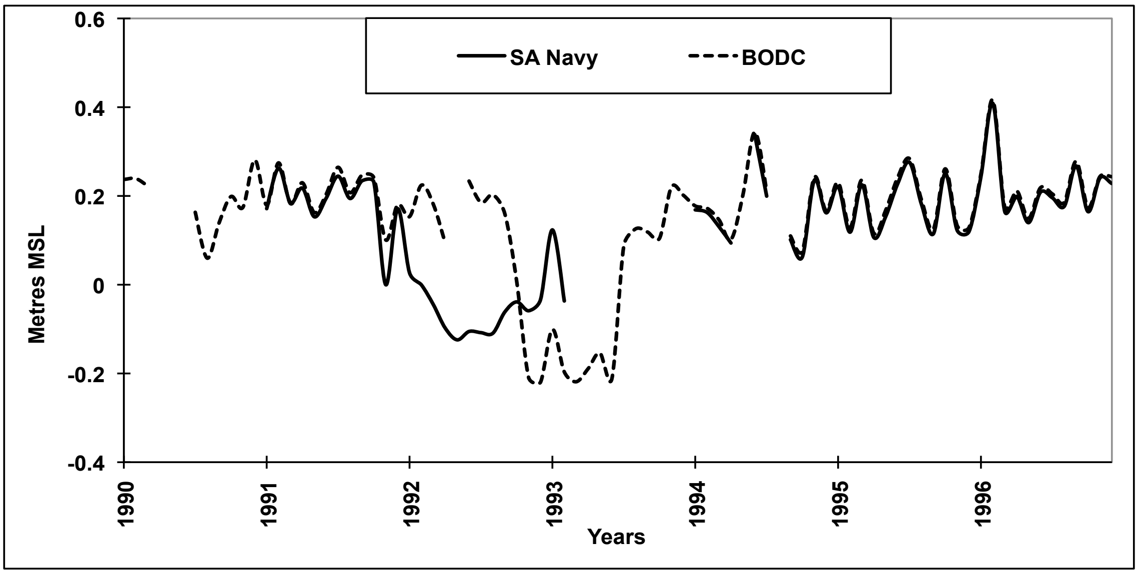

Figure 4.6: Mean monthly tide values between 1990 and 1997 using BODC and SA Navy data.

confidence.

Period:1997- end of 2002 The SAN and BODC datasets, measured in Chart Datum, were offset by the published correction of -1.113 m, from CD to MSL (South African Navy, 2006). However, despite this, the period is typified by the level of SAN data averaging around the +0.4 m MSL level while two different areas of recorded BODC data correlating with the SAN data in 1997. In 2000 the BODC profile appears clearly below the SAN profile.

For 2000, the BODC profile, while having the same shape as the SAN data, is exactly 0.2 m below the SAN data. This difference is in fact identical to the correction issued in the Notice to Mariners 117 of 2001 (South African Navy, 2001). The notice advised that a datum change had occurred for the 2002 data and sought to advise of the correction to the published incorrect tidal values and the unpublished correct ones. As indicated earlier, the mean monthly tide level (ML) at Durban, Richards Bay and East London is of the order of +0.2 m MSL, and the levels around +0.4 m MSL are questionable. It is unlikely that a change of about +0.2 m in mean tidal levels to about +0.4 m MSL over this period would have only occurred in Durban and not at the other centers.

The only feasible explanation is a shift in datum. It would appear that during this period some confusion arose in the SA Navys Hydrographical Office between ML and MSL. An additional offset of 0.2 m appears to have been inadvertently introduced in attempting to equate the two. This error of 0.2 m was the reason for the offset correction issued in the Notice to Mariners 117 of 2001. However, while this resulted in an expected return to normality in 2003, the proceeding years are noticeably higher. It would therefore appear that this error of 0.2 m extended back beyond 2002 and from an examination of the data it is deduced that this went back as far as 1997. There are two alternative ways to deal with this. Either these data are rendered unsuitable for data analysis and discarded, this being the more cautious approach; or that these data are corrected by an additional downward correction 0.2 m for all years between 1997 and 2002. In other words in order to use the SA Navy data sets between 1997 and 2002, an additional offset needs to be undertaken to correct these data. For example to correct the 2000 data to MSL requires the deduction of 1.313 m (i.e.−1.113 m less 0.2 m).

A summary of the offsets needed for the Durban data set from the SA Navy is shown in Table 4.3. It was also noticed that both the Richards Bay and East London tidal record showed a raised section over the same years between 1997 and 2002 (Figure 4.5). During the investigation the tidal record from the Permanent Service for Mean Sea Level (PSMSL) was also accessed and shows the same characteristics as the SA Navy data. Therefore it is concluded that the PSMSL data set also contains similar data anomalies which require the same corrections as outlined in Table 4.3. The PSMSL does advise that the entire Durban tidal data set has been flagged for further attention. The data sets, revised using the information above, are shown in Table 4.4. These new values form a far more reliable and correct reflection of mean monthly tidal levels reflecting more accurately the changing situation in Durban. The corrected Durban mean monthly tidal data is plotted and shown in Figure 4.7. It demonstrates a total change in sea level at Durban during the study period of 30 mm, and a mean annual change of approximately +2 mm.

Table 4.3: Summary of offsets for MSL for the SA Navy data for Durban.

Period	**Offset to Land Leveling Datum** (m) (MSL)
Up to 31 December 1978	−0.838
1 January 1979 to 31 December 1996	−0.900
1 January 1997 to 31 December 1997	−1.100
1 January 1998 to 31 December 2002	−1.313
1 January 2003 onwards	−0.913

4.1.5 Discussion

Global prediction of sea level change based on historical tide gauge records with 50 years data or more may be unreliable, since many gauge sites are located at the unstable edge of continental plates, on river deltas or along coasts which are subject to post glacial rebound. Such results cannot be assumed to reflect eustatic sea level

Table 4.4: List of Durban's acceptable annual tidal data for design and prediction purposes.

Year	**Source**
1970	SA Navy
1971	SA Navy
1972	SA Navy
1973	SA Navy
1974	SA Navy
1975	SA Navy
1976	SA Navy
1977	SA Navy
1978	SA Navy
1979	SA Navy
1980	SA Navy
1981	SA Navy
1982	SA Navy (New data set)
1983	SA Navy
1984	SA Navy
1985	SA Navy
1986	SA Navy
1987	SA Navy
1988	SA Navy and BODC
1989	SA Navy and BODC
1990	No data
1991	SA Navy and BODC
1992	No suitable data
1993	No suitable data
1994	SA Navy and BODC
1995	SA Navy and BODC
1996	SA Navy and BODC
1997	No suitable data
1998	No data
1999	No data
2000	BODC
2001	No suitable data
2002	No suitable data
2003	SA Navy
2004	No data
2005	No data
2006	No data

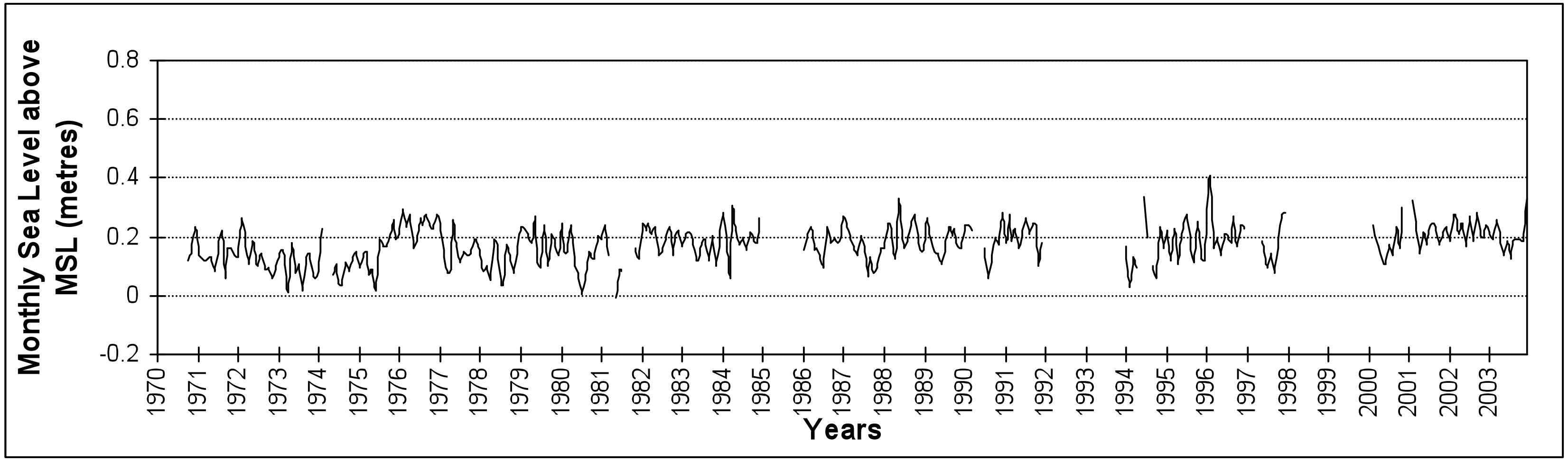

Figure 4.7: Corrected mean monthly tide values for Durban.

change only, but could indicate a local change in land height due to tectonism or some other reason. Emery and Aubrey (1991) evaluated 587 gauges with records longer then 10 years from around the world and, identified only 36 gauge records as originating from stable coastlines. Only 3 of these were from southern Africa and all were on the west coast. No records of significant length existed in south east Africa, although it may also be considered as geologically stable. The record of Durban in geologically stable eastern South Africa goes back 30 years, but until now has never been accurately analysed.

The analysis of this data provides a good scientific basis in which to evaluate sea-level change along the east coast of South Africa over the last 3 or so decades. The analysis described above highlights the problems and anomalies of the Durban tidal record but also clearly shows that the majority of the dataset is acceptable and can be used with confidence for design calculations provided it is carefully assessed before being used. Sea-level analysis from tide records is now made fairly simple by the use of a variety of techniques and computer programs (Intergovernmental Oceanographic Commission, 2002) and one has to be carefully that the data has been sufficiently screened before any conclusions are drawn. The unchecked Durban tide dataset was used in the Climate Future for Durban: Revised report in which a sea level trend of +4.5 mm per year was determined (CSIR, 2006). This figure is now recognized as being too high and subsequent trends will be subject to the results of this work.

4.1.6 Conclusion

An important result would be that the various datasets produced for Durban be revisited in the light of these findings. Errors in the order of 340 mm to 240 mm render the original data from the South African Navy, the Permanent Service for Mean Sea Level and the British Oceanographic Data Centre invalid for long term predictions of sea-level rise as these are normally in the order of one or two decimetres per century (Pugh, 1987). The use of the published Durban tidal record for design purposes also requires verification of the accuracy and validity of the data before it is applied. It is contended here that the revised values calculated in this study are a more accurate reflection of recent sea level, and are suitable for planning and design purposes.

4.1.7 Acknowledgements

The author wishes to record his thanks to the Hydrographic Office of the South African Navy, British Oceanographic Data Centre and the Permanent Service for Sea level Rise for the supply of the tidal data set for Durban.

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4.2 Linear and non-linear sea-level change at Durban, South Africa

4.2.1 Abstract

The tide record between 1970 and 2003 for Durban, South Africa, is analysed to determine the extent of recent linear and nonlinear sea-level trends in the light of

predicted global sea-level rise. Given the stability of the adjacent land mass, Durban is ideally suited to test global sea-level change. The linear trends of monthly mean sea level indicated a sea-level rise of +2.7 ± 0.05 mm per year and the yearly mean sea-level trend indicated a rise of +2.4 ± 0.29 mm per year. Nonlinear trends varied between 1 mm and +8 mm per year. These findings are similar to recently published results of global sea-level rise calculations over the last ten years derived from worldwide tide gauge and TOPEX/Poseidon altimeter measurements, which range between +2.4 and +3.2 mm per year.

4.2.2 The need to determine trends in sea-level change

There is growing worldwide awareness of the effects of climate change induced by human actions on our planet and, particularly, of the global effect of sea-level rise on coastal cities, towns and subsistence communities that rely on the sea for income and food. Urban settlements have expanded rapidly over the last thirty years, especially in developing countries, making more people vulnerable to this risk (Rakodi and Treloar, 1997). Sandy beaches, which make up 34% of the worlds coastline (Hardisty, 1990), form an integral part of most coastal cities tourism potential. Tourism is an important economic activity in KwaZulu-Natal, and Durbans beaches constitute the provinces most important tourist attraction, with 73% of domestic tourists visiting them (Tourism KZN, 2007). Rising sea levels will reduce the surface area of beaches, and the consequent damage to tourism infrastructure will impact adversely on the local tourism industry.

Coastal harbours are similarly vulnerable. Durban plans to double its container port capacity over the next few years (Mather, Redman and Akkiah, 2006). Port and harbour development is costly and developers plan for use of this infrastructure for up to a century or more. Measurement of sea-level change has been in progress for decades, with the main focus on the northern hemisphere. Data from tide gauges have traditionally been used for this purpose. In the late 1990s, however, the use of satellite data became more prominent, chiefly because of poor geographical coverage by tide gauges, the influence of tide gauge records by land movement and the superior accuracy provided by satellite data. Historically, the analysis of sea-level trends has been undertaken using linear regression techniques, but more recently nonlinear analysis has been introduced (Jevrejeva *et al.*, 2006).

This paper examines current rates of sea-level rise for Durban and surrounding coastal areas based on the tidal records of the South African Navys tide gauge located near the harbour entrance (31° 00” E, 29° 49” S) (Figure 4.8). No such analysis has been done to date for Durban or for any major coastal city on the east coast of Africa. The results are compared with published global sea-level changes.

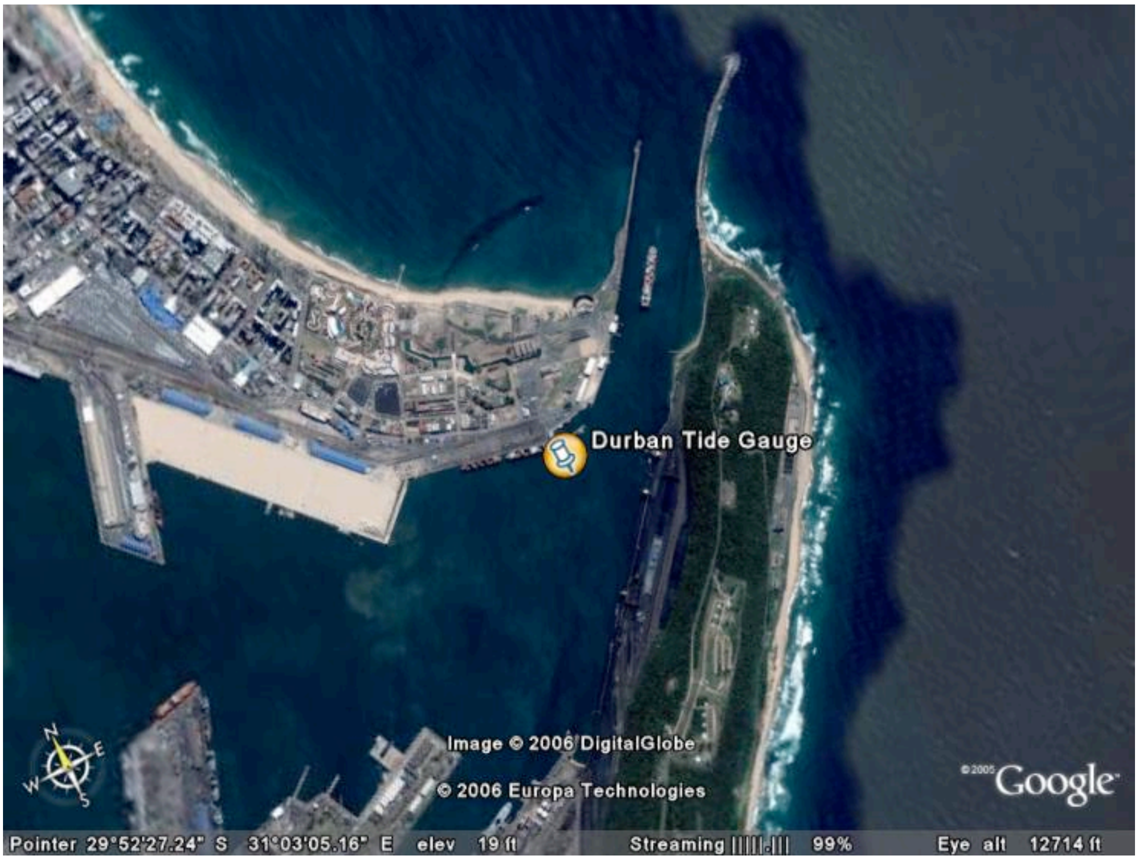

Figure 4.8: Location of the South African Navy tide Gauge at Durban, South Africa. Tide gauge located at centre of figure (Google Earth, 2006).

4.2.3 Method and Results

The tide data used for this analysis were sourced from the South African Navys Hydrographic Office. The most reliable records between 1970 and 2003 were selected and were received as hourly observed tide levels in Chart Datum (CD). The navy data were found to be unusable in their existing form. There are two other data records for Durban, one held by the British Oceanographic Data Centre (BODC) and the other by the Permanent Service for Mean Sea-level. These were evaluated and found also to contain several anomalies despite originating from a single tide recorder. This required a re-analysis of these data, to rectify and remove dubious records from the data (Mather and Garland, 2006).

The barometric data used in this study were obtained from the South African Weather Service, received as hourly recordings from the Durban International Airport weather station. Recorded tide data are influenced by meteorological effects. Compensation requires the extraction of the influence of barometric pressure, commonly referred to as 'inverted barometer' effects (Doodson, 1924), as these can mask the true sea-level change. Correlation coefficients were established between changes in apparent sea levels, using the Durban tide gauge and changes in barometric pressure. These were −8.7 mm per hPa for annual readings and −5.9 mm per hPa for monthly readings by Mather (2007) and were applied to the data. The longer the period of analysis, the closer the correlation tends to the theoretical relationship of −9.9 mm per hPa.

Two different levels of analysis were undertaken. In the first method, using annual records, the data were analysed according to Pugh (1987). This entailed refining the data, applying a weighting factor to account for discarded data, introducing a barometric correction and, finally, applying linear regression to the refined, weighted annual change. The second method used was similar to the first except for the omission of weighting factors, using monthly rather than annual change and the application of a barometric compensation of −5.7 mm per hPa, rather than the −8.7 mm per hPa used in the first method. Nonlinear trends for monthly mean sea levels were calculated using CATMV (www.gistatgroup.com) based on the singular spectrum analysis (SSA) method (Golyandina and Osipov, 2007; Hassani, 2007).

4.2.4 Results

The linear analysis of monthly mean sea levels (MMSL) yielded a rate of sea-level rise of +2.7 ± 0.05 mm per year at the 95% confidence level (Figure 4.9). The linear analysis of yearly mean sea level (YMSL) yielded a sea-level rise of +2.4 ± 0.29 mm per year (Figure 4.10). Nonlinear trends (Figure 4.11) show changes similar to the linear trends.

On examination of the moving annual average trends (Figure 4.12), however, it is possible to distinguish different phases. These range from approximately −1 mm per year to +8 mm per year. Only two periods show a negative trend, these being

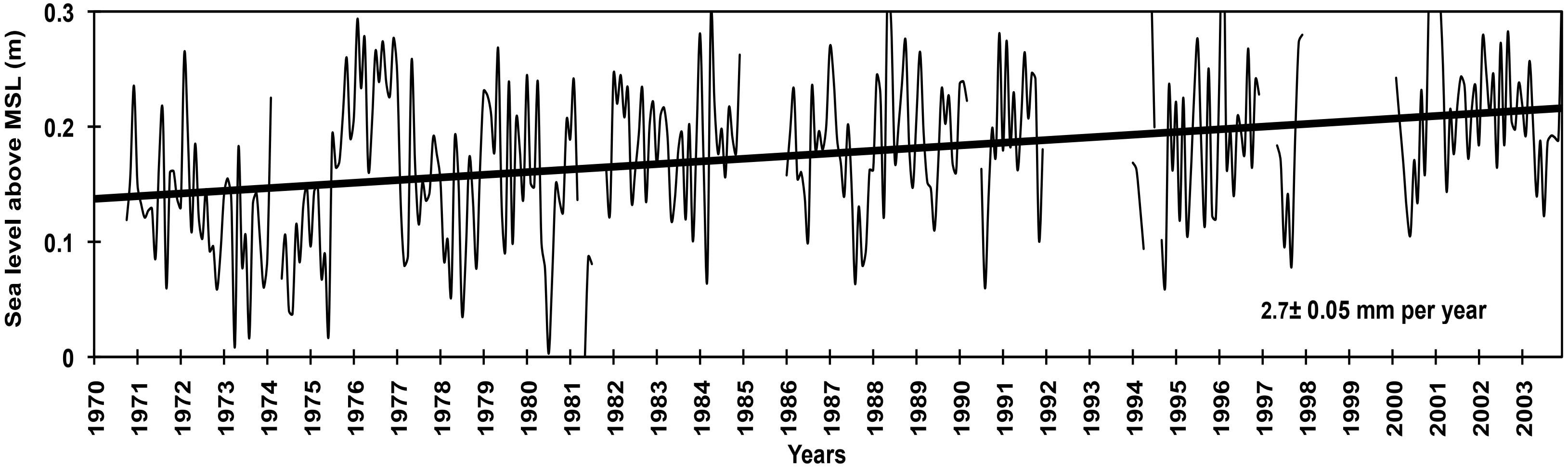

Figure 4.9: Monthly sea level changes and associated linear trend).

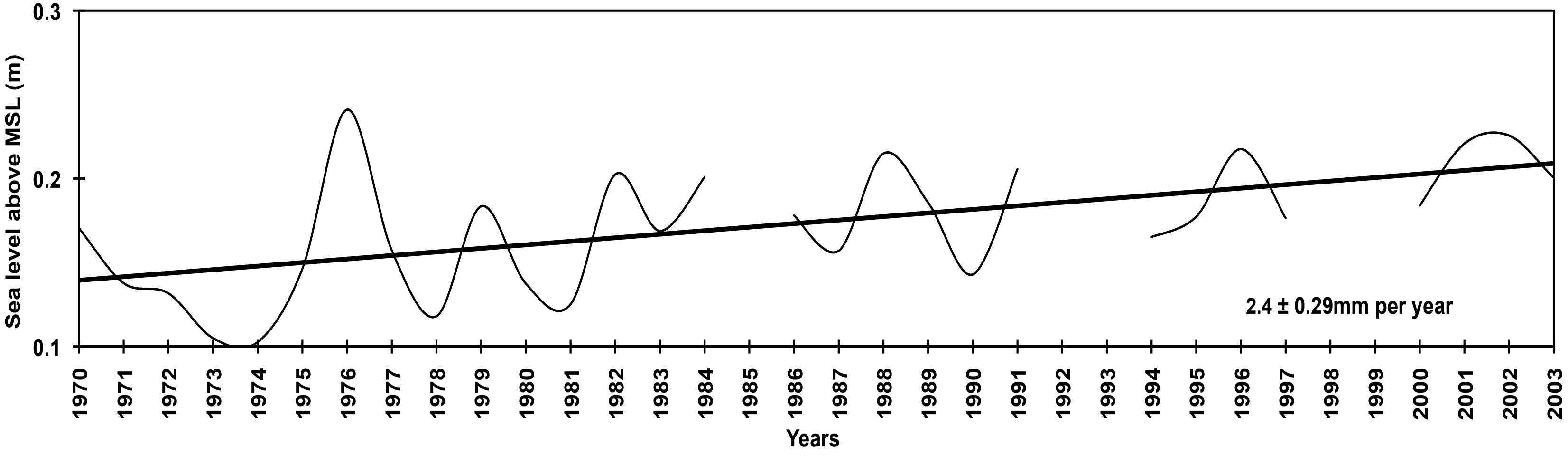

Figure 4.10: Annual sea level changes and associated linear trend.

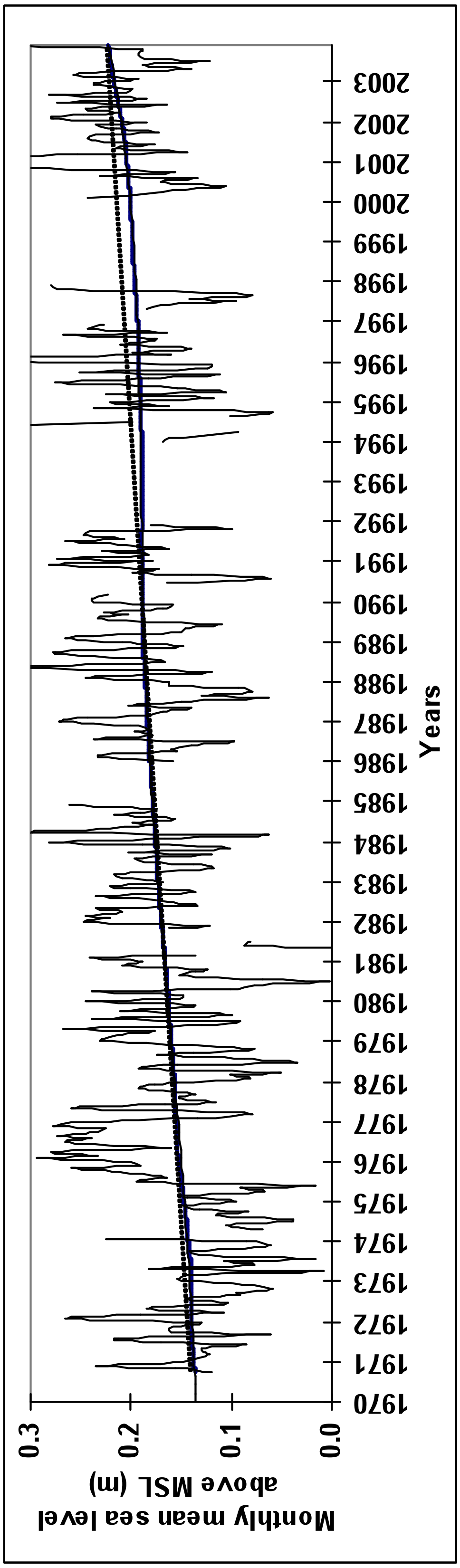

Figure 4.11: Monthly sea level changes and non-linear trend. Dotted line to show deviation from linear trend.

in 1972 and 1992. The two negative trends are of small magnitude, −1.1 mm per year and −0.6 mm per year, respectively. A positive trend is evident in the rest of the series, with the highest value of +8.4 mm per year recorded in 2002.

4.2.5 Discussion

Sea-level trends around the world have shown varying amounts of sea-level variation, depending on the location and geological history of the site. Emery and Aubrey (1991) evaluated 587 gauges with records longer than ten years and identified only 36 that originate from stable coastlines. Only three of these sites were from southern Africa and all were situated on the west coast. As the southern part of the African continent is founded on a stable cratonic base, this makes the land mass around Durban tectonically stable (Cooper, 1995). This obviates the need to correct for many of the other influences that pervade the tidal records, notably subsidence and post-glacial rebound. Durban is, therefore, one of relatively few sites in the world that can be used directly to assess global sea-level change.

Little recent research has been conducted in South Africa on rates of sea-level change calculated from tide gauge data. In 1984, Brundrit (1984) focused on sea-level changes only on the west coast of South Africa, and Hughes, Brundrit and Shillington (1991) examined changes on the west and Cape coasts with respect to sea-level measurements in the global context of sea level. Brundrit (1995) examined the tide gauge data at Lüderitz, Port Nolloth, Simon's Town and Mossel Bay, deriving trends from these sites. He omitted the east coast entirely, however. Except for the work of Cooper (1991), (1995a), (1995b) and Hughes (1992), who used estimates of sea-level change to model coastal impacts, even fewer sea-level studies have been undertaken specifically for Durban.

A comparison of our results with this previous work was made. Cooper (1991), quoting Hughes (pers. comm.), refers to Durban's tide record as showing 'little upward trend' and ascribes this to possible instrument error, land movement and/or other factors. This paper examines this particular period of the Durban record, and analysis clearly shows an upward trend. This anomaly may be attributable to previous workers use of the British Oceanographic Data Centre record for Durban, which shows a downward trend, and not the official tide record from the South African Navy. The BODC record originates from the University of Cape Town via the University of Hawaii. The work of Cooper (1991), (1995a) included a regional estimation of the effects that a +1 m sea-level rise could have on the KwaZulu-Natal coastline. This figure was chosen presumably as it reflected the upper limit of sea-level rise predictions at that time. All other previous work has been based on scenarios and none of the authors derived the actual sea-level rise for the east coast from tide data. Thus these data from this study are vital for future work.

The approach adopted in this study, based on MMSL and YMSL data from the recorded data, provides good correlation with more sophisticated analyses. Pugh (1987) points out that: '*This method is used by many authorities because it re-*

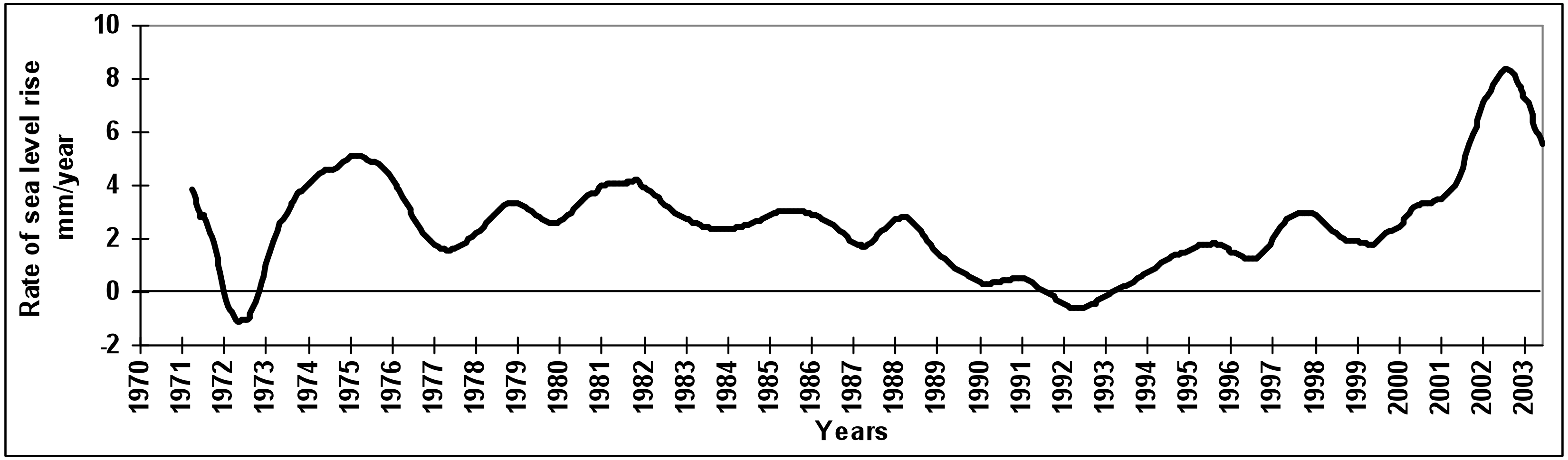

Figure 4.12: Rate of monthly sea level change.

quires little mathematical insight, yet produces values close to that obtained by more elaborate tide-elimination techniques (Rossiter, 1958)'.

It is important to note that calculations based on mean monthly sea level almost always yield different answers to those based on yearly mean sea-level calculations. Time series plots of YMSL values appear to be smoother than plots of MMSL values. As there are 12 times more data points in the MMSL, however, this effectively increases the sample size of MMSL plots, leading to a smaller standard error of the regression coefficient.

Linear regression analysis is a relatively easy and popular tool whereby sea-level trends can be obtained. This method has its defects, however. Regressional analysis is sensitive to the starting position of the analysis and, therefore, is inappropriate for periods of a decade or less, because of the multi-year cycles present in the tide record (Lisitzin (1974), Jevrejeva *et al.* (2006). These cycles, if not properly accounted for in the analysis, mask longer-term trends in the data.

Nonlinear techniques, on the other hand, are more robust and not as sensitive to the start position. Two approaches considered for this analysis were the empirical mode distribution (EMD) (Huang *et al.* (1998), Flandrin *et al.* (2004) and singular spectral analysis (SSA) (Golyandina and Osipov, 2007). Both are effective in decomposing time series into trends and residual frequencies, allowing better understanding of the latent trends in the data. As with most data series, however, gaps are common and are difficult to deal with. CATMV, which uses SSA was chosen here, as this software has a superior method of filling in data gaps (Hassani, 2007). The comparison of these results with worldwide figures is shown in Table 4.5.

Over the last century, the trend is towards an ever increasing rise-rate, which has led to speculation about future acceleration in rising sea levels. Church and White (2006) have subsequently established evidence of an acceleration in the rate of sea-level rise from extended (1870-2004) tide gauge records. For this reason comparisons with other sea-level changes are confined to time periods relevant to this study. Church and White (2006) examined the 1970-2003 period and obtained a global sea-level rise of 2.1 mm/yr. Many new analyses have been undertaken as a result of satellite altimeter data becoming available, Cabanes *et al.* (2001) and Nerem and Mitchum (2001) examined global sea-level rise 1993-1998 period and arrived at a figure of +3.2 ± 0.2mm and +2.5 ± 1.3mm per year, respectively.

Jevrejeva *et al.* (2006) arrived at a figure of +2.4 ± 1.0mm per year for the period 1993-2000. More studies were undertaken as the satellite data extended over longer time periods. Cazenave and Nerem (2004) and Leuliette *et al.* (2004) examined sea-level change over the period 1993-2003 and published results of approximately +2.8 ± 0.4 and +3.1 ± 0.7mm per year. Bindoff *et al.* (2007) updated the work of Cazenave and Nerem (2004) and obtained a linear rate of sea-level rise of 3.0 mm per year. All of these results are comparable and correlate well with the linear results of +2.7 ± 0.05 mm per year obtained for Durban.

Nonlinear results show a constantly changing trend influenced by the multitude of different global changes at play. Analysis shows that, apart from one short period

Table 4.5: Published information on global sea-level rise.

Author	**Year**	**Period of time considered**	**Av. rate of sea level rise s.d.** (mm per year)
Peltier	1996	1920 to 1970	1.94±0.6
Davis & Mitrovitch	1996	unspecified	1.5±0.3
Peltier and Jiang	1997		1.8±0.6
Douglas	1997		1.8±0.1
Nerem *et al.*	1997		2.1±1.2
Viliblic	1997	20th century	1.5 to 2.0
Lambeck *et al.*	1998	1892 to 1991	1.1±0.2
Mitchum	1998		2.3±1.2
Cazenave *et al.*	1998		1.4±0.2
Woodworth	1999	20th century	1.22±0.25
Nerem	1999	1993 to 1998	2.5±1.3
Peltier	2001	20th century	1.0 to 2.0
Cabanes *et al.*	2001	1993 to 1998	3.2±0.2
Nerem & Mitchum	2001	1993 to 1998	2.5±1.3
Proshutinsky *et al.*	2001	1950 to 1990	1.8
Church *et al.*	2001	20th century	1.0 to 2.0
Lambeck	2002		1.16 and 1.65
Johannesson	2002	1993 to 2000	1.9±0.2
Hunter *et al.*	2003	1841 to 2002	1.0±0.3
Church *et al.*	2004	1950 to 2000	1.8±0.3
Cazenave & Nerem	2004	1993 to 2003	2.8±0.4
Leuliette *et al.*	2004	1993 to 2003	3.1±0.7
Church & White	2006	1870 to 2004	1.44
		1900 to 2004	1.7±0.3
		1970 to 2003	2.1
Jevrejeva *et al.*	2006	1993 to 2000	2.4±1.0
		1920 to 1945	2.5±1.0
Bindoff *et al.*	2007	1993 to 2003	3.0

between 1972 and 1973 the major part of the record shows an upward trend of varying degree. The period between 1972 and 1973 shows a downward trend of −2 mm per year. The next period, which accounts for the majority of the time series, yields an almost uniform trend of +2.6 mm per year

A distinct advantage of nonlinear trends over linear trends is that discrete periods can be analysed against results obtained for comparable periods. A comparison for the period 1993-1998 with the results obtained by Nerem and Michum (2001) from satellite data of +2.5 ± 1.3mm year gives a notable comparison. Trends for this period from this study are 1.4 mm per year, which falls into the range provided by Nerem and Michum (2001). Cazenave and Nerem (2004) and Leuliette *et al.* (2004) undertook a further study for the period 1993-2003, which yielded +2.8 ± 0.4 and +3.1 ± 0.7 mm per year and, compared to the result of +2.7 mm per year obtained in this study, showed excellent agreement with global nonlinear variations of sea levels.

Based on the comparisons above, the linear rate of sea-level rise derived for Durban of +2.7 ± 0.05mm per year would appear to be valid for use at Durban and the surrounding areas.

4.2.6 Conclusion

The rate of sea-level rise of +2.7 ± 0.05mm per year for Durban and its adjacent coastline is consistent with previous worldwide research, clustering in a band between +2.4 and +3.2 mm per year. These results are important in that they provide for the first time a locally measured rate of sea-level rise that can be used for strategic coastal planning, coastal management and in the design of future port infrastructure and marine structures in the region.

4.2.7 Acknowledgements

I thank the South African Navy for the use of the tidal data and the South African Weather Service for the use of barometric data

4.2.8 References

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Epilogue to Chapter 4

In this Chapter the tidal records at Durban were examined and it was found that the data has a number of issues which have been resolved as far as possible or the suspect data has been removed prior to analysis. The results show that sea levels at Durban are rising at just under the global average.

Prologue to Chapter 5

The results from Chapter 4 have shown that at Durban the tidal records have required a number of corrections and that some corrections where unable to be made and data was therefore excluded from the record. The revised and corrected sea level data has provided the basis on which the historical change of sea level, between 1970 and 2003, has been determined as +2.7±0.05 mm per year.

This has lead to the need to determine what changes are being experienced by other South African tide station in the region. The purpose of Chapter 5 is then to, analyse the tidal records for the remaining South African and Namibian tide stations with the aim of determining the most accurate measurements of sea level change. Secondly to determine what factors are influencing this change and to what extent are these factors aggravating or mitigate sea-level change. And lastly to determine the eustatic sea-level trends along the southern and eastern coastline of Africa. This Chapter will then start to address the thesis questions of whether sea level has been changing along the south east coast of Africa and to determine the rate and direction of sea level change.

This chapter includes the thematically linked, published paper, which appeared as a peer reviewed research paper titled:

Mather, A.A., Garland, G.G. and Stretch, D.D. 2009. Southern African sea-levels: Corrections, influences and sea-level rise trends, *African Journal of Marine Science*, 31(2), 145-156.

The original journal publication has been reproduced in full with the permission of the Editor of the African Journal of Marine Science. The original journal publication is included in the Appendix.

Chapter 5

SOUTHERN AFRICAN SEA LEVELS: CORRECTIONS, INFLUENCES AND TRENDS

5.1 Abstract

The tidal records of existing South African and Namibian tide gauges are examined and corrected. Regional sea-level trends vary, with the west coast rising at +1.87 mm per year (1959-2006), the southern coast by +1.48 mm per year (1957-2006) and the east coast by +2.74 mm per year (1967-2006). The effects of barometric pressure and vertical crustal movement changes on these trends are examined. The derived relationship between sea-levels and barometric pressure changes were found to vary between 5.71 and 7.67 mm per hPa, significantly less then the theoretical inverse barometric correction. Barometric pressure has been dropping along the West Coast by 1.63 hPa per decade (1987-2006), remaining fairly static along the southern coast and rising at 0.30 hPa per decade (1970-2007) along the east coast of Southern Africa. West Coast barometrically corrected sea-levels trends show that most of the change can be attributed to falling barometric pressure, while along the East Coast, the barometric pressure increase is suppressing sea-level by 0.2 mm per year. Vertical crust movements vary, with the largest recorded movements of +1.11 ± 0.25 mm per year found along the East Coast. Movement rates reduce southwards. Eustatic sea level trends vary from +3.55 mm per year along the East Coast and +1.57 mm per year along the southern coast and +0.42 mm per year along the West Coast.

5.2 Introduction

Sea-levels vary in time and space because of a variety of natural factors acting on the Earths surface (Church *et al.*, 2001; Bindoff *et al.*, 2007), including solar and lunar tides (Pugh, 2004), waves and winds (Pugh, 1987), crustal movements (Baker, 1993; Pirazzolli *et al.*, 1994; Davis and Mitrovica, 1996) and atmospheric conditions (Dickman, 1988; Hoar and Wilson, 1994; Wunsch and Stammer, 1997), Proshutinsky *et al.* 2004) both at a localised and regional scale. The anthropogenic effects of mans activities on the planet have altered this natural state of dynamic equilibrium. These influences include warming (Warrick *et al.*,1996; Bindoff and McDougall, 2000), glacier and ice sheet melt (Dyurgerov and Meier, 1997) and surface and ground water storage (Gornitz, 2000).

Over the last few decades, driven by the concerns about the impacts of global warming, many researchers and organisations, such as the Intergovernmental Panel on Climate Change (IPCC), have sought to understand mans influence on global sea levels (IPCC, 1990, 1996, 2001; Bindoff *et al.*, 2007). Part of this research has been focused on the current and future rate of sea level rise (Church *et al.*, 2001). Until the introduction of satellite altimetry in 1993 (Nerem*et al.*, 1997), the analysis of sea level changes had been solely confined to tide gauge data, which was predominately based in the Northern Hemisphere. The use of satellite sea-level data has to some extent improved the geographical coverage; however, accurate tide gauge data are still needed to calibrate the satellite altimeter results (Mitchum, 1998).

Unfortunately the Southern Hemisphere, does not have many tide gauge records extend for longer then 50 years, the period deemed to be suitable for this type of analysis (Woodworth, 1990; Douglas, 1991). In an African context, the number of suitable tide gauge records diminishes even further, but there are plans to extend and upgrade this network along the African coastline (Woodworth *et al.*, 2007).

This chapter is focused on the tide gauges along the Southern African coastline (Figure 5.1). Whereas, not all the records meet the 50-year length criteria, it is imperative that some preliminary analysis be undertaken to inform key planning and policy decisions. Investigations on sea level changes around the South African coastline are limited. Earlier work focused on sea level changes on the West Coast (Brundrit 1984) and on the West and Cape coasts (Hughes *et al.* 1991). Later Brundrit (1995) derived sea level trends from tide gauge data taken at Lúderitz in Namibia and Port Nolloth, Cape Town and Mossel Bay on the West and South coasts. Recently Mather (2007) examined the linear and non-linear sea level trends for Durban on the East Coast.

Key to understanding these sea level change trends in a global context is the ability to separate out the various contributions by tides, waves, winds, which can be simply measured using tide-gauge data, over as long a period as possible. However, other important factors that can influence sea level such as vertical crustal movements and barometric pressure are briefly outlined below.

5.2.1 Vertical Crustal Movement

Although South Africa is located on a stable cratonic base (Cooper, 1995; Ramsay and Cooper, 2002), the African plate is subject to horizontal motion induced by plate

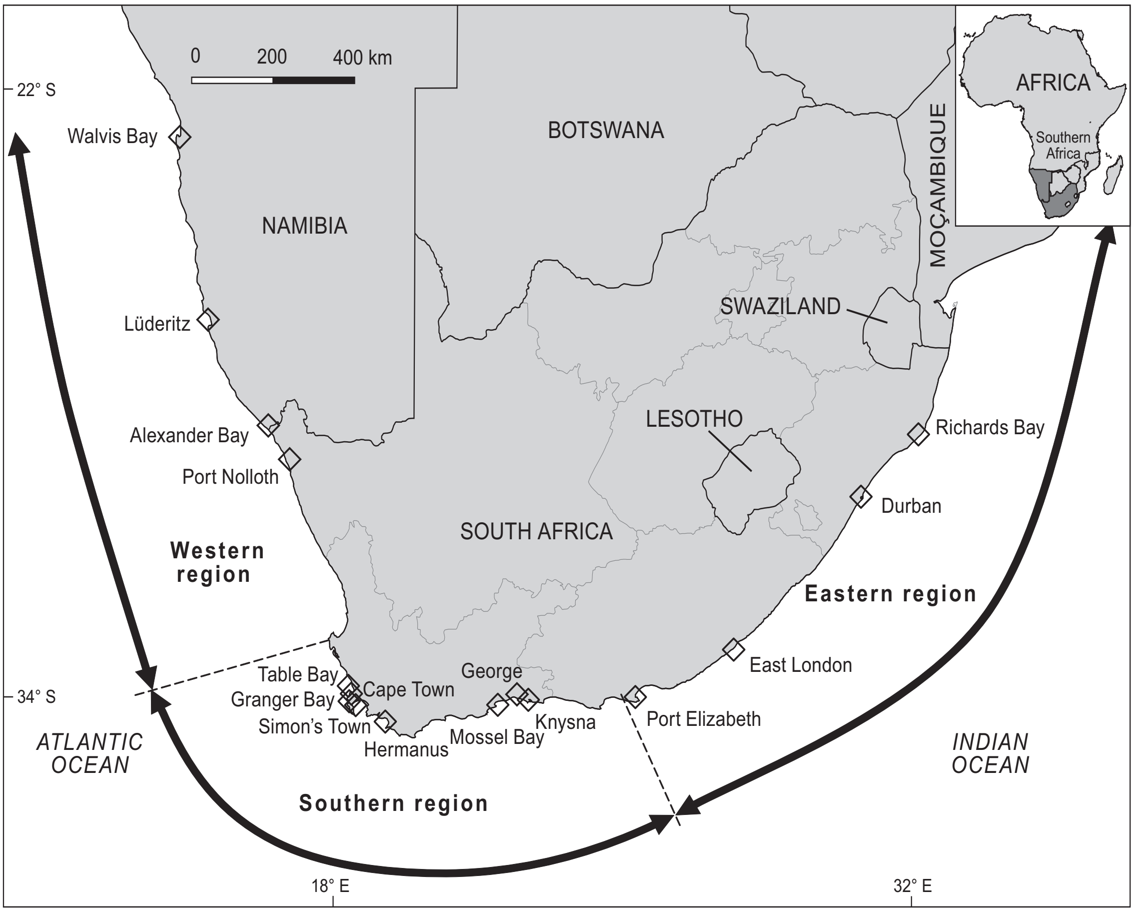

Figure 5.1: Map of Southern Africa showing the location of the tide gauge stations and the three geographical regions referred to in the text.

tectonics and results in some vertical movement. Vertical crustal movements have been difficult to quantify in the past because they have mainly been estimated using various models, e.g. the ICE-5G model (Peltier, 1994). With the advent of satellites, it has become possible to measure the land and water surface of the Earth against an imaginary geoid to determine the vertical and horizontal changes in the earths crust. This network of monitoring points is relatively sparse over southern Africa with only two stations in South Africa located at the coast at Simons Town and Richards Bay (Figure 5.1). These geodetic stations are located next to tide recording stations. Despite data limitations, corrections for vertical land movements are applied here to the observed sea level changes in order to provide some indication of eustatic sea level rise around the southern tip of Africa.

5.2.2 Barometric Pressure Influences

Barometric pressure has been reported to be the second-most important climatic variable other then temperature which may be influenced anthropogenically (Gillett *et al.*, 2003). Global barometric pressure trends yield a small positive trend of +0.02 hPa per year with values of -0.03 hPa per year occurring in localized areas (Church *et al.*, 2001). Northern European trends are of the order of +0.01 hPa per year (Woodworth, 1987). Trends for shorter periods (1960-1990) can have a larger influence on sea level trends of between -0.05 mm per year (Schönwise *et al.*, 1994) and +0.04 mm per year (Schönwise and Rapp, 1997). Thus, it is important that the impacts of local barometric pressure variations are understood and properly taken into account in the assessment of trends using tidal records over a relatively short time period. In southern Africa, where the available records of sea-level are only up to 37 years long, it is critical to ensure that barometric pressure effects are taken into account in the calculation of eustatic sea level change.

The barometric pressure relationship is governed by the simple relationship that increased air pressure forces the sea surface to drop and the excess water is distributed to other regions of the sea. This has been widely studied and was first postulated by Gissler (1747; cited in Roden and Rossby, 1999). Doodson (1924) continued this work and coined the term ‘inverted barometer response’, which is now in common use (Rossiter, 1962; Roden, 1966; Wunsch and Stammer, 1997). From the hydrostatic equation, it can be deduced that a barometric high or low pressure system should theoretically depress or elevate the sea surface. The theoretical ‘local inverted barometer’ (IB) correction for the sea surface can be calculated as (see Eq. 5.1):

$$\zeta_{ib} = -0.9948(p_a - 1013.3) \tag{5.1}$$

where ζ_{ib} is the change in sea-level in cm, p_a is the recorded barometric pressure in hPa, 1013.3 is the standard atmospheric pressure at sea-level in hPa and -0.9948 is the IB coefficient in cm per hPa (Hoar and Wilson, 1994).

The equation 5.1 shows that each hPa drop in pressure leads to a 9.948 mm (often approximated to 10 mm) increase in sea-level. The exact inverted barometric response is seldom found in practice (Pugh, 1987) and tide gauges around the world will have differing responses to this relationship, depending on many factors, including the amount of storm surge influenced by wind, as well as basin characteristics, continental shelf configurations, water depth, coriolis and global and local atmospheric pressure realignments. The variation of barometric pressure over the sea can have a significant influence on recorded tide levels, which at times can be of orders of magnitude greater then the annual change in sea levels (Bell *et al.*, 2000; Singh and Aung, 2005). Working on global data, Ponte (2006) found that the deduction of the IB signal can have the effect of up to a 40% increase or decrease in the sea level trend. The understanding of this relationship is critical in isolating the weather effects from shorter tidal records if sea-level changes are to be accurately computed.

5.3 Objectives of this paper

The objectives of this paper are to determine:

(1) the current relative rate of sea level rise at stations around the Southern African coastline

(2) the regional relative rates of sea level rise

(3) the impact of changes in barometric pressure on sea levels

(4) the influence of vertical land movements on the gauge readings of sea level and

(5) the regional rate of eustatic sea level rise along the coastline.

5.4 Materials and Methods

The analysis of the sea levels and their respective influences are based on a number of datasets. In some cases, more then one data set were available and a choice was made between them, for the reasons given below. The monthly and annual revised local reference (RLR) tidal data set for all South African and Namibian tide gauge stations was sourced from the Permanent Service for Mean Sea Level (PSMSL) at www.pol.ac.uk/psmsl. The tide data for Durban were derived from Mather (2007, 2008), which required some errors (detailed below). The sea level data used in this paper are shown in Figure 5.2.

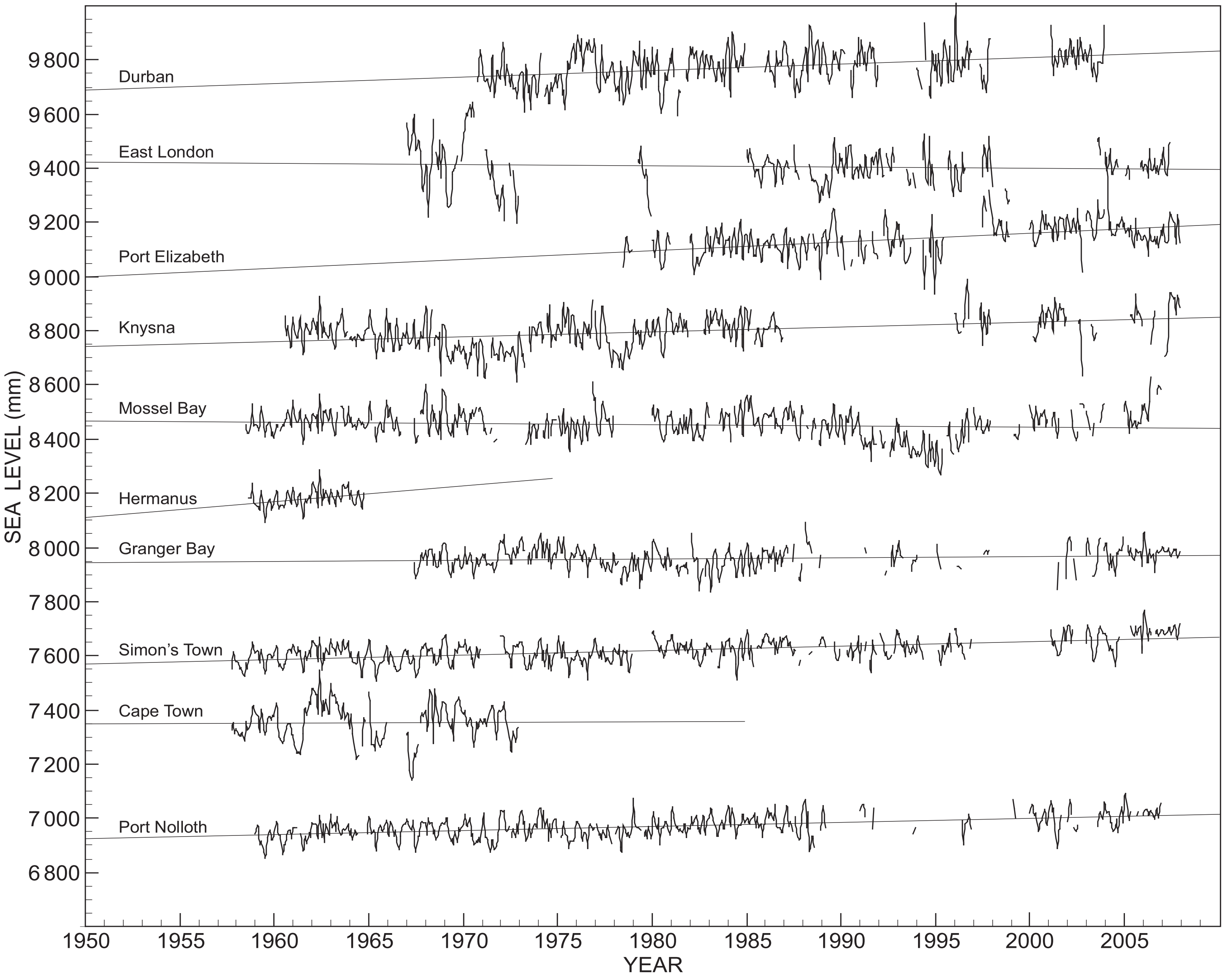

Figure 5.2: Tide gauge time-series for the different stations, 1959-2006.

Sea level pressure data (HadSLP2) were sourced from the Hadley Centre for Climate Change, UK, and monthly barometric pressure data were obtained from the South African Weather Service. The HadSLP2 data are in 5° x 5° grids over the period 1955-2004. Examination of the area of interest in this study revealed that in half of the grids required for the analysis, only one land station was located in the grid. Because the tide gauge and weather stations pairs to be examined (Alexander Bay and Port Nolloth) were not further than 80 kms apart, the actual weather station data rather then the HadSLP2 data were used (Figure 5.3). Vertical crustal movement data were available as model outputs at all the tide station sites from both the ICE-5G (VM2) and (VM4) models and were obtained from the PSMSL website. Vertical crustal movement from GPS stations coupled with tide gauge stations were supplied by Hartebeesthoek Radio Astronomy Observatory, South Africa (HartRAO).

A simple linear regression analysis was used to determine annual sea level trends from the monthly and annual tide gauge data. For each location, a proxy IB coefficient was determinated from the correlation of recorded monthly sea levels and monthly barometric pressure. A linear regression analysis was undertaken on the scatter plot to determine the slope of the line and hence the proxy IB coefficient applicable to monthly records of sea level. From these results, two methods were used to determine the effect of barometric pressure changes on the sea level trends. Method 1 involved the direct arithmetic deduction of the barometric trends from the sea level trends at each of the locations. Method 2 involved the correcting of the monthly sea level for every monthly recording at each of the locations, and thus a trend of the barometrically corrected sea levels could be calculated for each station. Both methods utilised the derived proxy IB coefficient for each station (for example, Durbans proxy IB coefficient used was -6.04 mm per hPa). This process was repeated for annual tide gauge data, but due to the small series of annual data, the analysis was confined to Method 1 only.

5.5 Results and Discussion

The main problem with the South African tide gauge records is confined particularly to the period between 1998 and 2002 when the data for recorded tide levels was confused with the mean level (ML) of each site. In the derivation of the chart datum (CD) to land leveling datum (LLD) conversion, an error was inadvertently introduced. This error was first identified in the analysis of the Durban sea level record (Garland and Mather, 2007) and has subsequently been found in other South African tide gauge records. The magnitude of the error varies between sites (Table 5.1). This overcorrection resulted in artificially raising sea levels during the period 1998-2002 (Garland and Mather, 2007). To obtain the correct LLD sea levels for the tide gauge locations, it was necessary to correct all records. This was achieved using (Table 5.2), which is based on the South African Navys conversion table (SAN

2008). Due to these problems, we used the PSMSL revised local reference (RLR) data, excluding Durban, as additional data correction processes have been applied. It must be noted that data in the period 1998-2002 has been largely removed from the RLR data by the PSMSL, possibly for the above-mentioned reasons.

Table 5.1: Chart Datum to Land Leveling Datum corrections for South African tide gauge sites between 1998 and 2002.

Port	**Correction to be applied to Chart Datum tide levels** (metres)
Port Nolloth	+0.12
Saldanha	-0.15
Cape Town	-0.11
Simons Town	-0.16
Hermanus	-0.19
Mossel Bay	-0.23
Knysna	-0.26
Port Elizabeth	-0.19
East London	-0.29
Durban	-0.20
Richards Bay	-0.19

Sea-levels from the various southern African locations using the PSMSL RLR data (excluding Durban) exhibited a scattering between rising and falling sea level (Figure 5.2). At each tide gauge location, an analysis of relative sea-level trends was undertaken (Table 5.3). All stations showed a rising sea level, except for Mossel Bay where there was a change of -0.40 ± 0.19 mm per year. Low results from Walvis Bay ($+0.38\pm0.33$ mm per year), Granger Bay ($+0.08\pm0.20$ mm per year) and East London ($+0.17\pm0.05$ mm per year) appear to be inconsistent with trends from adjacent locations and may suggest possible further data problems with these stations.

To improve reliability, records with periods longer than 30 years with at least 60% data coverage were selected and used to determine the regional relative sea-level trend (Table 5.4). Similarly, trends in barometric pressure were determined for the sites (Table 5.5).

These stations were then analysed further to determine the extent of barometric pressure influence on sea level. These sea-level trends were then barometrically corrected to provide an indication of the underlying rate of sea level change along the South African coastline. It should be noted that barometric stations are usually located at airports and can be situated some kilometers from the coastline. Ideally,

Table 5.2: Height of Chart Datum relative to Land Leveling Datum in South Africa in metres. Corrected datum conversions shown in bold. (* in use until 1 January 1994).

Port	**Up to 31 Dec. 1978**	**1 Jan. 1979 to 31 Dec. 1997**	**1 Jan. 1998 to 31 Dec. 2002**	**1 Jan 2003 onwards**
Port Nolloth	-0.718*	-0.900	**-0.955**	-0.925
Saldanha	-0.15	-0.900	**-1.125**	-0.865
Cape Town	-0.11	-0.900	**-1.085**	-0.825
Simons Town	-0.16	-0.900	**-1.163**	-0.843
Hermanus	-0.19	-0.900	**-1.168**	-0.788
Mossel Bay	-0.23	-0.900	**-1.168**	-0.933
Knysna	-0.26	-0.900	**-1.393**	-0.788
Port Elizabeth	-0.19	-0.900	**-1.308**	-0.836
East London	-0.29	-0.900	**-1.216**	-0.716
Durban	-0.20	-0.900	**-1.313**	-0.913
Richards Bay	-0.19	-0.900	**-1.395**	-1.015

Table 5.3: South African and Namibian sea level trends from the PSMSL data holdings except Durban (Mather, 2007).

Tide station	**Period of Record**	**Years of Record**	**Completeness of record** (%)	**Observed annual sea level trend using monthly data** (mm per year)	**Observed annual sea level trend using annual data** (mm per year)
Walvis	1958-1998	41	58	$+0.38 \pm 0.33$	$+0.67 \pm 1.06$
Lüderitz	1958-1998	41	78	$+2.73 \pm 0.81$	$+2.40 \pm 1.64$
Port Nolloth	1959-2007	49	75	$+1.25 \pm 0.23$	$+1.1 \pm 0.41$
Table Bay	1957-1972	16		Insufficient data	Insufficient data
Simons Town	1957-2007	51	78	$+1.5 \pm 0.22$	$+1.14 \pm 0.52$
Granger Bay	1967-2007	41	77	$+0.08 \pm 0.20$	$+0.44 \pm 0.53$
Hermanus	1958-1964	7		Insufficient data	Insufficient data
Mossel Bay	1958-2007	50	77	-0.40 ± 0.19	-0.66 ± 0.56
Knysna	1960-2007	48	64	$+1.27 \pm 0.50$	$+1.95 \pm 1.62$
Port Elizabeth	1978-2007	30	76	$+2.97 \pm 1.38$	$+2.89 \pm 2.05$
East London	1967-2007	41	50	$+0.17 \pm 0.05$	-2.03 ± 1.86
Durban	1970-2003	34	79	$+2.70 \pm 0.05$	$+2.40 \pm 0.29$
Richards Bay	1990-2000	11		Insufficient data	Insufficient data

Table 5.4: Regional relative sea level trends. Equal weighting was given to each location in the calculation of regional sea level trends in each region.

Region	**Port**	**Observed annual sea level trend using monthly data** (mm per year)	**Observed annual sea level trend using annual data** (mm per year)	**Regional relative sea level trends** (mm per year)
Western	Lüderitz	+2.73±0.81	+2.40±1.64	+1.87
	Port Nolloth	+1.25±0.23	+1.11±0.41	
Southern	Simons Town	+1.58±0.22	+1.14±0.52	+0.68
	Granger Bay	+0.08±0.20	+0.44±0.53	+1.48 excl. Granger and Mossel Bay
	Mossel Bay	-0.40 ±0.19	-0.66±0.56	
	Knysna	+1.27±0.50	+1.95±1.62	
Eastern	Port Elizabeth	+2.97±1.38	+2.89±2.05	+2.74
	Durban	+2.70±0.05	+2.40±0.29	

Table 5.5: South African barometric level trends.

Tide station	**Period of Record**	**Years of Record**	**Completeness of Record** (%)	**Observed monthly pressure trend** (hPa per month)	**Observed annual pressure trend** (hPa per year)
Alexander Bay	1987-2006	20	89	−0.0160±0.0034	−0.1630±0.0521
Cape Town	1970-2006	37	95	−0.000395±0.0001200	+0.0073±0.1220
George	1958-2007	27	95	−0.00384±0.00175	−0.0566±0.0157
Port Elizabeth	1978-2007	29	95	−0.0103±0.00160	−0.0114±0.0123
East London	1967-2007	37	98	+0.00221±0.00110	+0.0281±0.0074
Durban	1970-2003	37	97	+0.00277±0.00162	+0.0304±0.0071

the stations need to be adjacent to each other. However, because monthly or annual averages at the sites are to be used, the small variation between tide gauge and barometric station is assumed to be negligible or relatively constant between the sites (Figure 5.3).

To determine the proxy IB coefficient, monthly sea level recordings were correlated with monthly barometric pressure recordings((Figure 5.4 (a) to (g)).

With the exception of Alexander Bay, the proxy IB coefficients compared well with the globally distributed IB coefficients derived by Hoar and Wilson (1994) (Figure 5.4). The proxy IB coefficient for Alexander Bay of +3.60mm per hPa implies that when barometric pressure increases sea level also increases. Although this is contrary to the established theory, it has been reported elsewhere (e.g. in the Red Sea, El-Din *et al.*, 2007) and may reflect local conditions. The derived proxy IB coefficient for Durban, which is at the same latitude as Alexander Bay, was used as an alternative. Hoar and Wilson (1994) showed that the IB coefficient is latitude dependent and that for Southern Africa (28°-35°S) the expected values are between -5.3 mm per hPa and -6.9 mm per hPa. Using the derived barometric relationship the sea level trends were corrected for barometric influences for the selected datasets and are shown in Table 5.6 and Table 5.7.

In reviewing the vertical crustal movements from the Peltier ICE-5G model and the HartRAU GPS data, it was clear that the former model was relatively close to the actually recorded movements at Simons Town, but it appeared to underestimated the movement farther east at Richards Bay (Table 5.8). In order to provide a specific vertical crustal movement value at each tide station, the vertical movement was distributed linearly along the East Coast between the two stations. Because no data are available on the West Coast, those for Simons Town were used. This was on the basis that, the African plate is tilting upward in a south-west to north-east direction, the West Coast gauges would be approximately perpendicular to Simons Town. Comparison of the linear distribution of vertical crustal movement using the HartRAU data with those calculated by Peltier's model for Port Nolloth and Saldanha yielded a maximum difference in the results of 0.09 mm per year. This small difference was deemed to be insignificant.

The eustatic sea level trends where determined using the relative sea level trends corrected for barometric influences using Method 1 and 2 (as detailed earlier). Vertical land movements were then taken into account and the resultant local and regional eustatic trends were determined (Table 5.9 and 5.10). At a regional level, sea levels are rising around the southern African coastline. For comparative purposes, the coastline was divided into the western, southern and eastern coastal regions (Figure 5.2). The dissimilar physical factors between these regions could explain the differences found in sea level change.

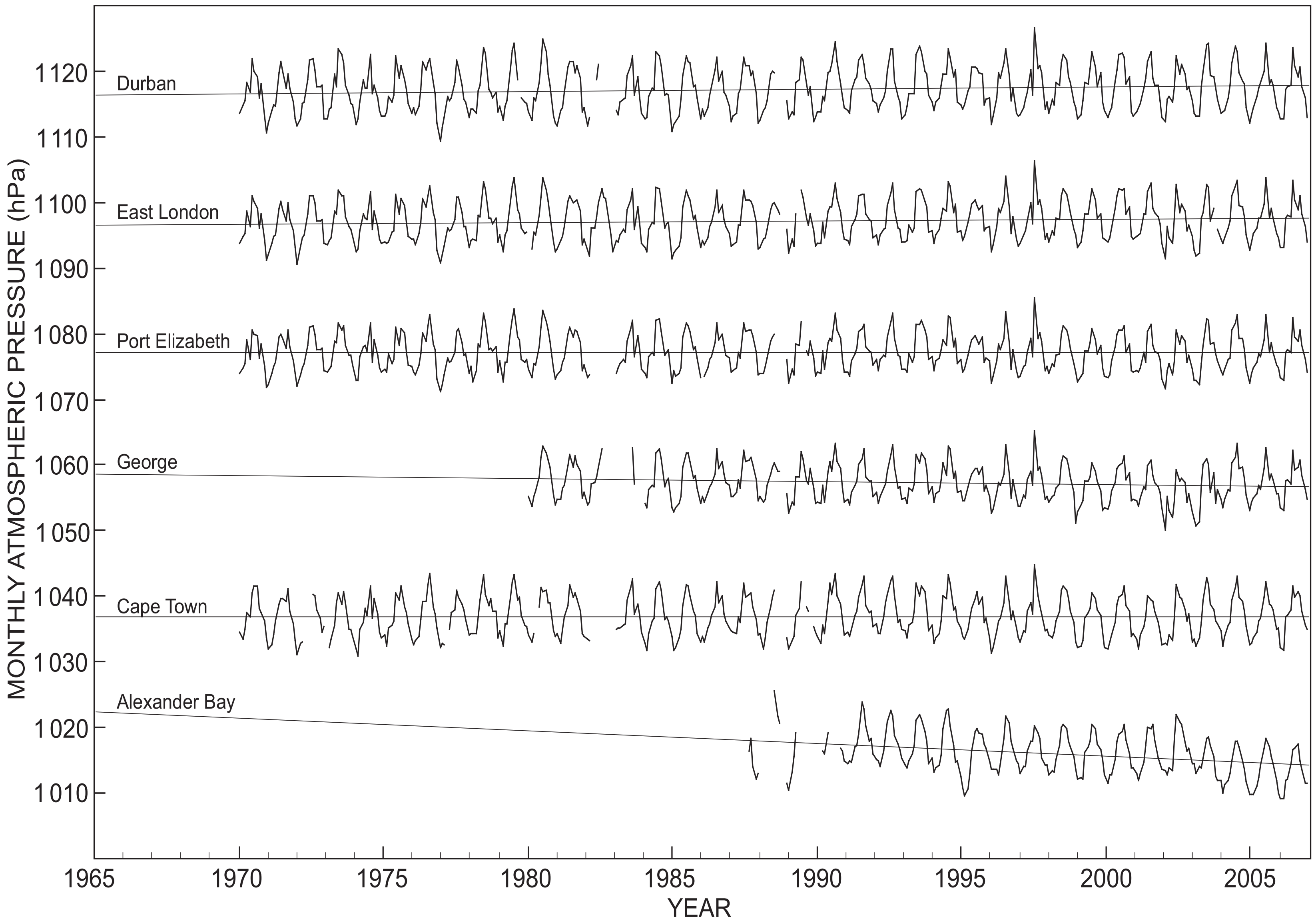

Figure 5.3: Monthly barometric pressure recordings for the different stations, 1970-2007.

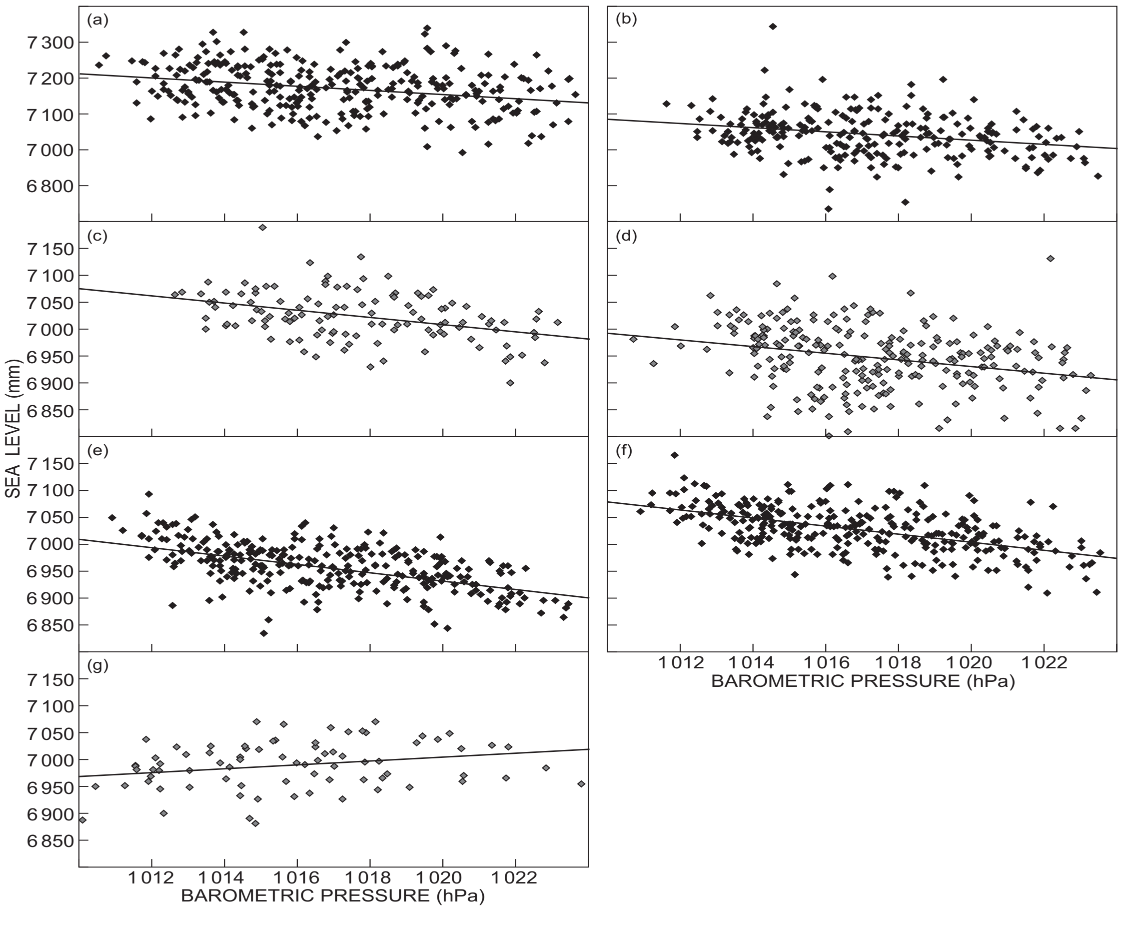

Figure 5.4: Relationship between monthly sea level and monthly barometric pressure, i.e. proxy IB coefficients for (a) Durban, (b) Port Elizabeth/Port Elizabeth, (c) George/Knysna, (d) George/Mossel Bay, (e) Cape Town/Granger Bay, (f) Cape Town/SimonTown and (g) Alexander Bay/Port Nolloth.

Table 5.6: Barometrically corrected annual sea level trends using monthly sea level data (*used Durban IB value as at equal latitude).

Region	**Stations: Tide Gauge station\Weather station**	**Observed annual sea level trend using monthly data**	**Proxy IB coefficients**	**Method 1**	**: summation of**	**trends**	**Method 2: Monthly barometrical corrected data**
		(mm per year)	(hPa per year)	**Linear barometric trends** (hPa per year)	**Linear barometric trends** (mm per year)	**Barometric corrected linear sea trends** (mm per year)	**Barometric corrected linear sea trends** (mm per year)
Western	Port Nolloth\ Alexander Bay	+1.25±0.23	−6.04±6.59*	−0.163	−0.984	+0.27	+0.76±1.11
Southern	Simons Town\ Cape Town	+1.58±0.22	−7.51±5.12	+0.007	+0.053	+1.63	+1.89±0.34
	Granger Bay\ Cape Town	+0.08±0.22	−7.67±7.20	+0.007	+0.053	+0.03	+0.39±0.20
	Mossel Bay\ George	−0.40±0.19	−6.19±8.21	−0.004	−0.020	−0.38	+0.22±0.46
	Knysna\ George	+1.27±0.50	−6.73±9.72	−0.006	−0.038	+1.23	+1.60±0.76
Eastern	Port Elizabeth\ Port Elizabeth	+2.97±1.38	−5.73±8.04	−0.011	−0.063	+2.91	+0.39±0.20
	Durban\ Durban	+2.97±1.38	−6.04±6.59	+0.0304	+0.180	+2.88	+0.39±0.20

Table 5.7: Barometrically corrected annual sea level trends using annual sea level data (*used Durban IB value as at equal latitude).

Region	**Stations: Tide Gauge station\Weather station**	**Recorded annual sea level trend using monthly data** (mm per year)	**Proxy IB coefficients** (hPa per year)	**Linear barometric trends** (hPa per year)	**Linear barometric trends** (mm per year)	**Barometric corrected linear sea trends** (mm per year)
Western	Port Nolloth\ Alexander Bay	+1.11±0.41	−6.04±6.59*	-0.163	-0.984	+0.13
Southern	Simons Town\ Cape Town	+1.14±0.51	−7.51±5.12	+0.007	+0.053	+1.19
	Granger Bay\ Cape Town	+0.44±0.53	−7.67±7.20	+0.007	+0.053	+0.49
	Mossel Bay\ George	−0.66±0.56	−6.19±)8.21	-0.004	-0.020	-0.64
	Knysna\ George	+1.95±1.62	−6.73±9.72	-0.006	-0.038	+1.91
Eastern	Port Elizabeth\ Port Elizabeth	+2.89±2.05	−5.73±8.04	-0.011	-0.063	+2.83
	Durban\ Durban	+2.40±0.29	−6.04±6.59	+0.030	+0.180	+2.58

Table 5.8: Vertical crustal movements along the Southern African coastline. [1]Same value as Simons Town. [2] Linear interpolation between Simons Town and Richards Bay.

Station	**ICE-5G VM2 model results (Peltier 2004)** (mm per year)	**ICE-5G VM4 model results (Peltier 2004)** (mm per year)	**HartRAU vertical crust movements for 2000-2007** (mm per year)
Port Nolloth	+0.33	+0.21	+0.29[1]
Saldanha	+0.30	+0.20	+0.29[1]
Cape Town	+0.29	+0.19	+0.29[1]
Simons Town	+0.27	+0.18	+0.29±0.18
Hermanus	+0.29	+0.20	+0.36[2]
Mossel Bay	+0.35	+0.25	+0.49[2]
Knysna	+0.34	+0.23	+0.54[2]
Port Elizabeth	+0.25	+0.15	+0.66[2]
East London	+0.23	+0.13	+0.78[2]
Durban	+0.21	+0.12	+1.03[2]
Richards Bay	+0.16	+0.08	+1.11±0.25

5.5.1 Western Region

This region contains one of four major coastal upwelling centres worldwide. The region is unique in that it is dominated by the cold upwelling waters of the Benguela system, which is trapped by warm waters to the north and south (Shannon and O'Toole, 2003). The western region is represented by three stations, Port Nolloth, Lüderitz and Walvis Bay. Unfortunately, the PSMSL does not have data for the past decade for these stations, which reduces the period of analysis. As mentioned earlier, the sea-level trend for Walvis Bay (+0.38 ± 0.33 mm per year) has been excluded from the analysis because of concerns regarding the reliability of the data. The Port Nolloth and Lüderitz tide stations yielded a regional relative sea-level trend of +1.87mm per year. The barometric correction was not applied to Lüderitz due to a lack of air pressure records at that station. However, the correction was applied to Port Nolloth, which yielded a sea level trend of between +0.76 mm per year and +0.13 mm per year. When vertical crustal movements were introduced, the eustatic sea level trend at Port Nolloth rose to between +1.05 mm per year and +0.56 mm per year , with an average of +0.80 mm per year.

These trends appears to concur with the IPCC assessment of global sea-level change when the contributions from ice melt and thermal expansion are considered. Global ice and glacier contributions have been estimated at +0.69mm per year (glaciers and ice cap +0.5±0.18 mm per year , Greenland ice sheet +0.05 ± 0.12 mm per year and Antarctic ice sheet +0.14 ± 0.41 mm per year) over a comparable

Table 5.9: Eustatic annual sea level trends using monthly data.

Region	**Stations: Tide Gauge station\ Weather station**	**Relative linear sea level trend relative to land (Table 5.3)** (mm per year)	**Barometrically corrected linear sea level trend (Method 1 from Table 5.6)** (mm per year)	**Barometrically corrected linear sea level trend (Method 2 from Table 5.6)** (mm per year)	**Vertical crustal movements from Table 5.8** (mm per year)	**Sea level corrected for vertical crustal movement and barometric changes (Method 1)** (mm per year)	**Sea level corrected for vertical crustal movement and barometric changes (Method 2)** (mm per year)	**Regional eustatic sea level change** (mm per year)
Western	Port Nolloth\ Alexander Bay	+1.25±0.23	+0.27	+0.76±1.11	+0.29±0.18	+0.56	+1.05	+0.80
Southern	Simons Town\ Cape Town	+1.58±0.22	+1.63	+1.89±0.34	+0.29±0.18	+1.92	+2.18	+1.23 or +2.00 (excluding Granger bay and Mossel Bay
	Granger Bay\ Cape Town	+0.08±0.22	+0.03	+0.39±0.20	+0.29±0.18	+0.32	+0.68	
	Mossel Bay\ George	−0.40±0.19	−0.38	+0.22±0.46	+0.49	+0.11	+0.71	
	Knysna\ George	+1.27±0.50	+1.23	+1.60±0.76	+0.54	+1.77	+2.14	
Eastern	Port Elizabeth\ Port Elizabeth	+2.97±1.38	+2.91	+3.38±1.48	+0.66	+3.57	+4.04	
	Durban\ Durban	+2.70±0.05	+2.88	+2.63±0.96	+1.03	+3.73	+3.66	+3.75

Table 5.10: Eustatic sea level trends using annual data.

Region	**Stations: Tide Gauge station\Weather station**	**Relative linear sea level trend relative to land (Table 5.3)** (mm per year)	**Barometrically corrected linear sea level trend (Method 1 from Table 5.7)** (mm per year)	**Vertical crustal movements from Table 5.8** (mm per year)	**Sea level corrected for vertical crustal movement and barometric changes (Method1) trends** (mm per year)	**Regional eustatic sea level change** (mm per year)
Western	Port Nolloth\ Alexander Bay	+1.11±0.41	+0.13	+0.29±0.18	+0.42	+0.42
Southern	Simons Town\ Cape Town	+1.14±0.51	+1.19	+0.29±0.18	+1.48	+1.14 or +1.97 (excluding Granger Bay and Mossel Bay)
	Granger Bay\ Cape Town	+0.44±0.53	+0.49	+0.29±0.18	+0.78	
	Mossel Bay\ George	−0.66±0.56	-0.64	+0.49	-0.15	
	Knysna\ George	+1.95±1.62	+1.91	+0.54	+2.45	
Eastern	Port Elizabeth\ Port Elizabeth	+2.89±2.05	+2.83	+0.66	+3.49	+3.55
	Durban\ Durban	+2.40±0.29	+2.58	+1.03	+3.61	

period (to this study) of 1961-2003 (Bindoff *et al.*, 2007). Thermal expansion of sea water has been found to be mainly confined to the upper layers of the ocean. Levitus *et al.* (2005) found that most (69%) of the ocean warming has occurred in the upper 700m over the period 1955-1998, a finding that was confirmed by Bindoff *et al.* (2007) for a slightly longer period of 1955-2003. Domingues *et al.*(2008) reported that 91% of the warming has occurred in the top 300m. Reporting on the Benguela Current Large Marine Ecosystem Shannon and O'Toole (2003) found a progressive warming of the surface waters of 0.7 C from 1920 to 2003 in the Benguela region. This figure would induce a thermal expansion component of 0.51 mm per year (using a depth of 700 m of sea water and thermal expansion coefficient β =88 x 10^{-6}m^3 per Kelvin) over a longer period than this analysis. The global thermal expansion component over the period 1961-2003 was estimated at 0.42 ± 0.12mm per year (Bindoff *et al.*, 2007).

The combined contributions of global glacial and ice melt (+0.69 mm per year) and global thermal expansion (+0.42 mm per year) of +1.11mm per year is similar to the rate of +0.80mm per year derived in our study, and is in the range of 0.8-1.6 mm per year provided by Ishii *et al.* (2006). The eustatic sea-level result of +0.42 mm per year using annual data appears to be low, which may have been influenced by the limited annual sea level data. Also, the large negative sea level trend recorded at Alexander Bay appears questionable. Unfortunately, this is the only sea pressure gauge in the area so it is difficult to confirm this result. The HadSLP2 data trends given in Gillett *et al.* (2005) also reflect a negative trend for this grid location. This negative trend, however, at Alexander Bay should be viewed with caution.

5.5.2 Southern Region

This region forms the south-eastern extreme of the Benguela system and upwelling has been observed seasonally as far east as Port Elizabeth (Shannon and O'Toole, 2003). The region is subject to variability in water temperature because of the mixing of the Benguela and Argulhas currents. Based on the work of Levitus *et al.*(2005), Bindoff *et al.* (2007) noted a significant warming off Cape Town and cooling off Mossel Bay/Knysna over the period 1955-2003. It is postulated that these two warm and cold seawater nodes are non-stationary and, depending on the relative strength of the Benguela and Agulhas currents, these nodes flux in an east/west and on-shore/off-shore direction, adding to the variability of the region.

There are four gauge sites exist along the coastline of the southern region (Figure 5.1), which provides better coverage in the calculation of regional sea-level changes then in the western region. Three of the tide gauges recorded rising sea-levels, whereas the one at Mossel Bay recorded a change of −0.40 ± 0.19 mm per year. This difference appears to be at odds with surrounding stations and previous results for Mossel Bay (i.e. +1.01 mm per year) for the period 1960-1988 (Brundrit *et al.* 1989). The tide records of Mossel Bay and Knysna, situated approximately 105 kms apart, were examined in more detail (Figure 5.5). The two gauges should record very similar sea levels because of their close proximity, but there may be small differences due to dissimilarities between the sites. For example, Knysna may be affected by the dynamics at the mouth of the lagoon due to the Knysna Heads. The records at Mossel Bay show a drop in sea levels of approximately 100 mm over the period 1991-1995. If this period is removed from the records then Mossel Bay shows little sea level change. The tide gauge record at Knysna is similarly affected, but at different times. Knysna has two drops in sea level of similar magnitude in the periods 1969-1972 and 1978-1979, and a rise of approximately 80 mm over the period 1996-2008. Removal of these periods from the record reduces the data set to such an extent that trend estimates are not reliable. These variations are not temporally synchronised at both tide gauges so they are not the results of large-scale oceanic processes. These drops in sea level could be as a result of data or gauge errors, which require further investigation to improve the quality of the data.

The stations of Simons Town and Knysna yielded a regional barometric corrected observed sea level change of +1.48 mm per year. When vertical crustal movements are factored in, the regional eustatic sea level trends are +1.97 mm per year and +2.00 mm per year respectively. The eustatic sea level change is higher then the warmer southern region than in the cooler western region.

5.5.3 Eastern Region

This region is affected by the warm Agulhas Current, which moves southwards along the coastline. The warm water is mainly near the surface, which has been exposed to rising air temperatures in the equatorial zone. There are four tide gauge stations along this coastline. Data from Richards Bay (11 years) and East London (50% coverage) have been set aside as the data coverage and length is insufficient to derive long term trends. The average regional sea level change rate of +3.03 mm per year estimated for this region was the highest found along the South African coastline. Correcting for local influences of barometric pressure at Port Elizabeth and Durban, results in both stations recording a marginally higher rate of sea level change compared to the uncorrected sea level trends. Those at Port Elizabeth ranged from +2.83 mm per year to +3.38 mm per year and at Durban from +2.58 mm per year to +2.88 mm per year. At both stations, increasing barometric trends are suppresses sea level changes to varying degrees, specifically in Durban, by as much as +0.18mm per year. When these sea level trends were adjusted for vertical crustal movements, the regional eustatic sea-level trends ranged from between +3.55 mm per year and +3.75 mm per year. These figures are greater than the global average figure of +3.0 mm per year (Bindoff *et al.*, 2007) which is to be expected for a region that is driven by warm water feeding in from the equator.

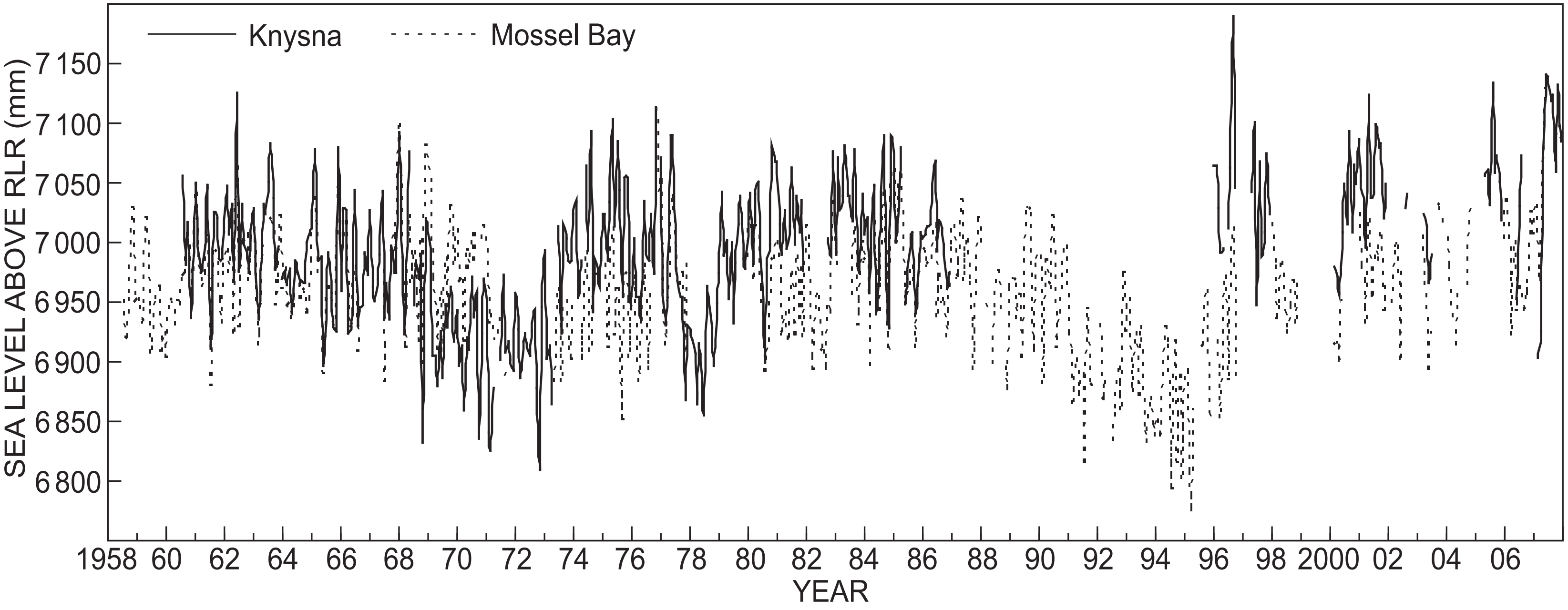

Figure 5.5: Tide records for Knysna and Mossel Bay, 1958-2008.

5.6 Conclusion

This is the first study to investigate all tide gauge sites along the Southern African coastline and to assess the problems associated with the tidal records. It also considers for the first time the effects of barometric pressure and vertical crustal movements on sea level trends along the coastline. Several problems with the SAN tide data have been identified, which need to be rectified using corrections derived in this study. Over the last 50 years, sea level change around the Southern African coastline has not been constant, thus it would be incorrect to apply a globally calculated sea level rise value uniformly to that coastline. The regional relative sea level trends determined here can be applied with more confidence to the various sections of our coastline for integrated coastal zone planning, adaptation responses as well as coastal infrastructural planning purposes. The variations in sea level change around the coast show distinctive differences in response, depending on their location. These changes are principally driven by the combination of physical characteristics at each location, most notably, by the influences and interactions of the Agulhas and Benguela currents, and in turn by water temperature, barometric air pressure changes and vertical crustal movements. Whether these results reflect long term trends, or are part of a shorter cycle will be better understood when more data are accumulated in the future.

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Epilogue to Chapter 5

This Chapter covered the analysis of the Namibian and South African tide gauges and the influence that changing barometric pressure and crustal movements have on eustatic sea level rise. The analysis shows that sea levels are rising at almost all stations however some stations show falling sea levels. The reasons for falling sea levels appear to be due to datum errors.

Prologue to Chapter 6

The results from Chapter 5 have shown that sea levels are influenced by the effects of barometric pressure, vertical crustal movements and ocean circulation systems. This has shown that the rate and directions of sea level change varies along the South African and Namibian coastline. It also highlighted corrections to the tide gauge data collected by the South African Navy. In addition regional sea level trends have been analysed providing an updated estimate of trends for the entire South African and Namibian coastline.

This has lead to the need to estimate what changes are being experienced by tide gauge stations outside of South Africa and Namibia in the rest of the southern and eastern coastline of Africa. The purpose of Chapter 6 is then to, analyse the tidal records from Mozambique, Mauritius, Tanzania, Kenya and the islands of Seychelles, British Indian Ocean Territories, Rodrigues Island, Reunion and Mauritius with the aim of estimating the most accurate measurements of sea level change. This Chapter will address the thesis questions of whether sea level has been changing along the southern and eastern coast of Africa and what the rate and direction of historical sea level change has been in the region.

This chapter includes the thematically linked, journal paper, which has been submitted to the African Journal of Marine Science.

Chapter 6

SEA LEVEL RISE FOR THE SOUTHERN AND EASTERN COAST OF AFRICA

6.1 Abstract

The effects of climate change on the world's oceans are resulting in changes in sea-levels around the world. sea-level rise remains a growing threat to the world's coast lines. However, this change is not likely to be uniform and it will vary within individual oceanic basins due to regional and local factors. The Western Indian Ocean (WIO) region comprising the southern and eastern seaboard of Africa and the islands of the Seychelles, British Indian Ocean Territory, Mauritius and Reunion. The WIO region has had little research on sea-level change although it is a heavily populated region. There is now considerable interest in bringing the region up to date by analysing sea-level trends across the region so that this new information can inform planning and adapting to sea-level rise throughout this region. The Southern and Eastern African sea-level records yields a range of sea-level changes from approximately -3.64 to $+4.35$ mm per year.

6.2 Introduction

Sea-levels have been constantly changing for millennia and this change has been accommodated by humans with relatively little negative impact. In most cases the nomadic lifestyles of people enabled them to move to new locations when things changed. This is in contrast to modern times where settlements are more permanent, communities are far more reliant on imported goods and foods and the increase in people living at the coast has become a worldwide trend (Rakodi and Treloar, 1997) . In these modern times the adaptability to increased sea-levels has been significantly reduced with the result that small increases in sea-levels have the ability to compromise coastal developments and especially those communities that are less affluent and mobile. In this paper the trends in sea-levels measured at tide gauges around the Western Indian Ocean (WIO) region will be analysed and interpreted to provide some guidance on what the changes have been and what may be expected into the future.

The WIO region comprises the southern and eastern seaboards of Africa and the islands of Madagascar, Seychelles, British Indian Ocean Territories (BIOT), Mauritius and Reunion as shown in Figure 6.1. This region has had little research on changes to sea-levels. There are relative few tide gauge recorders in this region. Apart from South Africa the rest of the region's tide gauge coverage is inadequate to provide an acceptable distribution of tide gauges as shown in Figure 6.1. This has been recognised as a gap and there is an initiative to increase the number of tide gauges in the region (Woodworth *et al.*, 2007).

The most comprehensive sea-level rise analysis in the region was undertaken by Mather (2007) and Mather *et al.* (2009) discussed in Chapters 4 and 5. They found that within the three regions around South Africa there were discernible variations in sea-level rise trends which were influenced by vertical crustal movements and barometric pressure changes (winds). Detailed examination of tide gauges outside South Africa has been limited. Mahongo (2009) analysed the Western Indian Ocean region using a total of 34 tide gauge stations from the PSMSL except for Reunion. Data for these stations covered periods from 1 to 37 years. Many of these stations records are too short to obtain confident trends given the short term cycles in sea-level change (Woodworth *et al.* 2007). Crustal movements were not taken into account in Mahongo's analysis and a number of significant corrections to the South African data have been undertaken since Mahongo prepared his paper (Nov. 2006) and so there is a need to revisit his results.

Mahongo and Francis (2010) examined the Zanzibar record for sea-level rise using spectral and multiple regression analysis and they found that sea-levels are falling at around −3.6 mm per year (1985 - 2005) based on hourly and monthly data downloaded from the University of Hawaii Sea Level Centre (www.ilkai.soest.hawaii.edu). They concluded that the drop in sea-levels is attributed to the increased strength of the northeast winds coupled with a potential reduction in the East African Coastal Current. Kebede *et al.* (2010) examined the Mombasa tide gauge as part of a climate change and sea-level rise vulnerability assessment. They found that the sea-levels are rising at +1.1 mm per year (1985 - 2002) however with a considerable amount of scatter in the trend which means that there is uncertainty in this trend. In the Kebede *et al.* (2010) study they decided to set this trend aside and to use a global scenarios of sea-level rise ranging from 0 to 1.26 m(IPCC, 2007: Rahmstorf 2007).

Recently Han *et al.* (2010) used satellite altimeter and tide gauge data to examine the entire Indian Ocean basin. They analysed 10 tide gauges with records longer then 30 years except Zanzibar which was 20 years. They concluded that the distribution of observed sea-level change within the WIO can be split into two distinctive regions along the 12 ° latitude line. The northern WIO region is typi-

Figure 6.1: Map of Southern and Eastern Africa showing the location of the tide gauge stations referred to in the text.

fied by falling sea-level while the southern WIO region shows rising sea-levels. This distribution is driven by a combination of long term trends in sea-level rise, vertical land movement, barometric pressure and wind changes which when combined at the local level creates this difference in sea-level. However, their choice of tide gauges appears questionable. For example, the inclusion of Zanzibar (20 years of record) and the exclusion of Mombasa (22 years of record) (Table 6.1) which is just 240 kms away. Zanzibar returns a falling sea-level which fits into their results but Mombasa shows a sea-level rise (Figure 6.1). This paper will discussed in more detail later in this paper.

Reliable sea-level change data is critical for a number of purposes. Port design engineers require a reliable estimate of sea-level rise in order to design port infrastructure. Similarly coastal managers and planners need a reliable record to define areas that require special management attention and/or special controls. Given concerns about current and future vulnerability to climate change and particularly sea-level rise, tidal records are becoming important indicators in monitoring the impacts of climate change around the world and can provide vital information to researchers in their efforts to assess the rate of change, the likely impacts of these changes and to give valuable input into future predictions of sea-level trends (Proshutinsky *et al.* 2001). An accurate tidal record is of great importance in this work as measurements are typically in the order of millimetres per year (Pugh, 1987).

6.3 Aims and Objectives of this study

As has already been pointed out there are a number of regional studies of sea-level trends which have been undertaken by Mather (2007); Mahongo (2009); Mather *et al.* (2009); Mahongo and Francis (2010); Kebede *et al.* (2010) and Han *et al.* (2010) in the WIO region. These studies have been undertaken at different scales for example, the single tide station of Zanzibar (Mahongo and Francis, 2010) to the whole Indian Ocean basin (Han *et al.*, (2010). Some of these studies are outdated as new information has come to light and so the aim of this paper is to reanalyse the region tide gauge stations in the light of recent new data and to assess the effects of vertical crustal movements and to review the completed research work on sea-level rise in the WIO region. It is hoped that this new information will allow for better planning and management, especially around adaptation to coastal erosion and sea-level rise, to be undertaken.

6.4 Materials and Methods

6.4.1 Sea-level records

The data used in this study has been sourced predominately from the Permanent Service for Sea Level Rise (PSMSL) (website: www.psmsl.org) during May 2011 and supplemented with recent detail sea-level rise analysis in the region. The PSMSL provides two sets of data from tide gauges, the 'Metric'data which is data received directly from the country of origin and the Revised Local Reference or 'RLR'data which is reassessed by the PSMSL for errors. These RLR records are assigned a different datum ±7000mm above mean sea-level to distinguish the RLR data from the Metric data.

All data used in this study are RLR data from the PSMSL data website except the South african data which are from Mather (2007) and Mather *et al.* (2009). The Southern African data has been recently reviewed and a number of errors have been identified and corrected providing improved data for sea-level rise trending. From the above-mentioned data records thirteen tide gauges located around the WIO region (Figure 6.1) were selected with a record length of at least 10 years as shown in Table 6.1. Ideally the period of record should be at least fifty years (Woodworth *et al.* 2007), however this would exclude virtually all the region's tide gauge stations. Given this limitation, the analysis should be considered a preliminary assessment as it is constrained by relatively short tide gauge records.

Table 6.1: Selected tide gauge station used in this study.

Station (see Fig 6.1)	**Country**	**Years of record**
Mossel Bay	South Africa	1958-2009
Knysna	South Africa	1960-2009
Port Elizabeth	South Africa	1978-2009
East London	South Africa	1967-2009
Durban	South Africa	1971-2009
Maputo	Mozambique	1961-2001
Point Des Galets	Reunion Island	1979-2009
Port Louis	Mauritius	1942-2010
Rodrigues Island	Mauritius	1986-2010
Diego Garcia	British Indian Ocean Territories	1988-2000
Pt La Rue	Seychelles	1993-2004
Zanzibar	Tanzania	1984-2004
Mombasa	Kenya	1986-2008

6.4.2 Vertical Crustal Movement

Although Africa is located on a relatively stable cratonic base (Cooper, 1995; Ramsay and Cooper, 2002), the African plate is subject to horizontal motion induced by plate tectonics resulting in some vertical movement. Vertical crustal movements have been difficult to quantify in the past because they have mainly been estimated using models, such as, the ICE-5G model (Peltier 1994). With the advent of satellites, it has become possible to measure the land and water surface of the Earth against an imaginary geoid to determine the vertical and horizontal changes in the earth's crust.

This network of monitoring points is relatively sparse over Southern and Eastern Africa with only four stations with sufficient data in the region. These are the global positions stations (GPS) at Richards Bay (200 kms north of Durban), Pointes Des Galets in Reunion, Diego Garcia in the British Indian Ocean Territories and Pt La Rue in the Seychelles. These geodetic stations are located next to tide recording stations. These data were downloaded from the Systeme D'Observation Du Niveau Des Eaux Littorales (SONEL) website www.sonel.org during May 2011 (Table 6.2).

6.5 Results

The tide stations were analysed for linear trends without atmospheric pressure correction and these results are shown graphically in Figure 6.2 where each gauge has been assigned an offset from their respective datum so that the individual station plots can be represented on a single figure and in tabular form in Table 6.3. One of the important observations arising from Mather *et al.* (2009) (Chapter 5) was that the trends in sea-levels from the Southern African region were questionable as the analysis at that time yielded trend reversals at sites 80 kms apart. A number of concerns regarding the accuracy of the South African Navy tide gauge data has been raised (Mather *et al.*, 2009). As a consequence the PSMSL data was used in the Mather *et al.* (2009) paper. Post the publication of the Mather *et al.* (2009) paper the South African Navy has undertaken additional analysis of these data and has provided the PSMSL with revised data. These data changes corrected some of the errors pointed out in the Mather *et al.* (2009) paper. Since these data have been corrected by the South African Navy the changes in SLR trends are notable and are shown in Table 6.4. This shows that the variance in sea-level trends has narrowed and adjacent station trends are now much more similar. The previous sea-level drop recorded at Mossel Bay has been reversed and now reflects a mild sea-level rise. East London now reflects a much higher rate of SLR. Durban now reflects a higher sea-level rise of +1.11 mm/yr., but still below the figure of 2.7 mm/yr calculated by Mather (2007).

Several authors (Church and White, 2006; Jevrejeva *et al.*, 2006; Jevrejeva, 2008; Woodworth *et al.*, 2009; Church and White, 2011) have been able to show accelerations in global sea-level rise using a variety of techniques. These analyses have been undertaken on long records as far back as the mid 1850's. Watson (2011) and Houston and Dean (2011) have recently published acceleration trends in Australia and North America respectively and both papers found a deceleration trend. This region's tide gauge records are limited however there are two tide stations with relatively long data namely Simon's Town, South Africa (1957-2009) and Port Louis,

Table 6.2: Vertical crustal movements along the Southern and Eastern African coastline relative to the geoid.

Station	**ICE-5G VM2 model results (Peltier 2004)** (mm per year)	**ICE-5G VM4 model results (Peltier 2004)** (mm per year)	**SONEL vertical crust movements** [1]Richards Bay, S. Africa [2]La Misere, Seychelles (mm per year)	**Period of record of SONEL vertical crustal movements** [1]Richards Bay, S. Africa
Mossel Bay	+0.35	+0.25	no data	
Knysna	+0.34	+0.23	no data	
Port Elizabeth	+0.25	+0.15	no data	
East London	+0.23	+0.13	no data	
Durban	+0.21	+0.12	+0.4±2.3[1]	2000-2009[1]
Maputo	+0.27	+0.18	no data	
Point Des Galets	−0.09	−0.13	−0.7±0.3	1999-2011
Port Louis	−0.03	−0.07	Insufficient data	2008-2010
Rodrigues Island	−0.07	−0.11	Insufficient data	2008-2010
Diego Garcia	+0.13	+0.07	+0.6±0.3[2]	1996-2009
Pt La Rue	+0.14	+0.15	−2.1±0.6	1995-2009
Zanzibar	+0.18	+0.13	no data	
Mombasa	+0.19	+0.14	no data	

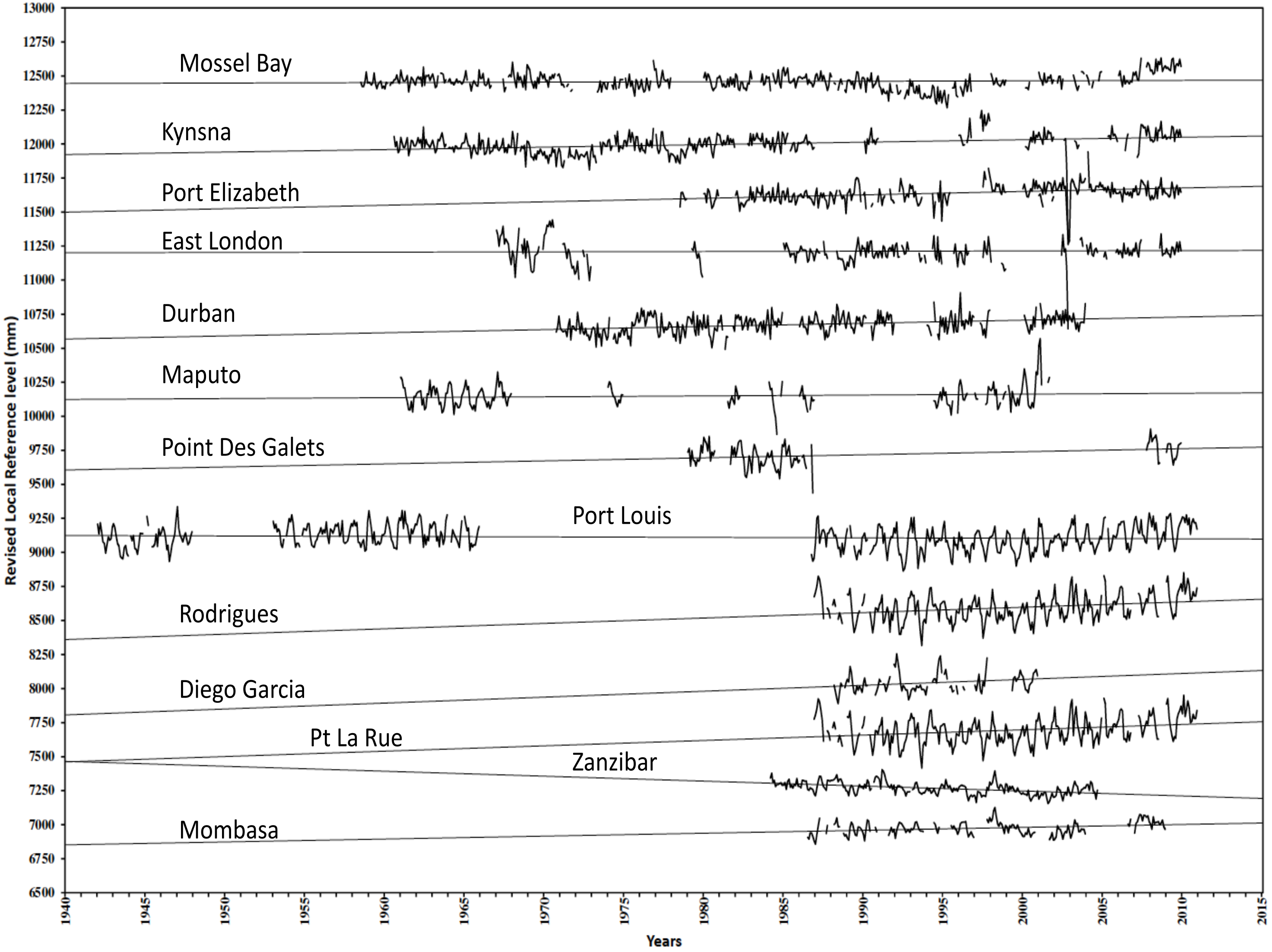

Figure 6.2: Sea level data for the selected stations. The straight line indicates the trend.

Table 6.3: Sea level changes along the Southern and Eastern African coastline from the PSMSL except as indicated.

Station (see Fig 6.1)	**Country**	**Sea level changes** [1] Mather 2007 [2] 1986-2010 (mm per year)
Mossel Bay	South Africa	+0.33±0.35
Knysna	South Africa	+1.81±0.54
Port Elizabeth	South Africa	+2.52±0.77
East London	South Africa	+2.30±0.93
Durban (ex PSMSL)	South Africa	+1.11±0.58
Durban	South Africa	+2.70±0.05[1]
Maputo	Mozambique	+0.63±0.47
Point Des Galets	Reunion Island	+2.19±1.57
Port Louis	Mauritius	−0.33±0.18
Port Louis	Mauritius	+4.30±3.18[2]
Rodrigues Island	Mauritius	+3.94±3.46
Diego Garcia	British Indian Ocean Territories	+4.35±7.61
Pt La Rue	Seychelles	+1.69±4.35
Zanzibar	Tanzania	−3.64±1.62
Mombasa	Kenya	+2.50±0.06

Table 6.4: Comparison between the sea-level changes calculated in Mather *et al.* (2009) and this paper.

Station	**Sea level changes** Mather *et al.* (2009) Chapter 5 (mm per year)	**Sea level changes** (mm per year)
Mossel Bay	−0.40±0.19	+0.33±0.35
Knysna	+1.27±0.50	+1.81±0.54
Port Elizabeth	+2.97±1.38	+2.52±0.77
East London	+0.17±0.05	+2.30±0.93
Durban	+2.70±0.05	+1.11±0.58

Mauritius (1942-2010). Typically a quadratic equation in the form of Equation 6.1 is fitted to the data.

$$y = a + bt + ct^2 \tag{6.1}$$

The acceleration term is the 2nd derivative of Equation 6.1 shown here as Equation 6.2.

$$\frac{d^2y}{dt^2} = 2c \tag{6.2}$$

The result of the analysis of acceleration in sea-levels is shown in Table 6.5 and the the tide gauge of Simon's Town is shown in Figure 6.3.

Table 6.5: Quadratic coefficients for Simon's Town and Port Louis tide data.

Station	**Coefficient c in Eqn. 6.1** (95% confidence limit) (mm per year^2)
Simon's Town	+0.0437±0.0147
Port Louis	+0.0281±0.0230

6.6 Discussion

Sea-levels from the various southern and eastern African locations using the PSMSL RLR data (excluding Durban) exhibited a scattering between rising and falling sea-level (Figure 6.2). At each tide gauge location, an analysis of relative sea-level trends was undertaken (Table 6.3). From earlier sea-level analysis it was observed that:

> "*Low results from Walvis Bay (*+0.38 ± 0.33 *mm per year), Granger Bay (*+0.08 ± 0.20 *mm per year) and East London (*+0.17 ± 0.05 *mm per year) appear to be inconsistent with trends from adjacent locations and may suggest possible further data problems with these stations*"
> (Mather *et al.* 2009).

After correction, all South African stations now show a rising sea-level. The Mossel Bay station which previously reflected a drop in sea-level of −0.40 ± 0.19 (1958 - 2007) is now reflected as having switched from a negative trend to a positive one and now shows a rise of +0.33 ± 0.35 mm per year (1958 - 2009). The station

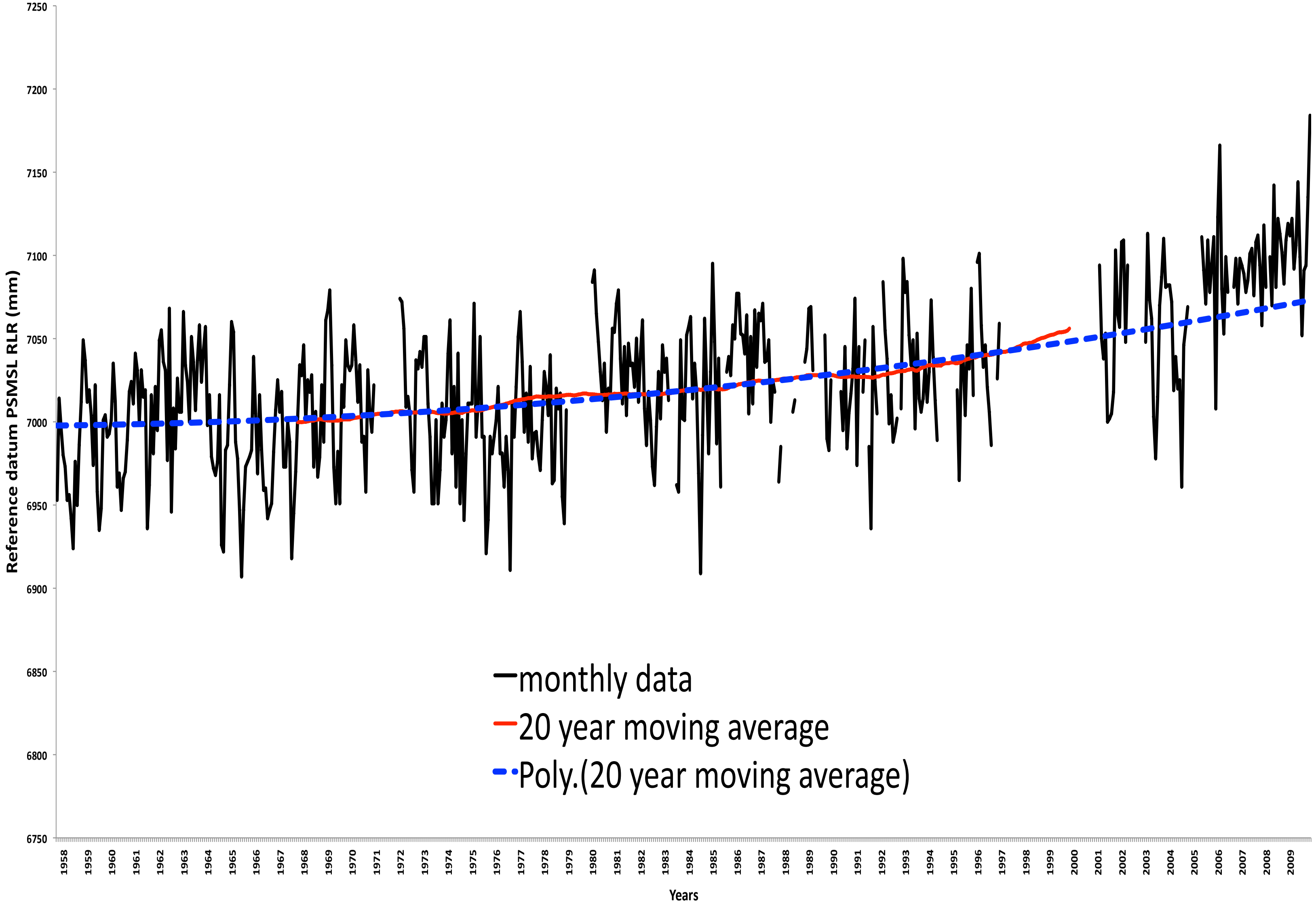

Figure 6.3: Simon's Town acceleration trend based on the methodology of Watson (2011).

at Knysna previously reflected a rate of rise of +1.27 ± 0.50 (1960 - 2007) and now shows an increase in a sea-level rise rate of +1.81 ± 0.54 mm per year (1960 - 2009). The East London station has also changed dramatically with an increase in sea-level rise trends from +0.17 ± 0.05 (1967-2007) to +2.30 ± 0.93 (1967-2009) mm per year. The tide station of Durban remains an anomaly as it did in previous work (Mather, 2007; Mather *et al.*, 2009).

The Durban record has been modified since 2007. Downloaded information from the PSMSL site on the 29 Aug. 2007 gave a linear trend of +0.0026 ± 0.68 mm per year (1971-2003) but is now showing an increase in sea-level rise of +1.11 ± 0.58 mm per year (1971-2009). This is still significantly lower then the corrected trend calculated by Mather 2007 which gave a sea-level rise trend of +2.70 ± 0.05 (1970-2003). The tide gauges along the east coast of South Africa namely Port Elizabeth (+2.52 ± 0.77 mm per year) and East London (+2.30 ± 0.93 mm per year) yield a sea-level rise value around +2.5 mm per year. It is therefore surprising that the Durban tide gauge station reflects a value of less then 50% of this average trend given the regional sea-level changes and vertical crustal movements at these sites will be very similar. For this reason it is suspected that the Durban tide gauge is still not correctly reflecting the actual sea-level rise trend and therefore in this paper the Durban sea-level trend that will be used will be that calculated by Mather (2007) of +2.70 ± 0.05 mm per year. These dramatic changes can only be ascribed to corrections undertaken by the authorities in light of the research work by Mather (2007) and Mather *et al.* (2009) and this is to be encouraged as only through these efforts can the correct information be provide to interested parties.

The sea-level trends to the north east of South Africa can be generally categorised into three distinct regions:

(1) The African mainland northwards from Maputo to Mombasa reflects sea-level trends which are generally smaller than those trends in the Southern African region (Table 6.6) with the notable exceptions of a fall in sea-level at Zanzibar −3.64 ± 1.62 mm per year. Mahongo and Francis (2010) concluded that the drop in sea-levels is attributed to the increased strength of the northeast winds coupled with a potential reduction in the East African Coastal Current.

(2) The Eastern African Islands comprising Mauritius, Reunion and Rodrigues Island. Here relative sea-level trends are at around +2.19 to +4.30 mm per year.

(3) The most northern islands of Seychelles and British Indian Ocean Territories where sea-levels are rising at +1.69 ± 4.35 and +4.35 ± 7.61 mm per year. The standard deviation of the linear trends is larger than the linear trends and so these figure should be treated with some caution.

As was pointed out earlier Kebede *et al.* (2010) examined the Mombasa tide gauge as part of a climate change and sea-level rise vulnerability assessment and they found that the sea-levels are rising at +1.1 mm per year. The data however was for the period 1985 - 2002 and they advised that this was the only data available at that time from the PSMSL. An analysis for the same period (1985 - 2002) was undertaken and the result obtained was +0.226 ± 1.512 mm per year. It is not clear why there is a difference in trends for the same period. Additional data has since been added extending to a slightly longer period (1986 - 2008). When this data was used a sea-level rise of +2.50 ± 0.06 mm per year was obtained. This is significantly different to Kebede *et al.* (2010) results and perhaps to some extent justifies their decision to use global sea-level rise trends in their case study.

Table 6.6: Sea level changes along the Southern and Eastern African coastline from the PSMSL except as indicated.

Region	**Station**	**Sea level changes** [1] Mather, 2007 [2] 1986-2010 (95% confidence limit) (mm per year)	**Averaged regional sea level trends** (mm per year)
Southern South Africa	Mossel Bay	$+0.33 \pm 0.35$	+1.07
	Knysna	$+1.81 \pm 0.54$	
Eastern South Africa	Port Elizabeth	$+2.52 \pm 0.77$	+2.51
	East London	$+2.30 \pm 0.93$	
	Durban	$+2.70 \pm 0.05$[1]	
Mozambique	Maputo	$+0.63 \pm 0.47$	+0.63
Eastern African Islands	Point Des Galets	$+2.19 \pm 1.57$	+3.48
	Port Louis	$+4.30 \pm 3.18$[2]	
	Rodrigues Island	$+3.94 \pm 3.46$	
BIOT	Diego Garcia	$+4.35 \pm 7.61$	+4.35
Seychelles	Pt La Rue	$+1.69 \pm 4.35$	+1.69
Central Eastern Africa	Zanzibar	-3.64 ± 1.62	−1.14
	Mombasa	$+2.50 \pm 0.06$	

So far the relative sea-level trends have been discussed. One of the major influences on the rate of sea-level change is the amount of vertical crustal movement experienced at the tide gauge site. To determine the actual rate from the geiod or so called ‘eustatic’ sea-level change, the observed (HartRAU or SONEL) or predicted (Peltier, 2004) rates where used to determine this rate at each tide gauge station. After this step stations were clustered into regionally similar groups. These groups were then analysed to determine a regional ‘eustatic’ sea-level change (Table 6.7).

Along the southern South African coast the ‘eustatic’ sea-level trend is +1.59 mm per year, rising to +3.06 mm per year along the eastern South African coastline.

In Mozambique the 'eustatic' sea-level change reduces to +0.85 mm per year and as one moves further up the East African coastline the 'eustatic' sea-level trend reverses and records a negative 'eustatic' sea-level trend at Zanzibar (−3.49 mm per year) and then reverses again to record a positive sea-level change at Mombasa (+2.66 mm per year). The western Indian Islands all record a rising 'eustatic' sea-level trend with a average of +3.2 mm per year. The results suggest that there is considerable variation in sea-level trends within the region.

While the tide gauges in the region show a rising sea-level no acceleration in sea-levels has yet been attempted or determined for this region. The two longest tide gauges in the region Simon's Town ($+0.0437 \pm 0.0147$ mm per year^2) and Port Louis ($+0.0281 \pm 0.0230$ mm per year^2) show a statistically significant weak acceleration in sea-levels over their respective period of record (Table 6.5). This is the first time that an acceleration (albeit weak) in sea-levels has been detected in this region. These results appear to be higher then the recent results from Church and White (2011) of 0.009 ± 0.003 mm per year^2 since 1880 and 0.009 ± 0.004 mm per year^2 since 1900. This may be due to the fact that only these two stations were available for this analysis whereas the study of Church and White (2011) utilised 230 stations including these two stations. The results here are in contrast to the weak decelerations found by Watson (2011) and Houston and Dean (2011).

Recently Han *et al.* (2010) analysised the same region and found that sea-levels were dropping north of the 12 ° latitude line while south of this line the sea-levels were found to be rising (Figure 6.4). The research work in this paper generally agrees with the conclusions that sea-levels are rising south of the 12 ° latitude line, However north of this line the results are mixed. Examining Table 6.7 there is agreement that the relative and eustatic sea-levels adjacent to Zanzibar are falling (-3.64 ± 1.62 and -3.49 mm per year respectively), however at Mombasa, just 240 kms north of Zanzibar, the relative sea-levels are rising at +2.50 mm per year. After applying the observed SONEL vertical crustal movement the sea-level remains rising at +2.66 mm per year.

Han *et al.* (2010) presented a coloured map described as Fig. 1 (on page 547) in their paper reproduced here as Figure 6.4 which shows the zones of sea-level rise and fall. A closer examination of Figure 6.4 shows a zone of sea-level rise along the coastline covering both the Zanzibar and Mombasa station locations. Figure 6.4 is partially covered by a series of white stars overlaying what appears to be a zone in which the Han *et al.* (2010) results show rising sea-levels despite placing significance on the fall in sea-levels being recorded at Zanzibar (Figure 6.5).

Perhaps this difference in the fall in sea-levels at Zanzibar is due to the increased strength of the northeast winds coupled with a potential reduction in the East African Coastal Current as concluded by Mahongo and Francis (2010). In contrast Mombasa does not reflect a fall despite its close proximity to Zanzibar. However Mombasa is located in a tidal estuary and would thus be less affected by changes in the East African Coastal Current.

Table 6.7: Eustatic sea-level changes along the Southern and Eastern African coastline from the PSMSL except as indicated.

Region	**Station**	**Relative sea-level changes** [1] Mather, 2007 [2] 1986-2010 (mm per year)	**Vertical crust movements** [3] Peltier, 2004 av. VM2&VM4 [4] SONEL (mm per year)	**Eustatic sea-level trends** (mm per year)	**Eustatic regional sea-level trends** (mm per year)
Southern	Mossel Bay	+0.33±0.35	+0.49[3]	+0.82	+1.59
South Africa	Knysna	+1.81±0.54	+0.54[3]	+2.35	
Eastern	Port Elizabeth	+2.52±0.77	+0.66[3]	+2.91	
South	East London	+2.30±0.93	+0.78[3]	+3.18	+3.06
Africa	Durban	+2.70±0.05[1]	+0.4±2.3[4]	+3.10	
Mozambique	Maputo	+0.63±0.47	+0.22	+0.85	+0.85
Western	Point Des Galets	+2.19±1.57	−0.7±0.3[4]	+1.49	
African	Port Louis	+4.30±3.18[2]	−0.05[3]	+4.25	+3.20
Islands	Rodrigues Island	+3.94±3.46	−0.09[3]	+3.85	
BIOT	Diego Garcia	+4.35±7.61	+0.6±0.3[4]	+4.95	+4.95
Seychelles	Pt La Rue	+1.69±4.35	−2.1±0.6[4]	−0.41	−0.41
North	Zanzibar	−3.64±1.62	+0.15[3]	−3.49	−0.42
Eastern	Mombasa	+2.50±0.06	+0.16[3]	+2.66	

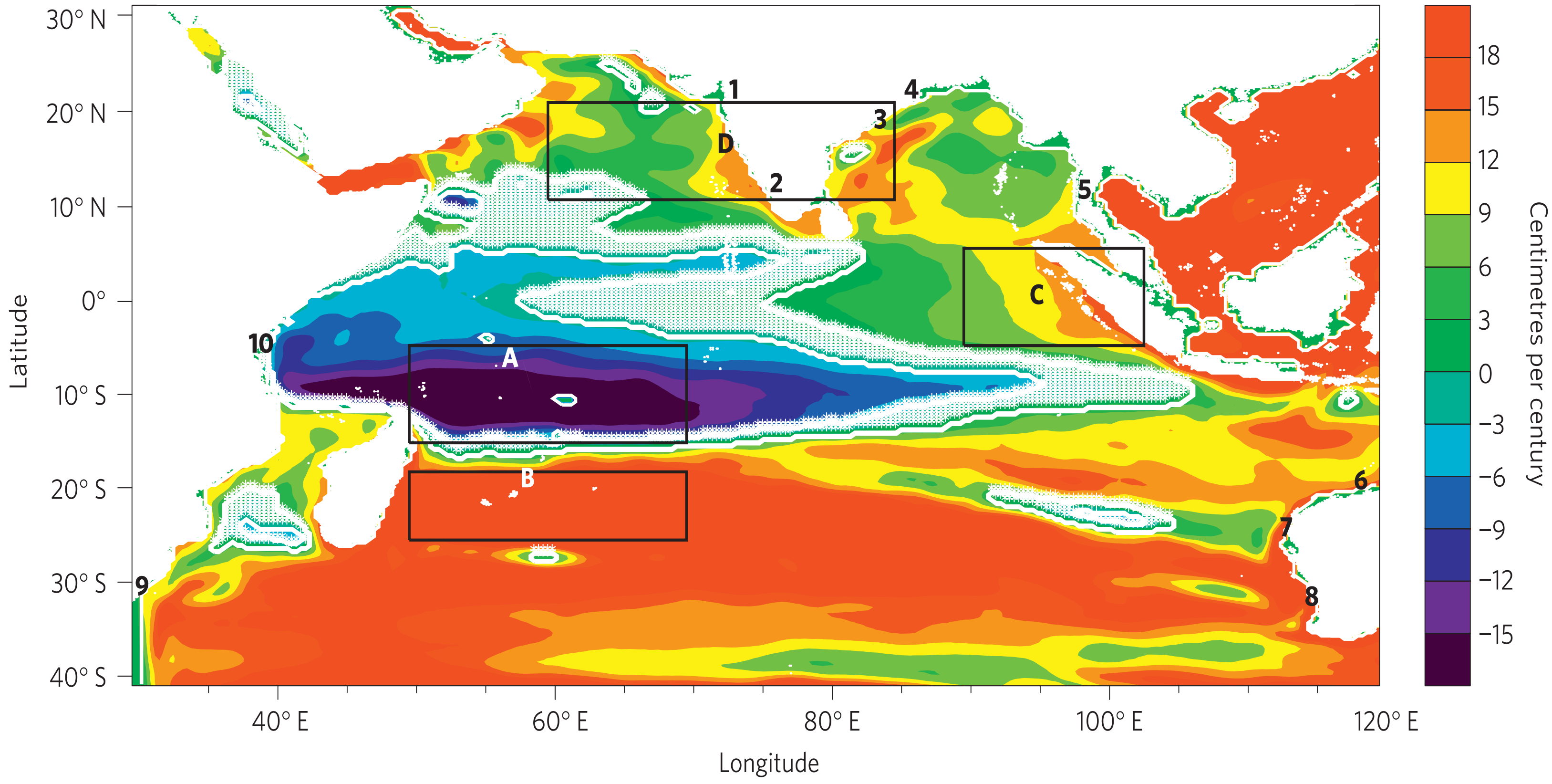

Figure 6.4: Sea-level changes in the Indian Ocean - Figure 1 from Han *et al.* (2010). Blocks ABCD relate to Han *et al.*(2010) analysis.

Figure 6.5: Magnified section around Mombasa and Zanzibar tide gauges from Fig. 6.4. This shows a positive rise in sea-levels (green) in conflict with Han *et al.*(2010). North at top of Figure.

6.7 Conclusion

This is the first study to investigate all tide gauge sites along the southern and eastern African coastline and to assess the problems associated with the tidal records. Over the last 60 years, sea-level change around the southern and eastern African coastline has varied with location. An application of a globally derived sea-level change figure would be incorrect. The regional relative sea-level trends determined here can be applied with more confidence to the various sections of our coastline for integrated coastal zone planning, adaptation responses as well as coastal infrastructural planning purposes. As was indicated earlier in this paper the trends should be taken as first estimates of sea-level changes in the region and with future monitoring these results will be the basis of determining if these reflect long term trends, or if they are part of a shorter cycle.

6.8 Acknowledgements

The author wish to acknowledge the data generously provided by the Permanent Service for Mean sea-level (PSMSL), the South African Navy's Hydrographic Office (SANHYDRO), Professor W.R. Peltier for his information which is hosted on the PSMSL website, Dr L. Combrinck of the Hartebeesthoek Radio Astronomy Observatory and Systeme D'Observation Du Niveau Des Eaux Littorales (SONEL).

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Epilogue to Chapter 6

The results from Chapter 6, while very preliminary, completes the tide gauge analysis of the Southern and Eastern coastline of Africa. What is clear is that the rates of sea level rise differ between the different stations.

Prologue to Chapter 7

The findings presented in Chapters 4, 5 and 6 show that the tide gauges in in the study area exhibit varying degrees of sea level rise and fall and has answered the question of whether sea level has been changing and what the rate and direction of historical sea level change has been along the southern and eastern coast of Africa.

What is now needed is to understand the impacts of sea storms especially when combined with raised water levels from sea-level rise. While sea-level rise is a slow and relatively gradual impact (press impact) storms are sudden large impacts (pulse impact). The combined impact of a severe storm with sea-level rise is likely to produce the largest amount of coastal erosion and shoreline change. It is the combination of these two impacts which interests us here. If these combined impacts can be understood and quantified, they can be planned for and managed. This will assist in ameliorating the likely impacts and losses. The purpose of Chapter 7 is then to determine the extent of impact on the sandy coastline of the region. This Chapter will aim to build the scientific basis underpinning the development of a model to determine possible impacts under current and future sea level scenarios and starting to address the question of how can these changes be managed.

This Chapter includes the thematically linked, journal paper, which has been published by the Coastal Engineering Journal as a research paper titled:

Mather, A.A., Stretch, D.D. and Garland, G.G. 2011. Predicting extreme wave run-up on natural beaches for coastal planning and management, *Coastal Engineering Journal*, Vol. 53, No. 2., 87-109.

The journal publication has been reproduced in full with the permission of the Editor of the Coastal Engineering Journal in the Appendix.

Chapter 7

PREDICTING EXTREME WAVE RUN-UP ON NATURAL BEACHES FOR COASTAL PLANNING & MANAGEMENT

A simple empirical model is proposed for predicting extreme wave run-up on natural beaches during severe wave events (deep water wave heights $H_0 \gtrsim 8$ m or return periods of about 50 years). The new model departs from traditional approaches that use the slope of the beach face β_f and the Iribarren number ξ_0 as parameters for predicting run-up and instead uses the distance offshore x_h to the $h = 15$ m depth contour to estimate a near-shore profile slope $S = h/x_h$. Extreme run-up R_x is then expressed in terms of S as $R_x/H_0 = C\,S^{2/3}$. Observations from recent severe storm events in South Africa are used to estimate the dimensionless coefficient $C \simeq 7.5$. The data are also compared with those of Holman (1986) and the results verify his regression equations and confirm they are valid for significant wave heights extending to 8.5 m for beach-face slopes around 0.1. The run-up predictions of Holman (1986), Nielsen and Hanslow (1991) and Stockdon *et al.* (2006) are compared to those of the proposed new model. The results suggest that the new model reduces the uncertainties in predicting wave run-up on natural beaches compared with previous models, and thus enables improved estimates of extreme wave run-up and the upper limit of beach change for coastal planning and management.

wave run-up; beaches; storms.

7.1 Introduction

The prediction of extreme wave run-up on natural beaches is of particular interest to coastal engineers, coastal managers and land use planners. Extreme wave run-up levels are important in many planning processes but especially for estimating appropriate development setback lines (Holland and Holman, 1993) and the upper limit of beach change (Roberts *et al.*, 2010). Wave run-up has been defined as the "time-varying location of the shoreline water level about still-water level" (Holman and Sallenger, 1985). Extreme wave run-up may therefore be defined as the maximum level, relative to the still water level (SWL), reached by a wave or by a series of waves as they break and run-up the natural beach profile. It is often visible as a line of debris left after a wave event and can also be marked by a small scarp at the back of the beach left by the eroding waves.

The magnitude of wave run-up depends on a number of factors. For example, the maximum run-up observed at a particular location will depend on the duration of the observations because longer durations mean higher probabilities of sampling more extreme events. Wave run-up is expected to depend on wave parameters e.g. deep water significant wave height (H_0), period (T_0) and steepness may all have some influence. Run-up can also depend on the shape of the storm peak tide (Nielsen, 2009). In this paper we focus on the extreme run-up of large storm waves defined as waves with H_0 exceeding 8 m and return periods (or average recurrence intervals) of about 50 years.

In developed areas extreme wave run-up is used to estimate the risk to existing and proposed infrastructure within the coastal zone. Early work on wave run-up was confined to laboratory experiments using regular waves on impermeable slopes (Iribarren and Nogales, 1949; Miche, 1951; Saville, 1956; Savage, 1958; Hunt, 1959; Battjes, 1974a, b) and extended by more recent work (Mase, 1989; Hedges and Mase, 2004). Under these conditions wave run-up is entirely predictable. Irregular waves on permeable slopes are less predictable and generate a range of wave run-ups over time as shown in Figure 7.1. The wave run-up $R(t)$ for a given range of wave conditions varies around an average value R_{av}, commonly referred to as the swash level (Holland and Holman, 1993), and between maximum and minimum values (R_{max} & R_{min}) that depend on the duration of the record (as noted above). Statistical measures based on exceedance probabilities are widely used to characterize extreme wave run-up values of R that are exceeded say 2% of the time (denoted R_2 herein) are commonly used. However, for practical applications in coastal planning or risk assessment, it is useful to know the wave run-up associated with storm events having a specified average recurrence interval or return period (Callaghan *et al.*, 2009). Those values are not in general simply related to exceedance statistics such as R_2. Since our main concern in this paper is risk assessment due to wave attack, we focus on extreme run-up due to storm waves with average recurrence intervals of about 50 years as a typical design life for coastal structures. These values will be compared with previously published results for R_2 which are often used for coastal management and planning purposes.

Despite the development of empirical models to determine wave run-up on slopes, relatively little work has focused on extreme run-up on natural beaches. Previous research concerning wave run-up on natural beaches has used two approaches. The first approach is where run-up due to a range of wave conditions is observed at a

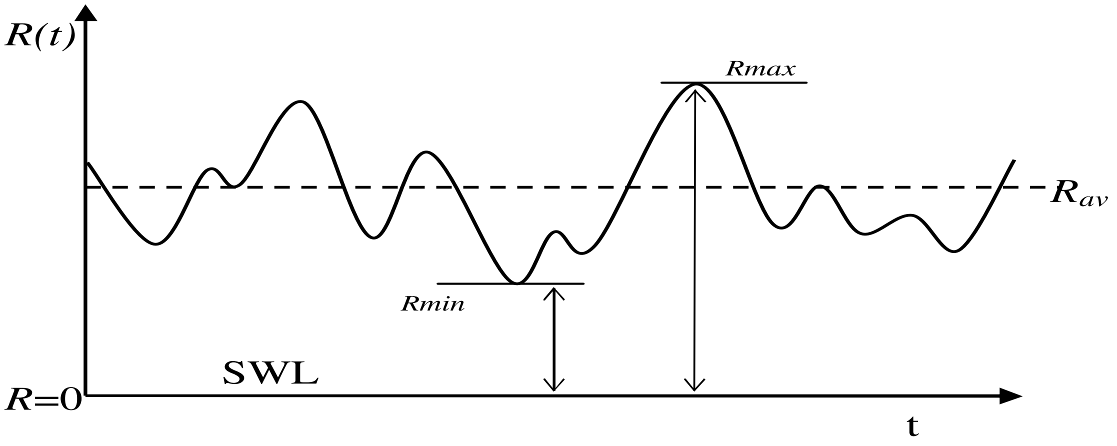


Figure 7.1: Definition sketch of random wave run-up over time. R_{max} is the maximum wave run-up level, R_{min} is the minimum wave run-up level, R_{av} is the average wave run-up level and SWL is the still water level determined as the tide level at the time of the wave run-up.

single location. For example Holman (1986) used observations from the US Army research facility at Duck, USA. The data were for a range of wave heights from 0.4 m to 4.0 m, but included only a narrow band of beach slopes near 0.1.

A second approach is where data is sampled from several geographical locations for generally short periods. An example of this approach has been the work of Nielsen and Hanslow (1991) who collected data from six beaches in New South Wales, Australia. The data coverage was for deep water root mean squared wave heights H_{0rms} ranging from 0.53 m to 3.76 m (H_0 ranging between 0.75 m and 5.32 m), significant wave periods from 6.4 s to 11.5 s, and beach foreshore slopes from 0.026 to 0.189.

There is a third possible approach where data from a single extreme storm event is collected from a large number of beaches of varying beach slope. In this case the range of wave heights is limited, but the beach parameters can vary considerably. This approach relies on the (rare) occurrence of extreme storm events that leave clearly visible 'telltale' signs of their effects on the beach which can subsequently be measured. This method was used for the present study. We could not find any published research that has previously adopted this approach for investigating wave run-up.

The variability of wave run-up has challenged researchers attempting to resolve the respective interactions which determine the extent of wave run-up infra-gravity waves, swash action and incident wave energy. The relative strength of these components varies in the onshore direction: decreasing incident wave energy is progressively balanced by infra gravity wave energy between the inner and outer surf zones (Aagaard and Greenwood, 1995). Infra-gravity waves comprise bound long waves,

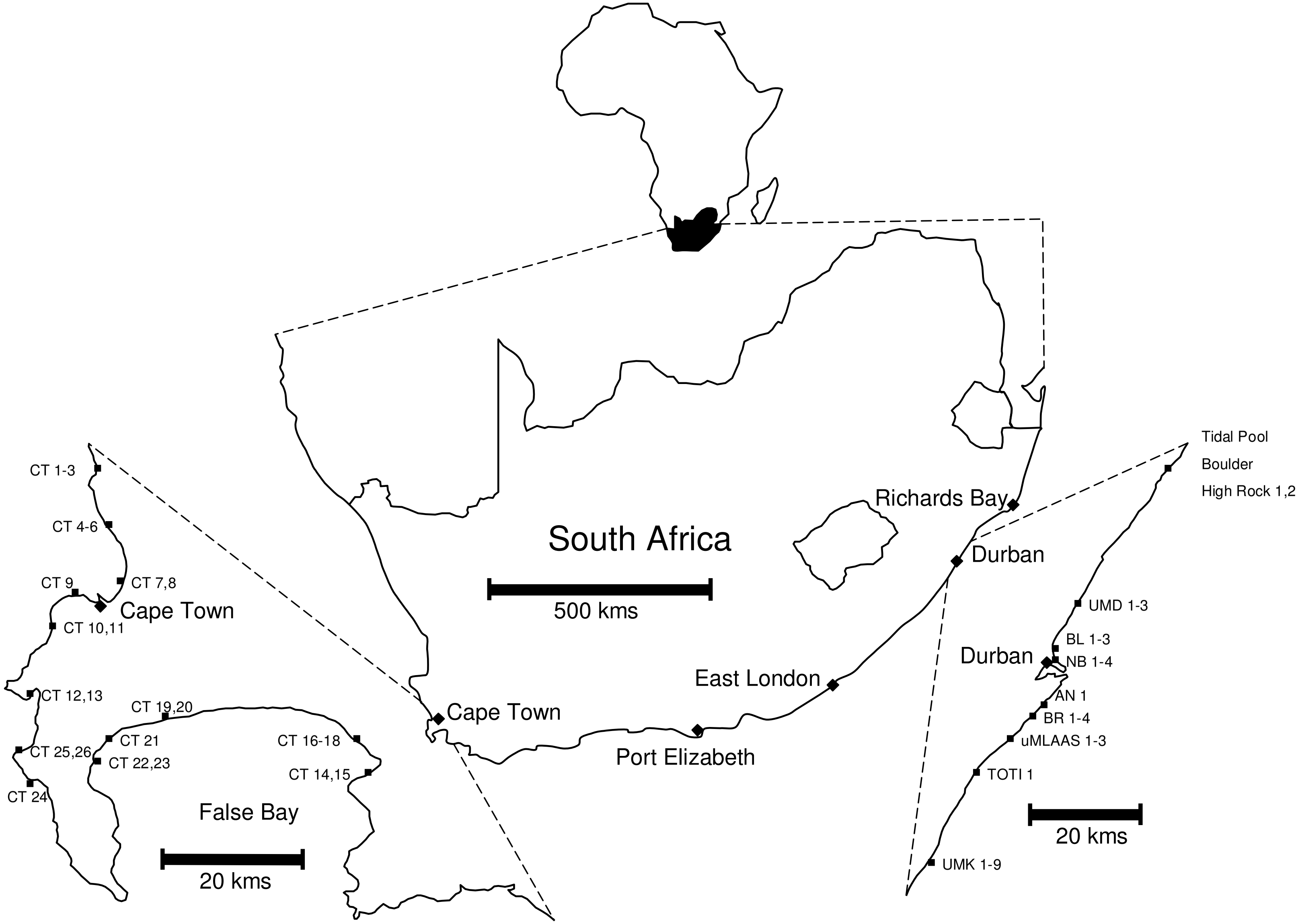


Figure 7.2: The South African coastline showing the location of the present wave run-up measurements.

leaky waves and edge waves (Bowen, 1972; Huntley and Kim, 1984) and bore and swash interactions (Emery and Gale, 1951; Carlson, 1984; Mase, 1995). In addition physical factors such as the beach topography will result in some variability of wave run-up. Secondary features of the storm event will also influence the magnitude of wave run-up, for example, eye-wall eddies of the cyclone wind field (Nielsen, 2009). The complex interaction of these factors in time and space produces considerable variability in wave run-up observations.

Observations by Mase (1989) have ascribed R to a combination of (1) the incident wave height (2) low frequency infra-gravity waves or 'surf beat' (Munk, 1949; Tucker, 1950) and (3) wave groups (as opposed to a single wave) resulting in a larger R. Aagaard and Greenwood (1995) have shown that infra-gravity waves dominate the surf zone and R is dominated by infra-gravity waves when $\xi_0 < 1.5$, as is the case here. The infra-gravity waves periodically raise the water levels allowing the incident waves to run further up the beach slope [Wright, 1980]. Previous work by Goda (1975), Guza & Thornton (1985) and Howd *et al.* (1991) have estimated that infra-gravity wave amplitudes vary between 20% and 60% of the incident wave height.

Our observations of extreme wave run-up are presented in §7.2 which is followed by a discussion of existing wave run-up models in §7.3. The wave run-up observations are compared to values of R_2 predicted by existing wave run-up models in §7.4. A proposed new model is introduced and evaluated in §7.5 and §7.6. Discussion and conclusions are presented in §7.7.

7.2 Observations

The coastline around South Africa can be described as having an energetic wave climate and is typically steep (due to absence of a wide flat coastal terrace) with water depths reaching 15 m within 750 m of the shoreline. Wave events, particularly in the southern coastline of South Africa, are influenced by coastal lows and cutoff low pressure systems generated by weather systems in the southern oceans. Along the east coast of South Africa these influences, as well as tropical cyclones that originate north-east of Madagascar, influence the wave climate (Taljaard, 1985). During these events the deep water significant wave heights occasionally reach 8 to 10 m (periods between 11 and 17 seconds) off Durban and 10 to 12 m (periods between 14 and 20 seconds) off Cape Town (Ematek, 1991). Two such extreme wave events that occurred recently were analysed for this study.

The first event occurred during 19 - 21 March 2007 when a stationary cutoff low pressure system induced a sea storm which impacted approximately 400 km of the South African coastline in the province of KwaZulu-Natal (KZN) between Richards Bay in the north to approximately 200 km south of Durban (refer Figure 7.2). Extreme waves persisted for several days and during the peak, significant wave heights $H_0 \simeq 8.5$ m were recorded in water depth of 30 m by the Richards Bay wave rider buoy (Mather, 2008). The waves inflicted severe damage (valued at about

US$100 million) to infrastructure and private homes (Mather, 2008).

Shortly after the storm had subsided a land surveyor collected data on the maximum wave run-up heights. The surveyor used the telltale debris line along the beach that marked the locations where debris had been washed up on the beach. In some instances a small scarp had been eroded on the upper beach and this was also recorded. These measurements were collected at twelve beaches along the KZN coastline (refer Figure 7.2 and Table 7.1). Beach slopes at these locations ranged from 0.020 to 0.129 and the Iribarren number ξ_0 varied between 0.145 and 0.918 'dissipative to intermediate beaches'.

The return period (or average recurrence interval) of this storm has been estimated by Phelp *et al.* (2009) to be between 35 and 85 years depending on the threshold used for their peak-over-threshold (POT) analysis (see Goda, 2010). Assuming an actual return period of say 50 years, and that the event causes run-up values with the same probability of occurrence, it follows that observed wave run-up heights during the event would be equalled or exceeded on average only once in any 50-year sample of continuous observations at the same location.

Visual observations after the storm revealed that the waves had propelled large rocks, concrete blocks and road works up the dune slopes as far as 10 m above Mean Sea Level (MSL) (Mather, 2008). The storm scoured out large volumes of sand off the visible beach and dumped this sand in a bar 400 m offshore (Ramsay, 2008). Shoreline retreat of 30 m was recorded in many locations (Smith *et al.*, 2010).

Observation made from the air during the event showed a correlation between surf zone width and the underwater bathymetry. In areas where the bathymetry was shallow, a wide (±500 m) surf zone was evident. In areas with steeper bathymetry, the surf zone was correspondingly narrower (±200 m) which suggests that the wave run-up is dependent on the bathymetric profile.

A second extreme event with significant wave heights $H_0 \simeq 10.7$ m occurred in the Cape province during the period 31 August to 4 September 2008. A frontal weather system developed approximately 600 km south-west of Cape Town. A secondary low pressure zone then grew as an example of explosive cyclogenesis (Hunter, 2008). The secondary low migrated in a north-easterly direction causing damage along approximately 1200 km of the South African coastline between Cape Town and Port Elizabeth (Figure 7.2). Significant damage to harbours, fishing craft, coastal infrastructure and transportation systems occurred due to the event. After the storm, wave run-up heights were measured at seventeen beaches around the Cape Town coastline using similar telltale signs as for the KZN storm event (refer Figure 7.2 and Table 7.2).

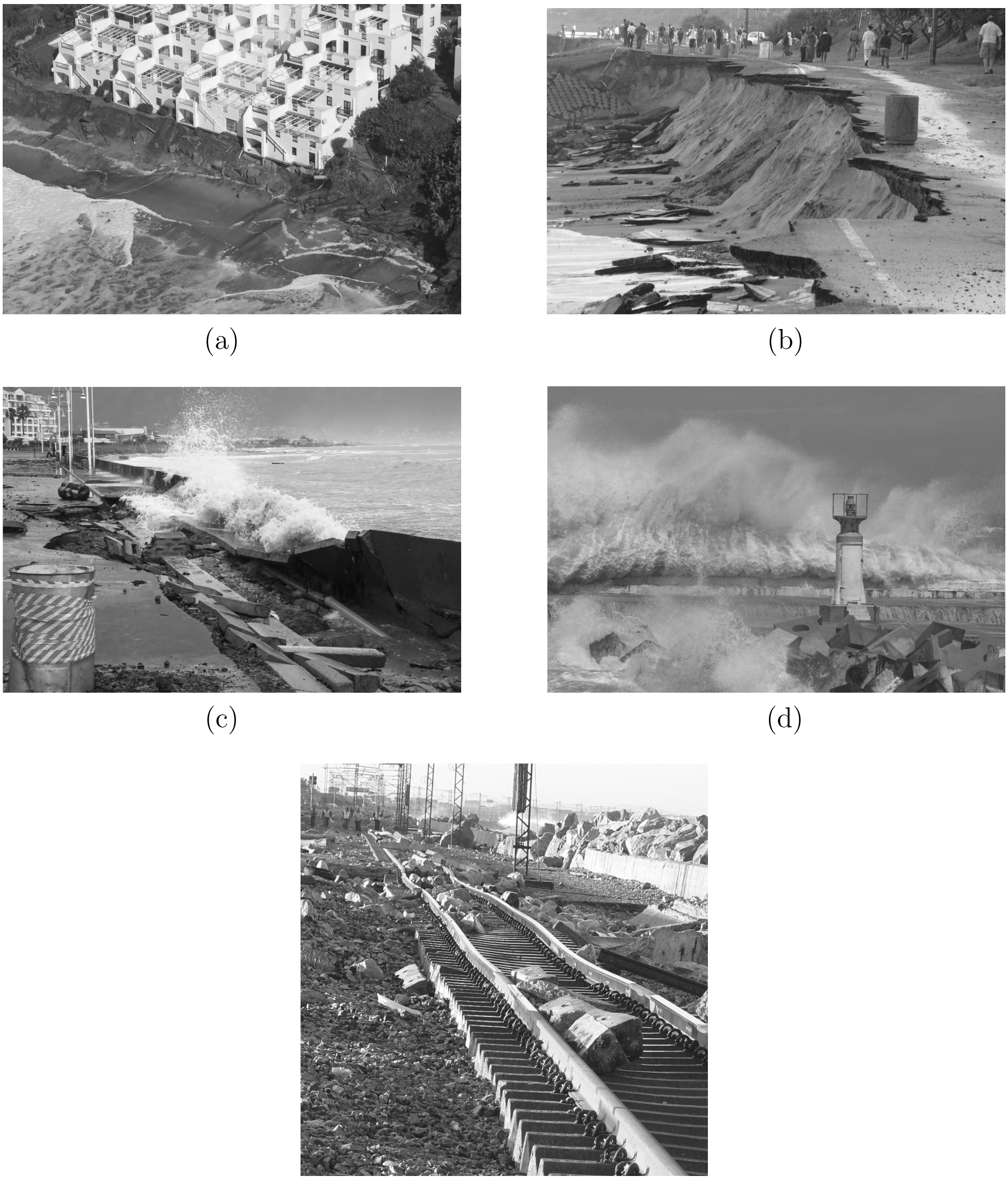
A sample of photographs taken during the above-mentioned storm events are shown in Figure 7.3 and illustrate some of the damage experienced.

Table 7.1: Extreme wave run-up measurements from a storm (March 2007) in the Durban region (see Fig. 7.2).

Locator Reference (see Fig 7.2)	**Run-up** (m above SWL)	**Beach Slope** $\tan\beta_f$	**Iribarren No** ξ_0
UMD 1	5.106	0.129	0.918
UMD 2	4.910	0.129	0.918
UMD 3	5.558	0.129	0.918
BL 1	3.090	0.020	0.145
BL 2	2.609	0.020	0.145
BL 3	2.202	0.084	0.594
NB 1	2.269	0.058	0.594
NB 2	2.213	0.058	0.413
NB 3	2.573	0.058	0.413
NB 4	2.921	0.058	0.413
NB 5	2.785	0.058	0.413
AN 1	5.615	0.100	0.413
BR 1	4.271	0.115	0.711
BR 2	5.399	0.115	0.817
BR 3	5.948	0.115	0.817
BR 4	6.539	0.115	0.817
UML 1	5.070	0.040	0.286
UML 2	5.041	0.040	0.286
UML 3	4.727	0.040	0.286
TOTI 1	4.669	0.054	0.384
UMK 1	4.133	0.086	0.610
UMK 2	1.870	0.086	0.610
UMK 3	2.742	0.086	0.610
UMK 4	2.893	0.086	0.610
UMK 5	4.579	0.054	0.383
UMK 6	4.012	0.054	0.383
UMK 7	5.852	0.054	0.383
UMK 8	5.551	0.054	0.383
UMK 9	5.907	0.054	0.383
TIDAL POOL	7.29	NA	NA
BOULDER	7.56	NA	NA
HIGH ROCK 1	10.46	NA	NA
HIGH ROCK 2	10.57	NA	NA

Table 7.2: Extreme wave run-up measurements from a storm (Aug/Sept 2008) in the Cape Town region (see Fig. 7.2). The coast type "small bay" refers to embayments with about 3 km between headlands, while "large bay" refers to embayments with about 40 km between headlands (see Fig. 7.2).

Locator Reference (see Fig 7.2)	**Run-up** (m above SWL)	**Coast Type**
CT 1	2.104	OPEN COAST
CT 2	3.464	OPEN COAST
CT 3	2.494	OPEN COAST
CT 4	2.864	OPEN COAST
CT 5	2.224	OPEN COAST
CT 6	2.064	OPEN COAST
CT 7	4.804	OPEN COAST
CT 8	4.534	OPEN COAST
CT 9	3.144	OPEN COAST
CT 10	7.864	OPEN COAST
CT 11	3.114	SMALL BAY
CT 12	2.054	SMALL BAY
CT 13	2.154	SMALL BAY
CT 14	4.734	SMALL BAY
CT 15	0.964	SMALL BAY
CT 16	1.294	LARGE BAY
CT 17	1.294	LARGE BAY
CT 18	2.324	LARGE BAY
CT 19	3.464	LARGE BAY
CT 20	2.304	LARGE BAY
CT 21	2.174	LARGE BAY
CT 22	1.504	LARGE BAY
CT 23	NO DATA	LARGE BAY
CT 24	2.374	OPEN COAST
CT 25	3.364	OPEN COAST
CT 26	2.534	OPEN COAST



(a)

(b)

(c)

(d)

(e)

Figure 7.3: Storm wave damage in KwaZulu-Natal at (a) Balito Bay (BL) (b) Umkomaas (UMK), and in the Cape Province at (c) Strand (CT16) (d) Kalk Bay (CT21), and (e) Port Elizabeth. Refer Fig. 7.2 and Tables 7.1 & 7.2 for location details. (Photos by S. Bundy, A. Mather, A. Theron, R. Klein, M. Hoppe).

7.3 Previous work on irregular wave run-up

The processes involved as waves propagate from deep water inshore to a beach are complex. However, it is well known that as waves approach a shoreline their shape and height change. This can cause a change in wave direction depending on the incident wave angle to the coastline. Svendsen *et al.* (1978) and Short (1999) have identified four hydrodynamic sections along a sloping beach: (1) a pre-breaking or shoaling section where waves steepness increases until the wave breaks, (2) an outer surf zone where the highest waves in the distribution break, (3) the inner surf zone section where waves transform into surges or bores, and (4) a wave run-up section which is of particular interest in this paper. The local maximum of the radiation stress at the breaking location generates a drop in water level at the start of the surf zone (wave set-down) and a rise in water levels (wave set-up) approaching the shoreline (Longuet-Higgins and Stewart, 1963; Bowen *et al.* , 1968; Nielsen, 1988). The surf zone accounts for most of the wave energy dissipation (Stockdon, 2006). When the waves reach the beach some of the remaining energy is converted to potential energy in the form of wave run-up on the slope of the beach (Hunt, 1959) and some is reflected back out to sea. The wave run-up provides some of the energy needed to rework the beach slope, erode the toe of any dunes (Ruggiero *et al.*, 2004; Sallenger, 2000) and attack any manmade structures in its path.

Holman and Sallenger (1985) analysed 154 wave run-up time series and found that

$$\frac{R}{H_0} \propto \xi_0 \tag{7.1}$$

where

$$\xi_0 = \frac{\tan\beta}{\sqrt{H_0/L_0}}. \tag{7.2}$$

where β is the beach slope, confirming the earlier work of Hunt (1959) and Battjes (1974). Holman (1986), using data gathered from Duck, USA, where deep water wave heights H_0 ranged between 0.4 m and 4.0 m and wave periods T_0 between 6 and 16 seconds, was able to deduce a relationship for R_2, the run-up exceeded for 2% of the time, as

$$R_2 = 0.45H_0 + 1.21 \tag{7.3}$$

where H_0 is the significant wave height (m) in 20 m water depth. Holman also gave an alternative regression equation in terms of ξ_0 as

$$\frac{R_2}{H_0} = 0.83\xi_0 + 0.20 \tag{7.4}$$

Douglass (1992) re-analysed the Holman (1986) field measurements and argued that beach slope was not an important parameter in predicting wave run-up on natural beaches. Douglass suggested the relationship

$$\frac{R_2}{H_0} = \frac{0.12}{\sqrt{H_0/L_0}} \tag{7.5}$$

where L_0 is the deep water wave length associated with wave period T_0.

Nielsen and Hanslow (1991) undertook field studies on beaches with irregular waves where deep water root mean squared wave heights H_{0rms} ranging from 0.53 m to 3.76 m (H_0 between 0.75 m and 5.32 m), wave periods between 6.4 s to 11.5 s, beach slopes between 0.026 and 0.189, and beach sand grain size d_{50} between 0.2 mm and 0.8 mm. Their results yielded an equation for the 2% exceedance wave run-up as

$$R_2 = 1.98\ L_{zwm} \tag{7.6}$$

where

$$L_{zwm} = 0.60\sqrt{H_{0rms}L_0}\ \tan\beta_f \quad \text{for } \tan\beta_f > 0.1 \tag{7.7}$$

$$L_{zwm} = 0.05\sqrt{H_{0rms}L_0} \quad \text{for } \tan\beta_f \leq 0.1 \tag{7.8}$$

Stockdon *et al.* (2006) examined data from beaches in the USA and the Netherlands and derived their formula for the 2% exceedance wave run-up as

$$R_2 = 1.1\left[0.35\beta_f\sqrt{H_0L_0} + 0.5\sqrt{H_0L_0(0.563{\beta_f}^2 + 0.004}\right] \tag{7.9}$$

where $0.1 < \xi_0 < 2.2$, $L_0 = {T_0}^2/2\pi$.

Predictive models of wave run-up have traditionally focused on the beach foreshore slope β_f as the key determinant of R in studies using regular waves (Miche, 1951; Hunt, 1959; Battjes, 1974b; Mase, 1989; Hedges and Mase, 2004) and irregular waves (Holman and Sallenger, 1985; Sallenger and Holman, 1986; Guza and Thornton, 1989; Nielsen and Hanslow, 1991; Sallenger, 2000; Ruggiero, Holman and Beach, 2004; Stockdon *et al.*, 2006). An exception is the model proposed by Douglass (1992) who argued that extreme run-up is independent of the beach-face slope β_f.

7.4 Performance of existing run-up models

The extreme wave run-up observations described in §7.2 provide an opportunity to test the wave run-up models discussed in §7.3. Using the data collected from the KZN March 2007 storm event, comparisons between observed wave run-up and predicted R_2 wave run-up were undertaken using the models of Holman (1986), Nielsen and Hanslow (1991), Douglass (1992) and Stockdon *et al.* (2006). The results are shown in Figure 7.4.

The models of Holman (1986, Figure 7.4a), and Nielsen and Hanslow (1991, Figure 7.4b) mostly over-estimate the observed extreme wave run-up from the storm event, a trend that has been previously reported in other contexts (CEM, 2006). The predictions of the Nielsen and Hanslow (1991) model (Figure 7.4b) has no dependance on beach slope for $\tan\beta_f \leq 0.1$ (see Eq. 7.8), which is evident in the results shown in the plot. The Douglass (1992) model (Eq. 7.5) over-estimates the observed wave run-up in all instances (Fig. 7.4c). It yields a maximum calculated value of 7.26 m compared to an observed value of 6.54 m (see Figure 7.4c) but the predictions over-estimate the observed run-up by up to a factor of 3.5. The Douglass model does not use any physical beach parameters and is understandably constrained by this fact. Eq. (7.9) from Stockdon *et al.* (2006) also over-estimates the observed wave run-up (Figure 7.4d) but its predictions show slightly less scatter that the other models.

Holman‘s equation provides a relationship between R_2 and H_0 (Eq. 7.3) for average beach slopes of about 0.1 and with wave heights limited to about 4 m. The data available from the present study for large wave heights provided an opportunity to verify the relationship between R and H_0 for an extended range of wave heights. The original Holman data (his figure 4a on page 534) was replotted against the wave run-up values obtained in the KZN event for beach face slopes between 0.10 and 0.13 (Figure 7.5). All the extreme wave run-up data are located within an envelope bounded by upper and lower limits given by

$$\text{Upper-bound} \qquad R_{max} = 0.5H_0 + 2.30 \tag{7.10}$$

$$\text{Lower-bound} \qquad R_{min} = 0.5H_0 \tag{7.11}$$

The linear regression line including the new data gives (see Fig. 7.5)

$$R = 0.49H_0 + 1.31 \tag{7.12}$$

for $\tan\beta \approx 0.1$ and $H_0 > 1.5$ m, which is very similar to that originally obtained by Holman (1986) and given earlier in this paper as Eq. (7.3). Note that for small H_0 a linear relationship may be expected to break down.

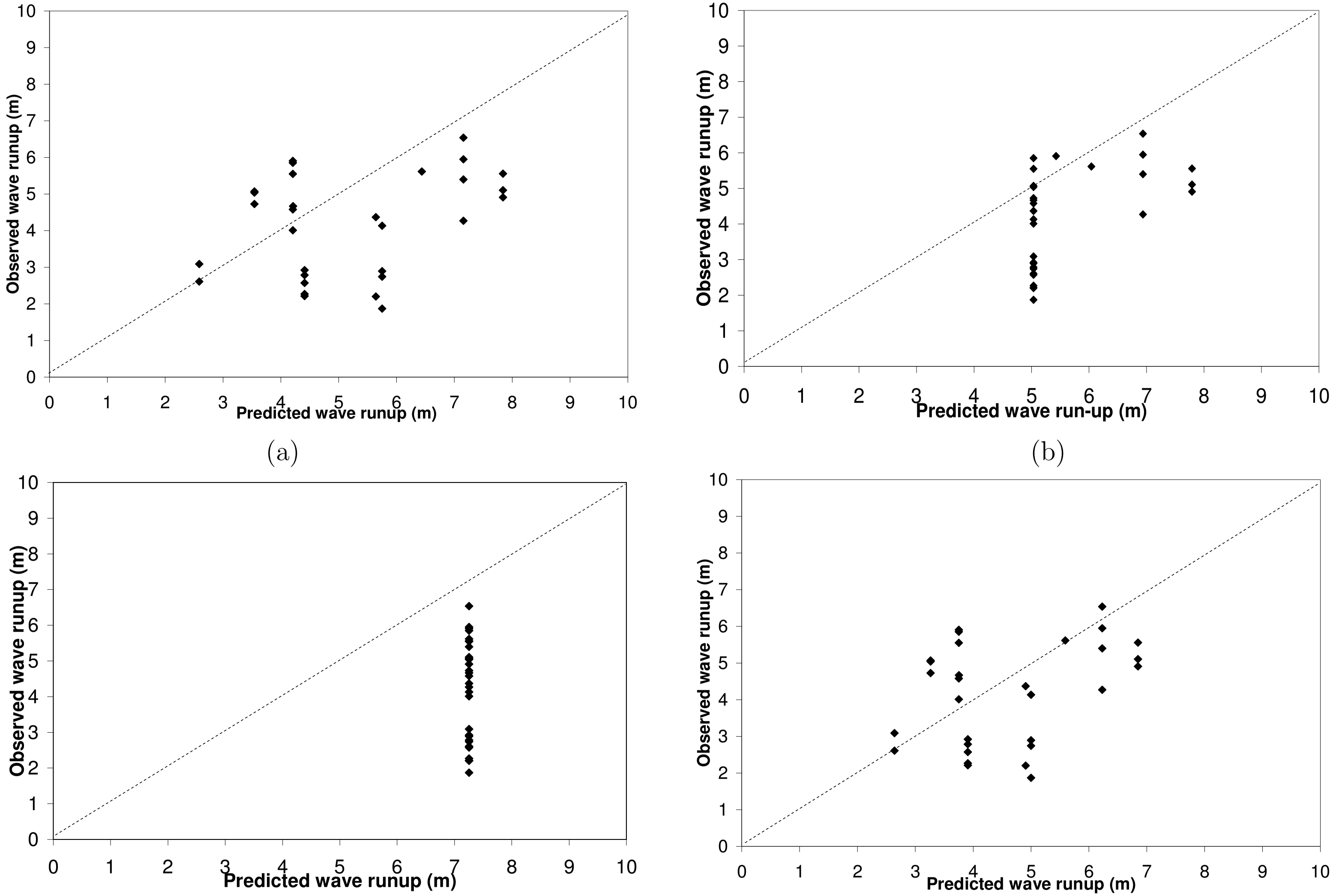
7.5 A proposed new wave run-up model

Our approach differs from previous research in this field as it focuses on parameters other than beach-face slope to define the amount of wave run-up. The basis of the model rests with the interconnected relationships between various natural beach attributes. Previous research on wave run-up has found it to be proportional to beach foreshore slope β_f Hunt (1959), Holman (1986), Mase (1989), Nielsen and Hanslow (1991), Sallenger (2000), Hedges and Mase (2004), and Stockdon (2006). The beach foreshore slope β_f has in turn been found to be proportional to beach sand grain size d_{50} by Bascom (1951), Emery and Gale (1951), McClean and Kirk (1969), King (1972), Komar (1976), Sunamura (1984), Antony (1998).

Bruun (1954), following on the initial work of Fenneman (1902), hypothesized that the smoothed bed profile can be represented by a power law in the form

$$h = Ax^p \tag{7.13}$$

where h is the depth below mean sea level at a distance x offshore, and A is an empirically determined coefficient. This was developed further by Dean (1977, 1987,



(a) (b)

(c) (d)

Figure 7.4: Observed against predicted wave run-up for the March 2007 storm (a) Holman (1986) (b) Nielsen & Hanslow (1991) (c) Douglass (1992) (d) Stockdon *et al.* ((2006).

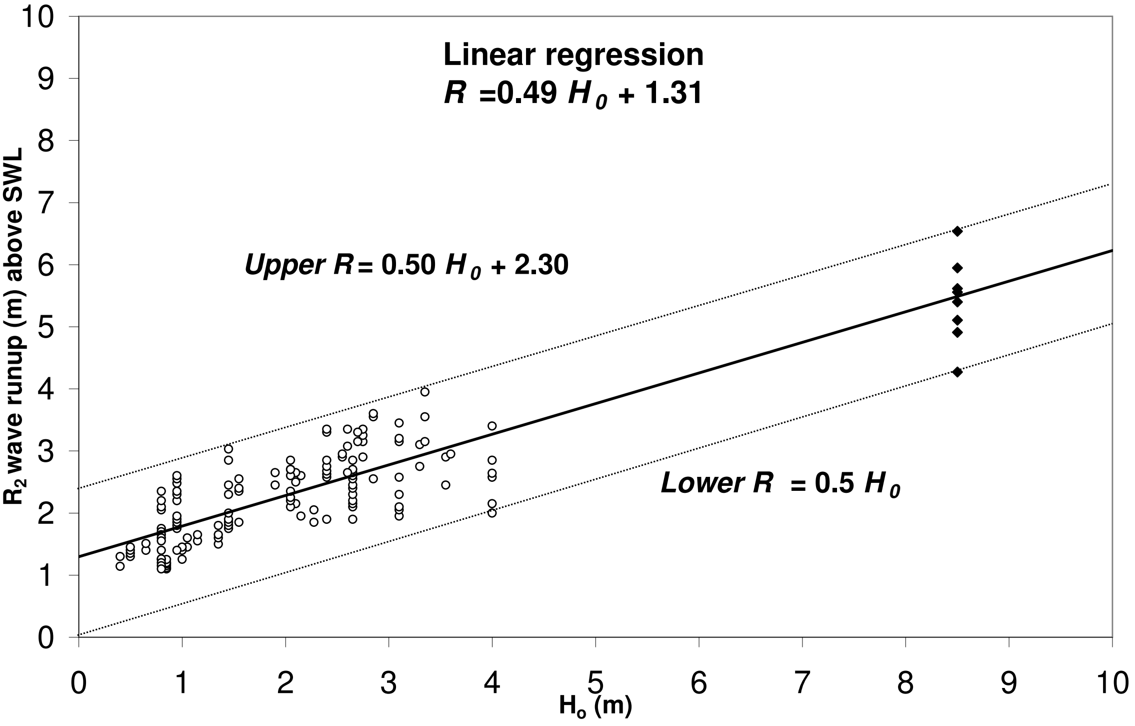


Figure 7.5: Re-analysis of Holman (1986) (shown as circles) with wave run-up data from the March 2007 storm (shown as solid diamonds). All data are for beach slopes between 0.1 and 0.13.

1990 and 1991) who provided a rationale for Eq. (7.13) and published the well known equilibrium profile equation

$$h = Ax^{2/3} \tag{7.14}$$

The parameter A in Eq. (7.14) governs the overall steepness of the profile. Further work found that A varied with sediment fall velocity (Work and Dean, 1991; Kreibel *et al.*, 1991) and with sediment grain size d_{50} (Rouse, 1937; Moore, 1982; Swart, 1974; Boon and Green, 1988; Dean, 1987).

The above-mentioned work suggests that there is a relationship between the offshore profile shape given by Eq. (7.14) and the beach foreshore slope β_f. In other words the whole beach profile from the high water mark to the closure depth is interrelated and shaped by the wave climate and sediment size available at each location. Therefore we postulated that it is possible to correlate wave run-up R with the shape of the offshore profile or more specifically to a specified point on the sea bed at a distance x_h and depth h seaward of the surf zone (see Figure 7.6), whence

$$\frac{R_x}{H_0} \sim (x_h/h)^p \tag{7.15}$$

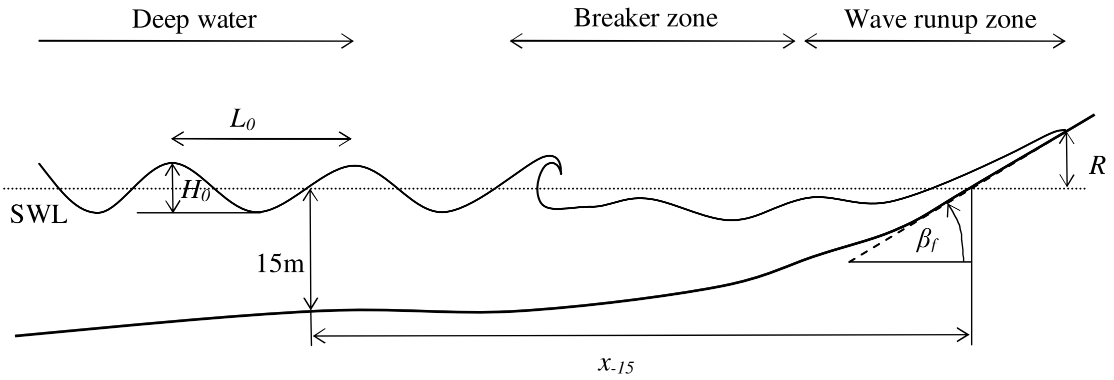


Figure 7.6: Sketch defining the parameters for the proposed new wave run-up model.

To test the new model, extreme wave run-up heights along the open KZN coastline were plotted against the slope of the nearshore bathymetry. For this analysis it was necessary to choose a depth contour and in this case a depth of 15 m was selected for three reasons. Firstly the closure depth h_c as defined by Bruun (1954) is between 10 and 18 m along this coastline (Theron, 1994; Mather, unpublished data) with $h_c \simeq 15$ m a representative average value. On physical grounds the closure depth seems an appropriate choice for characterizing the average nearshore bathymetry since it delineates the morphologically active profile from the less active deeper water profile. Secondly the 15 m depth contour is typically available on regional navigation charts (South African Navy, 2007). Thirdly this is approximately the depth where regional maximum wave heights of 8 to 10 m start behaving as shallow water waves ($h/L_0 \leq 0.05$ with $L_0 \approx 300$ m).

The recorded wave run-up levels are plotted against the distance offshore to the 15 m depth contour in Figure 7.7. All the open coastline data from Tables 7.1 & 7.2 are shown in the plot. From Figure 7.7, a relationship between observed extreme wave run-up R_x and the horizontal distance from the beach (SWL) to the selected depth contour can be expressed in the form

$$\frac{R_x}{H_0} = C\ S^{2/3} \tag{7.16}$$

where $S = (h_c/x_h)$ is a representative nearshore slope ($h_c \simeq 15$ m in our case), H_0 is the deep water significant wave height, and C is a dimensionless coefficient. The data in Figure 7.7 suggests that Eq. (7.16) with $3 \leq C \leq 10$ gives upper and lower bounds for R_x for all the open coastline measurements. Median values are described approximately by $C \simeq 7.5$.

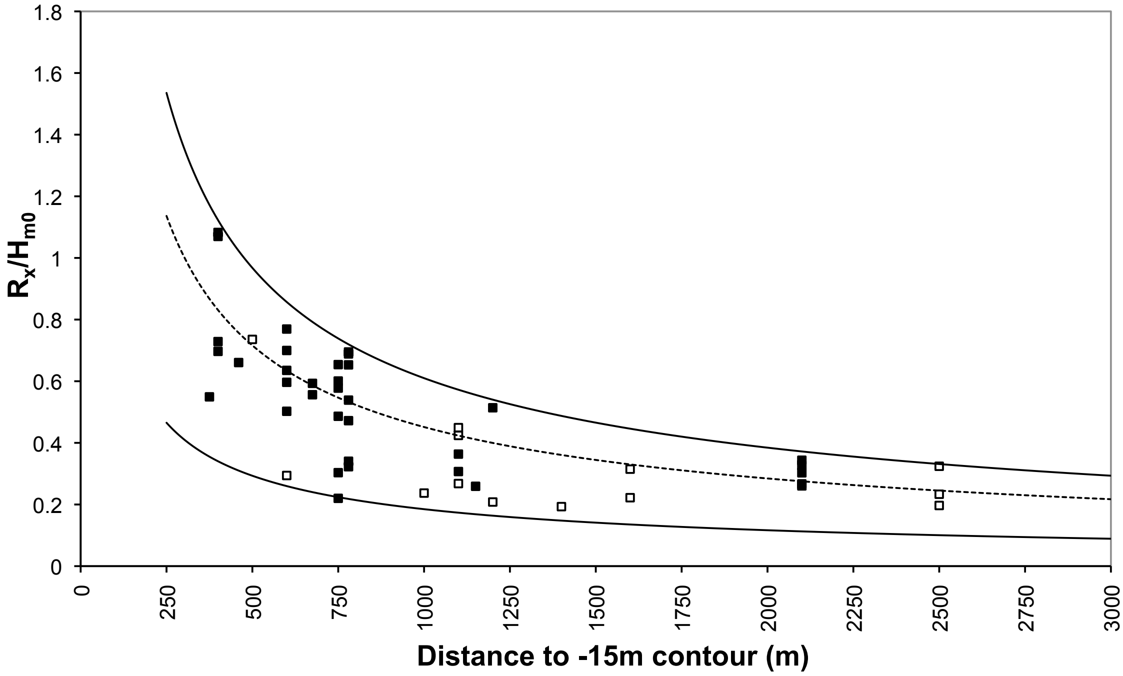


Figure 7.7: Open coastline run-up data for the KZN (solid symbols) and Cape (open symbols) storm events, plotted versus the distance offshore to the 15 m depth contour. The upper bound line is Eq. (7.16) with $C = 10$ and lower bound line has $C = 3$. The dotted line approximately represents median values with $C = 7.5$.

The run-up observations are shown re-plotted in Figure 7.8 for comparison with the previous model predictions shown in Figure 7.4. There remains considerable scatter in the data but a small improvement over the previous models is evident. Note that data from the Cape storm event are not included in Figure 7.4 since measurements of beach-face slopes β_f were not recorded in that case. Error statistics are summarised in Table 7.3 where it is evident that the two models which predict with the least dispersion are those of Stockdon *et al.* (2006) and that proposed in this paper.

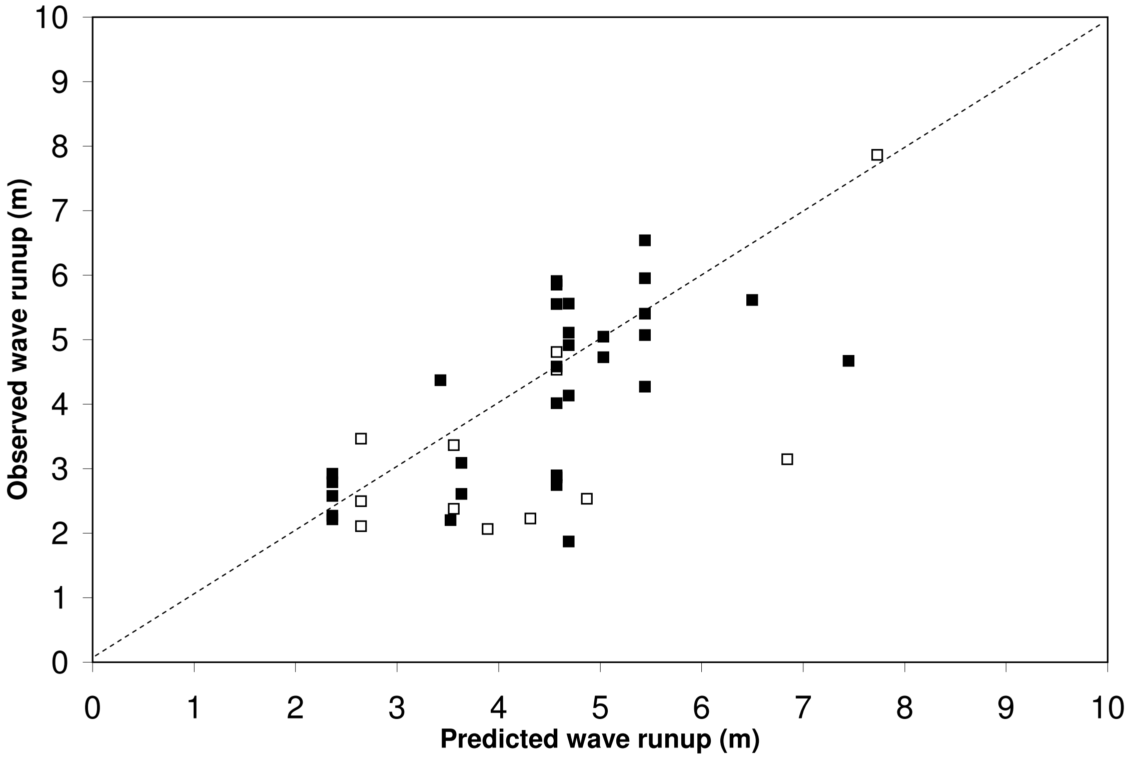


Figure 7.8: Open coastline run-up data for the KZN (solid symbols) and Cape (open symbols) storm events, compared with the predictions of Eq. (7.16) with $C = 7.5$.

As a further test of the proposed new model, it was used to predict an extreme wave run-up line along the KZN coastline for the March 2007 storm conditions ($H_0 \simeq 8.5$ m). Comparison between the model predictions and an observed wave run-up line was undertaken. The latter was determined visually from aerial photography taken shortly after the storm. The most obvious feature was the small beach scarp or wave-cut platform left on the back beach. This wave-cut line was mapped using GIS and compared with the model prediction in several locations. Approximately 1000 values (a 5% sample) of the differences between the observed and predicted horizontal wave run-up positions were thus obtained. The result of this analysis is shown as a histogram in Figure 7.9, and indicates that 52% of the predicted wave run-up positions are within a horizontal distance of about 1 m from the observed positions. The model on average over-predicts by a horizontal distance of 1.6 m.

Table 7.3: Root mean square error statistics comparing various model predictions of extreme wave run-up.

Model	Sample Size	RMS Error
Holman (1986)	29	2.28
Nielsen & Hanslow (1991)	21	2.28
Stockdon *et al.* (2006)	29	2.01
Mather *et al.* (this paper)	29	1.55

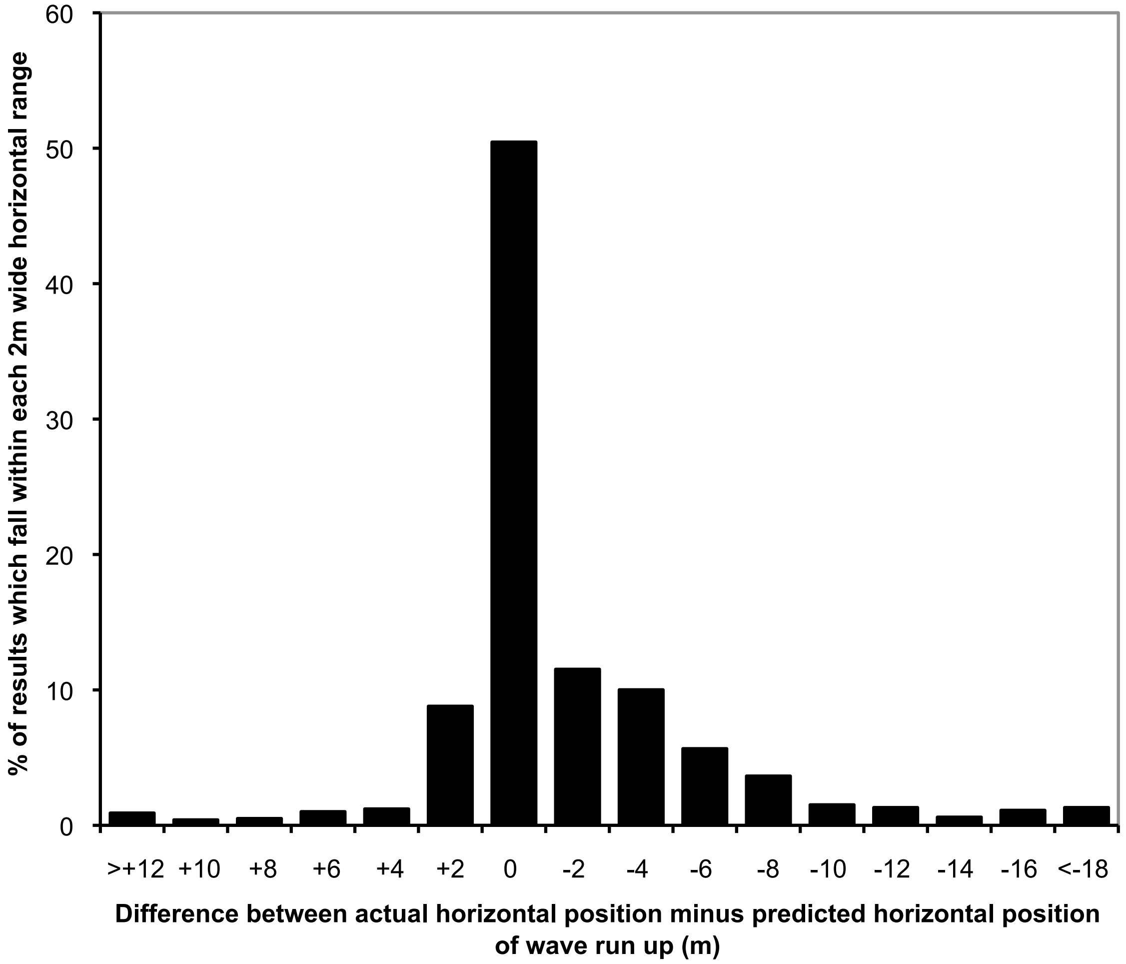


Figure 7.9: Histogram of the differences between the actual horizontal wave run-up position versus the positions predicted using the proposed new run-up model.

7.6 Extension to different coastline types

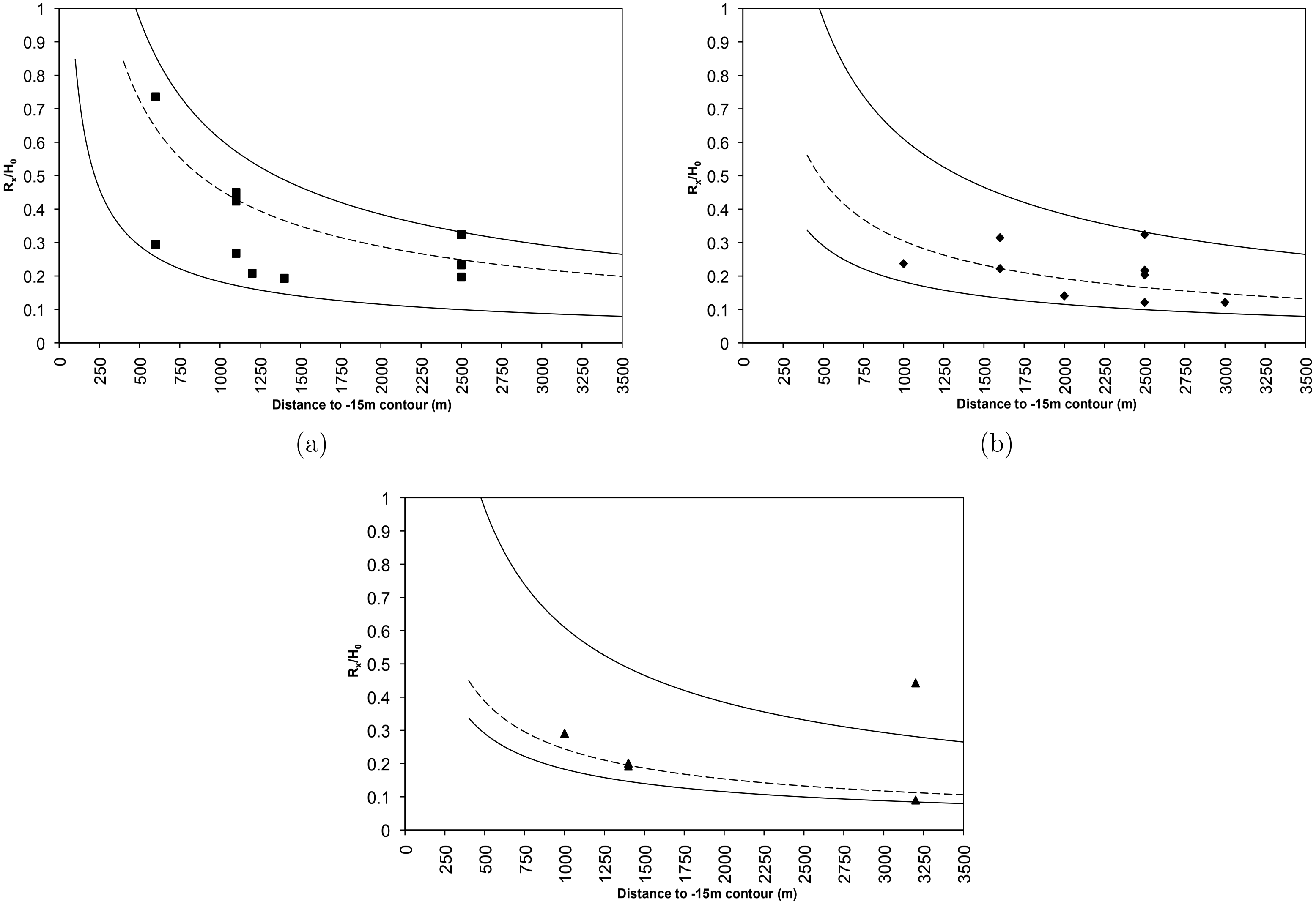
The new run-up model was initially developed and tested for the long straight open KZN coastline. For this model to be useful it was necessary to verify its applicability at alternative locations and for different types of coastlines. In order to test this, the Cape and KZN data were combined by normalizing R_x by H_0 and plotting all the data together as shown in Figure 7.7. A similar pattern emerges in that wave runup is confined between an upper bound where $C = 10$ and a lower bound where $C = 3$. The combined data confirm the original KZN formulae of $R_x/H_0 = C\ S^{2/3}$ where $C \simeq 7.5$. Further separation of the data into open coastlines, large embayments and small embayments are shown in Figure 7.10. The family of applicable C values is summarised in Table 7.4. In Figure 7.10(c) there is a single outlier point, and closer examination revealed that the measurement was made adjacent to a man-made structure which focussed the incoming wave energy causing a local anomaly.

Table 7.4: Model coefficients (refer Eq. 7.16) for predicting extreme wave run-up on different coastline types. Coefficients are shown for upper/lower bounds and median values as depicted in Fig. 7.10. The coast type "small bay" refers to embayments with about 3 km between headlands, while "large bay" refers to embayments with about 40 km between headlands (see Fig. 7.2).

Coastline Type	**Upper Bound**	**Median**	**Lower Bound**
Open Coast	$C = 10$	$C = 7.5$	$C = 3.0$
Large Embayment	$C = 10$	$C = 5.0$	$C = 3.0$
Small Embayment	$C = 10$	$C = 4.0$	$C = 3.0$

7.7 Discussion & Conclusions

Predicting wave run-up is difficult given the complexities of processes such as energy dissipation through the surf zone. This has lead to the development of empirical models. The seminal work undertaken by Holman (1986) and Nielsen and Hanslow (1991) has been widely used to predict extreme wave run-up. More recent work by Stockdon *et al.* (2006) on setup, swash and run-up has further advanced our understanding of these processes. However, the empirical models produce a wide scatter of results when applied to real situations (Fig. 7.4). This scatter may be the result of small differences in beach slope, underwater features such as rocky outcrops, and the fact that not every section of the beach was exposed to the same incoming wave energy. The random, distributed nature of the incoming wave energy could cause spatial variations even in the same study area. For practical applications in coastal management and planning it is important that uncertainties are minimized to provide improved confidence in the predicted results.



(a)

(b)

(c)

Figure 7.10: Run-up data from the Cape coast (refer Table 7.2) re-plotted as a function of the distance to the 15 m depth contour, but grouped as (a) open coastlines, (b) large embayments ($\sim$ 40 km between headlands), and (c) small embayments ($\sim$ 3 km between headlands). The upper and lower bound curves in each plot are Eq. (7.16) with $C = 10$ and $C = 3$ respectively. Curves for median values are shown using $C = 7.5,\ 5,\ 4$ for each case (refer Table 7.4).

In this paper we have approached the problem from a different perspective. Using established relationships between beach variables, the extreme wave run-up associated with storm conditions with a particular return period has been related to the near-shore profile as parameterized by the distance offshore to a chosen depth contour. We have shown that the proposed model slightly over-predicts run-up position (an average of 1.6 m horizontal distance inland) but this over-prediction may well be a related to the use of the beach scarp as an indicator of maximum run-up location. This scarp slope may have moved further inland with a longer storm duration. Under the circumstances, the small bias in the model predictions is considered negligible and the proposed model provides a good indication of wave run-up position on natural beaches.

In contrast, existing models are predominately based on the final portion of the beach profile i.e. the beach face slope β_f. The performance of these models has been compared to our new model (Figures 7.4 & 7.8). All models exhibit scatter in their predictions, which is not surprising given the complexities of the processes they are trying to explain. The error statistics in Table 7.3 indicate that the two models which predict extreme run-up with the least dispersion are those of Stockdon *et al.* (2006) and that proposed in this paper.

Previous run-up models require significantly more information than the new model the model of Stockdon *et al.* ((2006) requires information about the beach face slope β_f which would need to be gathered in the field. The new model also departs from the models of Holman (1986), Nielsen and Hanslow (1991) and Stockdon *et al.* ((2006) by not including any dependance on ξ_0. Initially this appears to be surprising as ξ_0 has been incorporated into most run-up formulae to date. However, recent large scale laboratory tests by Roberts, Wang & Kraus (2010) have shown that the exclusion of ξ_0 provides better predictions. Roberts *et al.* (2010) were able to show that wave run-up is dependent only on the breaking wave height $R_{tw} = H_{bs}$ where R_{tw} is the vertical excursion of total wave run-up and H_{bs} is the significant breaking wave height. Their comparisons with the models of Holman (1986) and Stockdon *et al.* (2006) indicated that their simple model was superior. The next best predictor for wave run-up was the model of Guza and Thornton (1982). Guza and Thornton's model also does not use ξ_0. Roberts *et al.*(2010) also discussed the Nielsen and Hanslow (1991) model, and they confirm that ξ_0 does not appear to be a factor in wave run-up on gentle beaches with a slope of less than 0.1.

The prediction of extreme wave run-up is an important component in coastal management. Our research has shown that while there are several wave run-up models available, they give a wide range of predicted wave run-ups when applied to storm waves impinging on natural beaches. One aim of this research was to develop a simple yet practical extreme wave run-up predictive tool which can be used for natural sandy beaches by coastal planners or managers. There are financial and technical resource limitations for organizations along the African coastline. It is only in extremely rare cases that detailed information, such as wave height, period and beach-face slope, is available to predict wave run-up in accordance with most existing models. The present study should assist these under-resourced organizations to better plan for extreme events and provide a guide for assessing hazards associated with extreme wave run-up.

A problem in practical applications of run-up models based on beach face slope is that the latter is likely to change during storm events. Even an H_0 of 2 m is sufficient to alter the beach face profile (Holman *et al.*, 1978). It is therefore less reliable to base predictions of extreme wave run-up on the pre-storm beach-face slopes, although this has become a common approach to predicting wave run-up. The bathymetric profile during storms, particularly at depths beyond the closure depth (or about twice the wave height) is more stable and easier to measure, and does not undergo as much change during a storm. This makes it a superior indicator of the profile shape than the beach-face slope for use as a parameter in predicting extreme wave run-up heights.

7.8 Acknowledgments

The authors wish to thank the eThekwini and Cape Town Municipalities for the use of the wave run-up data, Simon Bundy for the generous help in arranging for the field data measurements in Ballito, and Andre Theron for the informative discussions and debates about wave run-up.

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Epilogue to Chapter 7

In Chapter 7 a new wave run up model was developed for the Southern and Eastern African coastline. The model has been made simple to apply deliberately so that a rapid assessment of the potential wave run-up hazard area can be identified. This is particularly important given the skills and capacity constraints facing most African countries in the region.

Prologue to Chapter 8

The findings presented in Chapter 7 show that a new model of wave run up has been developed in the region. This model is capable of using the off shore wave height and the state of the tide to determine the wave run up heights along varying coastal profiles. The model has been found to be superior to the existing established models of Holman (1986), Nielsen and Hanslow (1991) and Stockdon *et al.* (2006) when applied in the region.

This model makes it possible to address the need to determine the possible physical impacts of future sea levels in the region using appropriate future scenarios of sea level change. The purpose of Chapter 8 is to define realistic scenarios of future sea level change in the region using the international sea level projection models, to examine these scenarios in the context of coastal management legislation in South Africa as this legislation has been promulgated and to provide some guidance in planning for these future changes along the shorelines of the region.

This Chapter includes the thematically linked, conference paper titled:

Mather, A.A. Stormy seas ahead: Planning for sea level rise, *Proceedings of the South African Planning Institute conference, Durban, South Africa*.

The peer reviewed conference publication has been reproduced in full in the Appendix.

Chapter 8

STORMY SEAS AHEAD: PLANNING FOR SEA LEVEL RISE

8.1 Background

The impact of climate change, and particularly its effect on rising sea levels, beach realignment and a changing wave run up climate, will have an effect on coastal cities, towns and coastal communities who live along the coast. It is estimated that of the worlds total shoreline, sandy shorelines account for about 34% (170 000 kms) (Hardisty, 1990). It is these sandy coastlines, where there are concerns about their vulnerable to sea level changes, particularly where urban development has been placed in close proximity. Sandy shores by their very nature are easily erodable by wave action allowing wave energy to erode the cost and endanger infrastructure. South Africa has approximately 3100 kms of coastline of which 71% (Harris *et al.*, 2011) are these sandy shorelines. Over the last thirty years there has been a worldwide expansion of development along the coast (Rakodi and Treloar, 1997). The United Nations has estimated that by 2020 about 75% of the total world population will live within 60 kms of the sea (UN, 1993).

South Africa is not isolated from this trend and recent work in KwaZulu-Natal has shown that the narrow strip of land 100m inland above the high water mark has seen a transition for 28% developed in 1994 to over 50% developed in 2006 (excluding the iSimangaliso Park (formally called the Greater St Lucia Wetlands Park)) (Cilliers, L. pers. comm.). Ports and Harbours, critical in the chain of international trade, are also likely to be adversely affected by rising sea-levels. Many countries are very reliant of the movement of goods (and aid) by sea particularly as this is currently the cheapest way to move goods. Any restrictions or inefficiencies induced by sea level rise will have negative effects on these countries. This makes the long-term viability of ports and harbours a key element in many cities economic survival into the next century. Rising sea-levels are a potential threat to the viability of ports in South Africa and indeed worldwide and therefore need to be carefully considered in planning for the future.

The coast of South Africa belongs to the people of South Africa and the newly enacted Integrated Coastal Management Act (ICM Act, 2008) provides both benefits and obligations on the public. Therefore it is important that these rights and responsibilities are communicated to the public. There are three main issues affecting those living at the coast and these will be discussed next.

8.1.1 Sea Level rise

It is generally accepted that one of the main drivers of sea-level rise (SLR) is global warming which results in the polar ice caps and glaciers melting, thermal expansion of the oceans and increased break-up of the Antarctic and Greenland ice sheets. Recent estimates put global sea-level rise at 3.0 mm per year (Bindoff *et al.*, 2007). Sea-levels have been changing over millenniums, however, globally in the modern era a significant number of large human settlements (or mega cities defined as a city with a population exceeding 20 million people) are now located adjacent to the shoreline, and so the impacts of rising sea levels, even if only small compared to historical geological sea level changes, would have major impacts for the viability of these coastal cities. Sea level change is spatially variable, in other words each location will experience a different rate of sea level rise as SLR depends on a number of physical processes such as rates of glacial melt, the changes in sea water temperatures which increase the volume of the ocean by thermal expansion and vertical movements of the land through plate tectonics. Most of the time references to sea level change are given as the relative (between land and ocean) sea level change and this will be the convention adopted in this paper.

Rising sea levels have a double impact in that not only does the water level rise relative to the land but the increase in water depth allows increased penetration of waves into the hinterland. This has the effect of providing additional energy which modifies the shoreline through sediment redistribution in the long shore (along the coast) and cross shore (normal to the coast) direction. The cross shore sediment processes are of particularly interest as these are particularly strong during storm events and result in erosion of sandy beaches, endangering and sometimes causing the undermining of coastal structures built in the erosion zone.

8.1.2 Coastal Erosion

Coastal erosion and sedimentation is a continuous process occurring along all sandy beaches. Coastal erosion is the abrasive weathering of rocks and the removal of beach or dune sediments by wave action, tidal currents or stormwater drainage. However, it is often the erosional changes that are most often noticed by the public. Part of the reason is that sedimentation occurs generally during ‘fair weather’ conditions and is a relatively slow process while erosion is often associated with sea storm events where large volumes of sand can be stripped off the beaches in a matter of hours. Rising sea levels have the effect of increasing the potential for additional erosion of the shoreline over and above that which is already happening as part of the natural rhythm of nature. The increase in sea levels lead to a landward migration of the shoreline over time.

8.1.3 Movement of the High Water Mark

An important defining feature of the coast is the High Water Mark. This line has existed for nearly 160 years along parts of the South African coastline and was originally defined to demarcate the area where the waves ran up the beach during normal storms that coincided with normal spring tides. The ICM Act has revised this definition however it has retained its importance in defining the different land parcel description described in the Act. The ICM Act stipulates that in cases where the high-water mark moves inland due to sea-level rise, erosion or other processes, ownership of any land seaward of the newly determined high-water mark is lost and belongs to the state.

8.2 Recent Sea Level Changes

In recent years there has been an increase in the number of researchers around the world looking at global sea level rise. Until recently the sea level trends have been linear, however, Church and White (2006) have shown that the global rate of sea level rise is accelerating slightly. This acceleration while small currently could have significant long term impacts unless it is reduced through an effective mitigation strategy. In the next section a brief review of sea level change research will be discussed.

8.2.1 Worldwide Sea Level Rise Research

Recent research into global sea level rise over the last 2 decades has shown that the rate of sea level rise is variable depending on the region in which the studies were conducted but also that the reported rate of sea level rise appears to be increasing over time as can be seen in Table 8.1. Early studies reported figures around +2 mm per year while the later studies report figure around +3 mm per year.

8.2.2 South Africa

As has been pointed out the rate of sea level rise varies depending on the local influences and therefore one cannot simply take a global figure and use this in the absence of understanding the complex interaction between two key factors in the South African region. The two major influences are the currents off the coast namely

Table 8.1: Published information on global sea-level rise.

Author	**Year**	**Period of time considered**	**Av. rate of sea level rise s.d.** (mm per year)
Peltier	1996	1920 to 1970	1.94±0.6
Davis & Mitrovitch	1996	unspecified	1.5±0.3
Peltier and Jiang	1997		1.8±0.6
Douglas	1997		1.8±0.1
Nerem *et al.*	1997		2.1±1.2
Viliblic	1997	20th century	1.5 to 2.0
Lambeck *et al.*	1998	1892 to 1991	1.1±0.2
Mitchum	1998		2.3±1.2
Cazenave *et al.*	1998		1.4±0.2
Woodworth	1999	20th century	1.22±0.25
Nerem	1999	1993 to 1998	2.5±1.3
Peltier	2001	20th century	1.0 to 2.0
Cabanes *et al.*	2001	1993 to 1998	3.2±0.2
Nerem & Mitchum	2001	1993 to 1998	2.5±1.3
Proshutinsky *et al.*	2001	1950 to 1990	1.8
Church *et al.*	2001	20th century	1.0 to 2.0
Lambeck	2002		1.16 & 1.65
Johannesson	2002	1993 to 2000	1.9±0.2
Hunter *et al.*	2003	1841 to 2002	1.0±0.3
Church *et al.*	2004	1950 to 2000	1.8±0.3
Cazenave & Nerem	2004	1993 to 2003	2.8±0.4
Leuliette *et al.*	2004	1993 to 2003	3.1±0.7
Church & White	2006	1870 to 2004	1.44
		1900 to 2004	1.7±0.3
		1970 to 2003	2.1
Jevrejeva *et al.*	2006	1993 to 2000	2.4±1.0
		1920 to 1945	2.5±1.0
Bindoff *et al.*	2007	1993 to 2003	3.0

the warm Agulhas and cool Benguela currents and the vertical crustal movement of the land mass.

8.2.2.1 Agulhas and Benguela Currents

One of the largest contributors to global sea-level rise is the warming of the water in the oceans causing it to expand. The current view is that even if warming could be stopped now the lag in thermal expansion of the oceans will continue until at least until the year 2300. The east coast is strongly influenced by the Agulhas Current which brings warmer equatorial water to the coastline. This warm water, in contrast to the surrounding sea water, is lighter and therefore yields its full thermal expansion component in the form of sea-level rise. A warming trend in the Agulhas and Benguela currents will result in increased thermal expansion and sea-level rise. Since the 1980's increasing water temperature in the Agulhas and Benguela currents has been observed contributing to rising sea levels.

8.2.2.2 Local Vertical Crustal Movements

Local vertical crustal movements affect the relative change in sea-level experienced at different locations along the coastline. Observations from the Hartebeesthoek Radio Astronomy Observatory show that the African plate and specifically the South African land mass is rising at different rates. In the north, Richards Bay is rising at +1.11 ± 0.25 mm per year and in the south, Simons Town is rising at 0.29 ± 0.18 mm per year (Mather *et al.*, 2009). While these rates appear small the relative rate is comparable to observed sea level rise figures. In other words had it not been for this uplift movement of the land mass offsetting some of the increase in sea-level, relative sea level rise would be larger.

8.2.2.3 Southern African sea level trends

Recent research on all the Southern African tide gauges has been undertaken by Mather *et al.* 2009 and it can be seen from Table 8.2 that there is indeed a difference in sea level trends throughout Southern Africa. These rates are for individual tide gauge stations located around the Southern African coastline and what is evident is the variability of the trends. In the case of some stations the trends are negative. Closer examination of these negative trends reveals quality control issues with the data at those stations. (For a full analysis of the tide gauges the reader is referred to Mather *et al.* 2009 or Chapter 5 in this thesis).

By selecting the most reliable gauges the regional trends can be calculated and these are shown in Table 8.3.

Table 8.2: South African and Namibian sea level trends from the PSMSL data holdings except Durban (Mather, 2007).

Tide station	**Period of Record**	**Years of Record**	**Completeness of record** (%)	**Observed annual sea level trend using monthly data** (mm per year)	**Observed annual sea level trend using annual data** (mm per year)
Walvis	1958-1998	41	58	+0.38±0.33	+0.67±1.06
Lüderitz	1958-1998	41	78	+2.73±0.81	+2.40±1.64
Port Nolloth	1959-2007	49	75	+1.25±0.23	+1.1±0.41
Table Bay	1957-1972	16		Insufficient data	Insufficient data
Simons Town	1957-2007	51	78	+1.5±0.22	+1.14±0.52
Granger Bay	1967-2007	41	77	+0.08±0.20	+0.44±0.53
Hermanus	1958-1964	7		Insufficient data	Insufficient data
Mossel Bay	1958-2007	50	77	−0.40±0.19	−0.66±0.56
Knysna	1960-2007	48	64	+1.27±0.50	+1.95±1.62
Port Elizabeth	1978-2007	30	76	+2.97±1.38	+2.89±2.05
East London	1967-2007	41	50	+0.17±0.05	−2.03±1.86
Durban	1970-2003	34	79	+2.70±0.05	+2.40±0.29
Richards Bay	1990-2000	11		Insufficient data	Insufficient data

Table 8.3: Regional relative sea level trends. Equal weighting was given to each location in the calculation of regional sea level trends in each region (Mather *et al.*, 2009).

Region	**Port**	**Observed annual sea level trend using monthly data** (mm per year)	**Observed annual sea level trend using annual data** (mm per year)	**Regional relative sea level trends** (mm per year)
Western	Lüderitz	+2.73±0.81	+2.40±1.64	+1.87
	Port Nolloth	+1.25±0.23	+1.11±0.41	
Southern	Simons Town	+1.58±0.22	+1.14±0.52	+0.68
	Granger Bay	+0.08±0.20	+0.44±0.53	+1.48 excl. Granger and Mossel Bay
	Mossel Bay	-0.40 ±0.19	-0.66±0.56	
	Knysna	+1.27±0.50	+1.95±1.62	
Eastern	Port Elizabeth	+2.97±1.38	+2.89±2.05	+2.74
	Durban	+2.70±0.05	+2.40±0.29	

8.3 Projections of future sea levels

The amount and rate of sea-level rise into the future is not known. Many authors have attempted to project future sea levels based on the link between CO_2 increases and sea levels as well as by extrapolating tidal records. Over the last few decades the science behind the models used to provide these projections has improved and the range has narrowed from the estimates in the 1980‘s however there still remains much uncertainty. The 2007 IPCC report gives a global range of sea level rise to the year 2100 ranging between 0.18 to 0.59 m depending on what emissions scenario is selected. However these are broad averages of global sea level change projections and it is important to look at how these could affect the region in which we are interested. Recent work on downscaling from the global scale to the local scale in order for a better local understanding has been carried out for Durban by Mather (2009) and the results are summarized in the following sections.

8.3.1 Temperature/sea level rise relationship

This method was initially proposed by Rahmstorf (2007), who derived a relationship between temperature and sea-levels. Rahmstorf correlated the increase in global temperature with the increase in global sea levels. From this relationship Rahmstorf calculated that sea levels, using the temperature change as a proxy, would rise to between 0.5 and 1.4 m above 1990 levels, based on the IPCC Special Report on Emissions Scenarios (SRES) scenarios. The author has re-performed Rahmstorf’s analysis but has departed from Rahmstorf’s approach by (1) not undertaking smoothing of the data and (2) using only the more reliable data recorded after 1950 (referred to as the modified Rahmstorf in the rest of the text). This has resulted in lower figures of future sea-level change as detailed in Table 8.4. The Durban Climate Change project (CSIR, 2006) has predicted increased temperatures along the Eastern region and these were used to give an indicative rate of thermal expansion. Using the modified Rahmstorf relationship for each degree of air temperature increase yields a 117 mm rise in sea level.

8.3.2 Tide gauge projections

South Africa’s tide gauge network is only just able to provide a long enough length of record to produce sea-level tends which are reflective of the general underlying changes. However, with the exception of Simon’s Town, they are not long enough to identify any acceleration in sea level rise to within acceptable statistical uncertainty limits (Woodworth *et al.*, 2007). Short sea-level records can be distorted due to seasonal and decadal variations and careful attention needs to be paid when considering these shorter records (Woodworth *et al.*, 2007). All South African tide gauges are able to provide a linear trend. Some are over relatively short time periods and therefore would be subject to possible inter-decadal variations making the statistical

Table 8.4: Eastern region sea level projections using temperature/sea level relationship.

Author	**Method**	**Predicted temperature increase** Deg C	**2090-2099 sea levels above 1980-1999 level** (mm)
Modified Rahmstorf 2007	Global temperature and sea level relationship	1	117
		2	234
		3	351
		4	468
		5	585
		6	702

level of confidence in the results questionable.

Bearing in mind the issue above it is possible to develop a hybrid approach to determining the extent of sea level rise accelerations of local South African stations. This requires using the linear trend at each local station and adding on to this an acceleration term "borrowed" from the global analysis undertaken by others using much longer tide gauge records. The linear trend from local records can be used to project the likely sea-level in the future however by ignoring this acceleration term this approach can underestimate likely future sea-levels. The basis of the analysis is the decomposition of a quadratic equation into the three component parts (see Eq. 8.1).

$$y = ax^2 + bx + c \tag{8.1}$$

Where y is the sea level, a is the acceleration term, b the linear rate term and c the constant term. This can be shown diagrammatically below (Figure 8.1).

This composite approach provides a projection of sea levels which are slightly higher then the straight linear trend approach and therefore can be viewed as more conservative then a linear approach. The Eastern region sea level rise trends have shown the highest rates of sea level rise in the country and so we will use this data. The summarised results are shown in Table 8.5.

This practical approach does provide a range of sea level rise projections for Southern Africa and avoids the pitfalls of using a global average value. Based on this approach the eThekwini Municipality has determined three sea level rise scenarios for its planning work till the year 2100. These are 300 mm, 600 mm and to address recent concerns about accelerated ice melt an additional scenario of 1000 mm (Mather, 2009). These scenarios are seen to be both workable and believable, an important consideration when it comes to convincing the public, politicians and developers.

The outcome of the future scenario predictions have been plotted on a freeware

Table 8.5: Eastern region sea level projections using temperature/sea level relationship.

Author	**Method**	**Acceleration increase** Deg C	a (mm per year^2)	b (mm per year)	**2090-2099 sea levels above 1980-1999 level** (mm)
This paper	Using Church and White (2006) acceleration with eastern region linear sea level rise	0.0127	0.00635	2.74	358
	Using modified Jevrejeva *et al.* (2008) acceleration with eastern region linear sea level rise	0.00922	0.0046	2.74	338

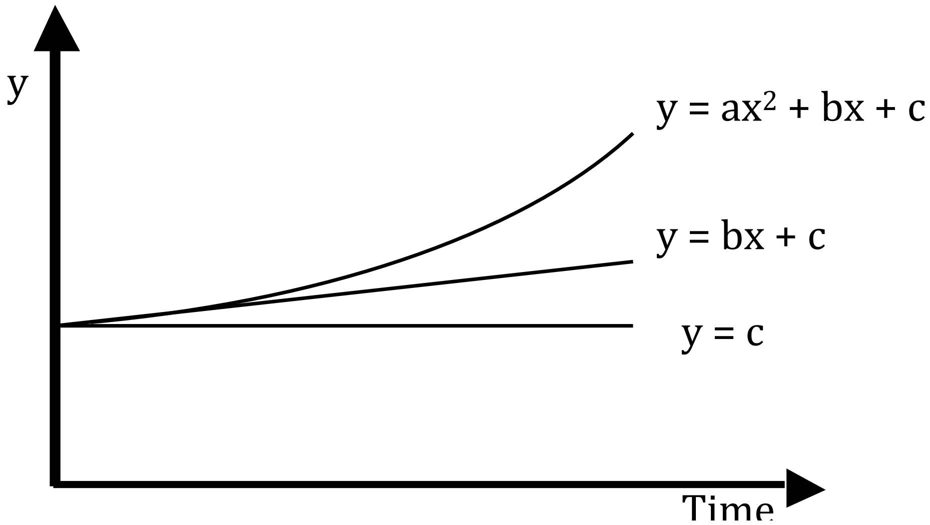

Figure 8.1: Decomposition of tidegauge accelerations in the three principal components.

GIS platform and have been made available to local planners, scientists, engineers and policy makers so that they can see the possible impacts of future sea level rise on the shoreline. This information forms part of a Shoreline Management Planning process currently underway in the municipality. The typical maps available from the viewer are shown in Figures 8.2 and 8.3.

8.4 Planning for sea level rise in South Africa

Planning for sea level rise is still in its infancy in South Africa. Historically some municipalities have taken a proactive approach, for example, Durban included 300mm of sea level rise in its coastal erosion lines in the mid 1980's. However, it is only recently that several local authorities and developers have started to factor this into their planning. Recent sea level rise impact studies have been conducted in the Cape Metropolitan, Nelson Mandela Bay Metropolitan, Richards Bay and Eden Municipality. In this section, the context and nature of these planning initiatives are discussed.

8.4.1 Coastal Planning Schemes

The newly enacted Integrated Coastal Management Act (ICM Act, 2008) provides for the development of a new planning instrument referred to as a coastal planning scheme. This is distinct from a coastal land use scheme in that it is there to achieve coastal management objectives rather then managing the built form. The coastal

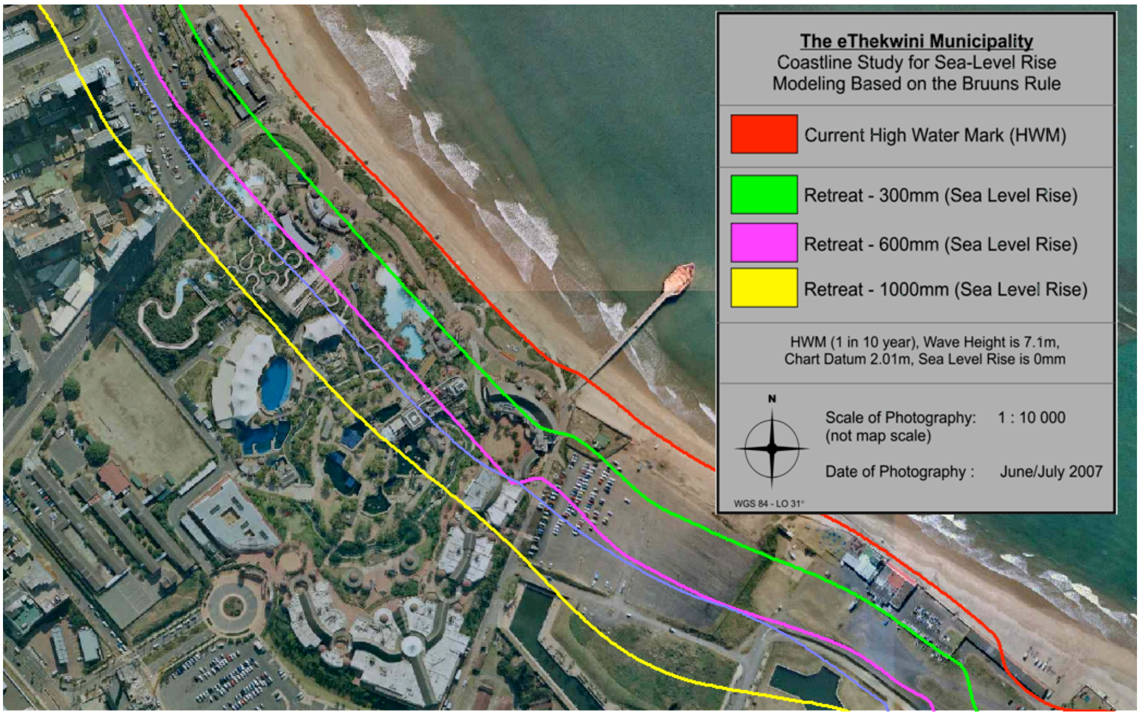

Figure 8.2: Durban Point area showing the mapped sea level rise scenarios.

planning scheme must define areas within the coastal zone or coastal management area in which certain activities can be permitted, such as, where boat launch sites can be established. Additionally, the coastal planning scheme must also define activities which are excluded/prohibited from a certain area, such as fishing within a particular stretch of coast.

A coastal planning scheme must integrate a range of management plans developed for the area including any national/provincial/municipal coastal management programmes as well as shoreline and estuary management plans. The Act provides the authorities with the mandate to establish coastal planning schemes provided the detail contained in all coastal planning schemes be aligned between municipalities, provinces and national. The typical hierarchy of national coastal planning schemes taking precedence over provincial and provincial over local is embodied in the ICM Act.

For more information the reader is directed to the ICM Act 2008, Sections 56 and 57.

8.4.2 Sea level rise scenarios

At the present time there are no guiding principles or methodologies which have been accepted in the country to assess future sea level rise impacts and as a result

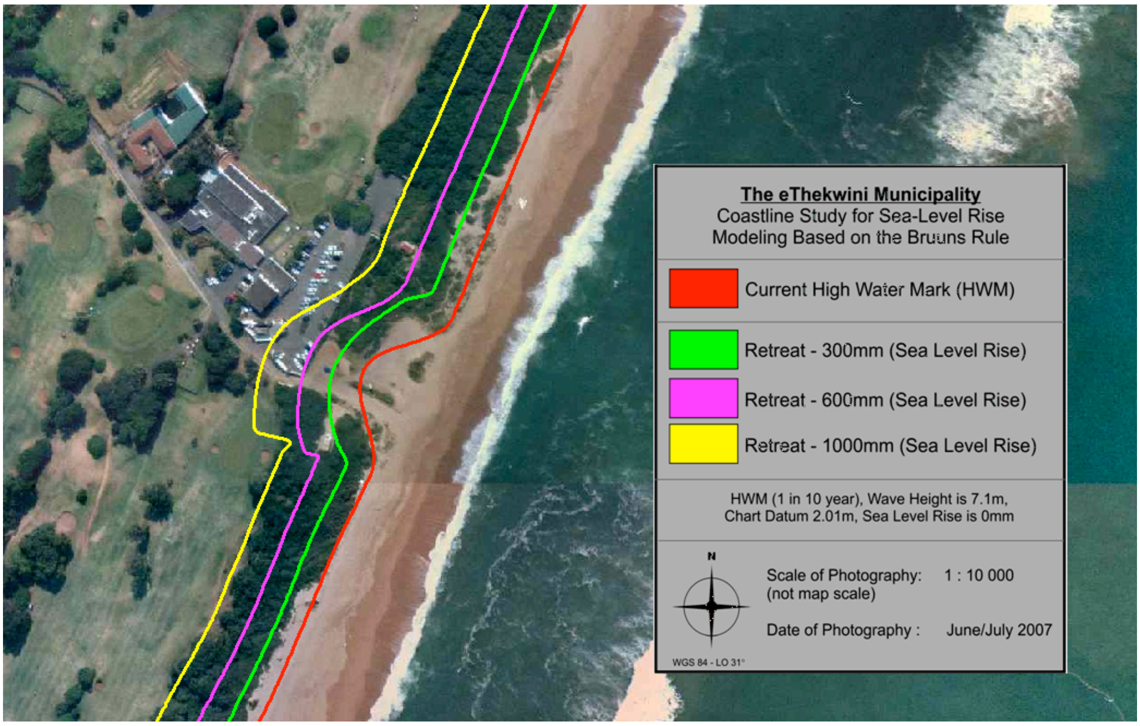

Figure 8.3: Beachwood golf course north of Durban showing the mapped sea level rise scenarios.

what is emerging from the current work around the country is that each province or municipality is approaching the analysis differently. The current studies have also considered a wide range of sea level rise scenarios as the country has yet to decide on what scenarios should be used to determine future impacts. Ultimately if this situation is allowed to continue the comparative evaluation of the sea level rise impacts between different locations along the coast will be difficult if not impossible. It is therefore vital that South Africa adopt unified scenarios for sea level rise assessment. To generate some discussions the following sea level rise scenarios are put forward for consideration. As shown previously current sea level rise varies around the coastline, however the eastern region has experienced the highest rates to date. Therefore, if one was to adopt a single national set of sea level rise scenarios one would be inclined to select the eastern region as the reference case. This is of course slightly conservative given that sea level rise in the southern region are about half the eastern region. Notwithstanding this difference given the uncertainties this is a reasonable approach. The projections from Section 8.3.2 give a range of future sea levels to year 2100 of between 270 mm (linear current trend) to 585 mm (temperature increase of 5° C). However there has also been much concern regarding accelerated ice melt, which was left out of the IPCC scenarios, and so an additional scenario of 1000 mm should also be included. This 1000 mm is similar the German and Dutch sea level rise planning scenarios for 2100. This is fine for infrastructure which has about a 50 to 100 year life span but arguably not sufficient for longer term key infrastructure like new ports, nuclear power stations and desalination plants which will be required to operate beyond 100 years. In this case an additional scenario of 2000 mm should be used for planning purposes. The SLR scenarios are therefore summarised below in Table 8.6. The most important issue that must be addressed is reaching some consensus on the range of sea-level rise that must be planned for in South Africa.

Table 8.6: Proposed South African sea level rise planning scenarios.

Sea level rise scenario	**Amount of sea level rise** (mm)
Scenario 1 using current sea level rise	300
Scenario 2 using the maximum temperature range/acceleration in SLR	600
Scenario 3 using accelerated ice melt	1000
Scenario 4 for infrastructure that will exist beyond the year 2100	2000

8.4.3 Coastal set back lines

In the previous section the issue of scenarios of different sea level rise were discussed and a set of proposed sea level rise scenarios for South Africa were proposed. The implications of the various sea level rise scenarios become important when the modeled impacts of these scenarios are mapped onto the real coastline and the impacts can then be evaluated in terms of possible damage and loss of recreation and infrastructural assets. The tool which will provide for the management of development activities along the coastline will be the coastal set back lines proposed in the ICM Act (Section 25) and therefore an understanding of what these are is important to planners working in the coastal zone.

8.4.3.1 Legal definition

Coastal setback lines are important development control mechanisms which limit the risk of wave attack on infrastructure planned for the coastal zone. The coastal setback lines are defined in the ICM Act as meaning

'a line determined by the MEC in accordance with section 25 in order to demarcate an area within which development will be prohibited or controlled in order to achieve the objects of this Act or coastal management objectives'.
ICM Act (2008)

Section 25 relates to the establishment of coastal set-backs and reads as follows:

"25. Establishment of coastal set-back lines
(1) An MEC may in regulations published in the Gazette -
(a) establish or change a coastal set-back line
(i) to protect coastal public property, private property and public safety;
(ii) to protect the coastal protection zone;
(iii) to preserve the aesthetic values of the coastal zone; or
(iv) for any other reason consistent with the objectives of this Act; and
(b) prohibit or restrict the building, erection, alteration or extension of structures that are wholly or partially seaward of that coastal set-back line.

(2) Before making or amending the regulations referred to in subsection (1), the MEC must -
(a) consult with any local municipality within whose area of jurisdiction the coastal set-back line is, or will be, situated; and
(b) give interested and affected parties an opportunity to make representations in accordance with Part 5 of Chapter 6.

(3) A local municipality within whose area of jurisdiction a coastal set-back line has been established must delineate the coastal set-back line on a map or maps that form part of its zoning scheme in order to enable the public to determine the position

of the set-back line in relation to existing cadastral boundaries.

(4) A coastal set-back line may be situated wholly or partially outside the coastal zone. ”

8.4.3.2 Theoretical overview of Coastal Setback Lines

What are coastal set back lines?
Historically in South Africa there have been two lines determined along a coastline. The first line is the coastal erosion line. This line represents the impacts of a chosen storm combined with a chosen amount of sea level rise on this environment. In the case of the eThekwini Municipality where the coastal erosion line has been mapped, it was determined using as a 1 in 50 year storm combined with 300 mm of sea level rise. The second line is the building control limit line/development set back line. This line is further inland of the coastal erosion line. The difference between these lines is that an allowance over and above the coastal erosion line is provided for re-establishment of vegetation and as a safety margin.

Why have these been established?
A prime feature of South Africa's asset base is its coastline. The coastline is generally sandy with very little rocky shoreline and the wave regime is regarded as high energy. This leads to a high potential for erosion of our sandy coastline. The development setback lines are *"designed to protect both the natural environment from encroachment by buildings as well as protecting beachfront developments from the effects of storms and coastal erosion"* (Breetzke *et al.*, 2009).
Encroachment by historical developments have compromised and destroyed many of the dunes systems along thecoastline. This is unfortunate as these dunes provide a number of services that not only act as a natural asset for biodiversity, but also form an important coastal defence system. The dunes are mobile as high seas erode the dune and the sand moves onto an offshore bar. This alters the slope of the bathymetry which causes waves to break further out to sea and therefore reduces the wave energy and erosion potential at the beach face. This self-regulating cycle requires an onshore reservoir of sand (dunes) to provide for this. When there is no buffer accelerated sand erosion occurs.

Very few local authorities have voluntarily implemented coastal set back lines. One of the few was the eThekwini Municipality who initiated this programme in the 1980's to maintain its coastal assets through scientific management. They have studied the history of shoreline variance through aerial photographs, beach monitoring/surveys and underwater surveys over the last 70 years. Base information for the determination of these setback lines stretches back to 1935 in the case of aerial photographs and 1960 for physical surveys.

8.4.3.3 Advantages of Coastal Setback Lines

The benefits of the setback line approach are that human development and nature are separated by means of this line. Each is given its own space to exist and move within, in a manner that is not likely to affect the other, except in a catastrophic event. The net result is a more natural shoreline with allowance for sustainable development on its margins. The buffer between the coastal set back line and the sea allows for the re-establishment of the natural dune system and vegetation after major erosion events and visibly creates more natural looking dunes and green areas surrounding the beaches. Additionally, given future climate change uncertainties the ability to buffer developments against future climate scenarios is important given the extent of possible future losses if sea levels reach the maximum levels being projected by climate researchers.

8.4.3.4 Disadvantages of Coastal Setback Lines

The disadvantages of setback lines are that these are artificial lines based on limited human experience. Many of these lines are determined with limited data, sometimes only a few years. Once these lines are determined they are often viewed as absolute lines where anything can take place behind the coastal set back lines and have zero risk of wave attack in perpetuity. This false sense of security is a major disadvantage of the establishment of coastal set back lines which of course reduces as the period of data increases. The alternative is to approach the coastal set back lines from a risk point of view. In other words accepting that the risk cannot be completely reduced however one can decided what risk is acceptable for different types of development and therefore balance the issue of risk of failure against usability of the coastal zone. This will be discussed next.

8.5 A risk-based approach to Coastal Setback Lines

There is a real danger that in the process of setting coastal set back lines the least risk (or no risk) scenario is chosen. This scenario is likely to be the aggregation of all possible variables at their perceived maximum extent. For example, one could chose a maximum sea level rise forecast over the next 100 years combined with a sea storm with a return period of 1 in 100 years, combined with a eroded shoreline based on a long term erosion trend of 1 m per year all occurring at the Highest Astronomical Tide (HAT) level. Such a coincident of these variables all occurring simultaneous is highly improbable. But if this was the approach used then the prohibition of any infrastructure seaward of this set back line would restrict the use of a significant area of the coastal zone.

The rate of change of sea level rise is relatively slow so by taking the aggregated extreme value the impact of this will be to neutralise all development in this zone. Some developments/infrastructure have a relatively short life (less then 20 years) and could easily be placed in this zone and reach the end of their economic life before the impacts of sea level rise have a detrimental impact on the infrastructure in question. By adopting a very conservative approach the ability to place low value/short lifespan infrastructure particularly for beach recreation purposes becomes limiting.

Given that the approach in the ICM Act is based around human use and activities along the coast the balance between the opposing risk extremes of asset loss and the usage of the coast for recreational purposes must be balanced. If one then reviews the philosophy of coastal set back lines it is clear that one single setback line is impractical. There are two real issues which need to inform the development of set back lines. The first issue which needs to be defined is the extent of the hazard zone (this is an area where the coastal processes are able to play themselves out) and secondly the appropriateness of infrastructure and how close this can be placed to the hazard zone. This leads to the result that in fact at least two coastal set back lines need to be determined.

8.5.1 Coastal Hazard Line

This is the easiest line to define and explain to the public as this line includes the seasonal variability of the shoreline and the extent of wave run up which the public is generally able to see play itself out. This line is by definition the current hazard zone based on current conditions and processes occurring at the site in question.

8.5.2 Coastal Development Restriction Line

The second line is more difficult for the layperson to conceptualise. Simple put this is similar to the coastal hazards line except that the dimension of time is included. For example this could be the coastal hazard line with future erosion and sea level rise included. Typically this is a modeled line based on the Coastal Hazard Line using expert coastal engineering judgement and different future scenarios of sea level rise and coastal erosion. These are typically the lines which have the potential to restrict current and future development.

An alternative approach is to construct the coastal development control lines based on the value and/or life span of the infrastructure. This approach seeks to strike a balance between the one extreme where all development is restricted as it is statistically at risk even if there is little chance that failure will occur for several decades to come and where infrastructure is exposed to what could be seen as an acceptable risk. As risk is related to occurrence probability and value of possible loss this approach makes good economic sense.

However this approach requires some education of the public, developers and regulators as this approach will mean that at some future date the development will be lost. In other words the developers need to understand that whatever developments are proposed, their life spans are finite, bounded by physical processes which are being driven by coastal erosion and shoreline retreat induced by natural and anthropogenic processes. This approach should be backed by a guideline or framework in which the selecting of the coastal development control line can be determined for different types and values of infrastructure. This can be typically described as shown in Table 8.7 where depending on the type/value/lifespan of the proposed infrastructure a suitable risk approach can be chosen.

Table 8.7: Decision matrix for risk selection to sea level rise for coastal developments.

Value of Infrastructure	**Life of Infrastructure**	**Impacts of failure of the Infrastructure**	**Planned amount of sea level rise** (mm)
Low (up to ZAR2 million) Recreational facilities, car parks, board walks, temporary beach facilities	**Short term** less then 20 years	**Low** Minor inconvience, alternative facilities in close proximity, short rebuild times	300
Medium (ZAR2 to 20 million) Tidal pools, piers recreational facilities, sewer pump stations	**Short to Medium term** between 20 and 50 years	**Medium** Local impacts, loss of infrastructure and property	600
High (ZAR20 to 200 million) Beachfronts, small craft harbours, residential homes, sewerage treatment works	**Medium to Long term** between 50 and 100 years	**High** Regional impacts, loss of significant infrastructure and property	1000
Very High (greater then ZAR200 million) Ports, desalination plants, nuclear power stations	**Long term** In excess of 100 years	**Very High** Major disruption to the regional and national economy, failure of key national infrastructure	2000

8.6 Conclusion

It has become apparent that the impacts of global warming, particularly sea level rise do not appear to be slowing down and therefore the emphasis on adaptation to the consequences of climate change and sea level rise is where planners, engineers and coastal managements need to focus their attention into the future. We need to re-plan the way coastal developments are currently implemented. The majority of proposed public amenities such as toilets, car parks and lifesaving facilities need to be close to the coast but larger more expensive infrastructure can be set back behind an appropriate coastal setback line. Private developments are similarly affected and would be required to be situated behind the development setback line. Existing developments would need to be managed more carefully going into the future and restrictions on expanding existing developments would have to be enforced. Landowners would need to be informed that in the event of a partial or total loss of the property it is unlikley that they would not be permitted to rebuild the same development in the same place. Relocation/retreat of existing buildings would need to be evaluated on a cost/benefit basis if they have not been damaged or destroyed to date.

By applying a risk based approach the balance between inappropriate and essential infrastructure can be assessed allowing what is effectively a time based retreat approach to managing sea level rise impacts into the future. This will allow for the maximum human utilisation of the coastal zone in the knowledge that the most essential infrastructure has been placed in the less risky locations.

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Epilogue to Chapter 8

In Chapter 8 an assessment of future sea level rise scenarios were developed from a combination of Global Climate Models downscaled to the region and using both tide level/temperature relationships coupled with the linear sea level rise trend component a range of future sea level scenarios were proposed. Scenarios were specifically chosen to cover the potential range of future scenarios as there is much debate and uncertainty about what the actual sea level rise will be as this is linked to mankind's behaviour to curbing green house gas emissions.

Prologue to Chapter 9

The results from Chapters 7 and 8 have shown that the physical processes of sea-level rise, wave run-up and coastal erosion have been incorporated into a model which has been developed and is suitable for use in the region. The model requires information which is readily available along the coast making it simple and easy to apply. The model provides the extent of the wave run-up zone at current sea levels and future sea levels based on scenarios informed by regionalised global sea level rise projections. The shoreline retreat under these shorelines is mapped and areas of vulnerability have been determined.

The development of scientific models and research is but only the first step in the process of management. The most frequently difficulty experienced is the ‘cross over’ of the scientific research into the operational management domain. Often scientists and management do not have access to the same information; management is sometimes uninformed about the facts or alternatively applies their own interpretation of the facts. This gap is an area which has the potential to undermine the proper management of the coastal zone under the threats of sea level rise and coastal erosion. The real challenge in improving the risks in the coastal zone is to raise awareness of the issues facing the coastal community. Included in this initiative is the capacity and skills of coastal planners and managers whose day to day work influence the scale and form of all aspects of the natural and built coastal environment. This Chapter will start to address the issue of constraints to the management of shoreline changes by addressing the capacity of local government in dealing with sea level rise and coastal erosion.

This Chapter includes the thematically linked, journal paper, which has been published as a research paper titled:

Mather, A.A. 2007. Coastal erosion and sea-level rise: are municipalities prepared?. *IMIESA*, March 2008, 49-70.

The published journal publication has been reproduced with the permission of the Editor of the Journal of Municipal Engineers in South Africa in the Appendix.

Chapter 9

COASTAL EROSION AND SEA LEVEL RISE: ARE MUNICIPALITIES PREPARED?

9.1 Abstract

Worldwide there is an increased awareness of the effects of climate change brought about by human impacts on our planet and of particular relevance are the issues of sea-level rise and increased storminess and the impact this would have on coastal cities infrastructure. Sea-level changes over the centuries have been widely documented, however the predictions of the extent of the rate of sea-level rise in the next century has remained a debated issue. The rate of sea level rise on the east coast of South Africa has not been studied in any detail to date despite most of the largest South African cities being located along this stretch of coast. This paper will detail the latest research findings for sea-level rise from detailed analysis of the Durban tide gauge data and its applicability along the east coast.

In March 2007, a cut-off low-pressure system induced a sea storm, which wreaked havoc along the KwaZulu-Natal coastline causing damage running into hundreds of millions of rands. The paper will examine the mechanisms, which led to this event, its frequency and likelihood of recurrence and the steps taken to limit future damage. This paper will discuss the challenges and approaches in coastal management faced by the eThekwini Municipality prior to and post this recent storm, the current legal frame work relating to development within the coastal zone and concludes with setting out proposed principles that allow for re-built and new future coastal infrastructure to be more sustainable than at present.

9.2 Introduction

Climate change will impact directly on coastal cities, towns and subsistence communities who have built a lifestyle around the coast, who rely on the sea for income and who depend on the sea to provide food for their families. The worlds sandy coastline is estimated to be in the order of 170 000 kms (approximately 34% of the worlds coastline) with numerous urban settlements dotted along this ribbon of sand (Hardisty, 1990). The United Nations has indicated that over half of the worlds population lives within 60 kms of the coast and that this will rise to three quarters by the year 2020 (UN, 1993).Urban settlements have expanded rapidly over the last thirty years and particularly in the developing countries (Rakodi and Treloar, 1997). Recent work along the KwaZulu-Natal coast has shown that the strip of land 100m inland of the high water mark (HWM) has been transformed from 28% urbanised in 1994 to 50% in 2006 (excluding the Isimangaliso Park (formally called the Greater St Lucia Wetlands Park)) (Cilliers, L. pers. comm.). This is not surprising, as we know that people are drawn to this rich and unique landscape where the land meets the sea.

Ports and harbours have long been part of the preferred logistical transport network for nations to trade. The majority of international imports and exports are moved by sea transport because this method of transport is by far the cheapest compared to road, rail and air transport. This makes the long-term viability of ports and harbours a key element in many cities economic survival into the next century. Port and harbour development is hugely expensive and the developers of this infrastructure expect to use this infrastructure for extended periods of up to a century. Durban along with other coastal ports in South Africa are planning to expand their capacity (Mather *et al.*, 2006).Rising sea-levels, therefore are a potential threat to the viability of ports worldwide and therefore need to be carefully planned, with as much information as possible about potential sea-level changes.

Global foreign tourism direct spend was estimated at US$ 681.5 billion in 2005 with South Africas direct spend accounting for ZAR 53.4 billion. A visit to the beach by foreign tourists was ranked as fifth after shopping, nightlife, social and visiting natural attractions. For the domestic tourism market, the beaches form the most important tourism attraction with 73% of all domestic visitors to KwaZulu-Natal visiting the beaches (Tourism KZN, 2006). Tourism is most closely associated with sandy beaches, which make up 34% of the worlds coastline (Hardisty, 1990). The east coast of Africa provides the ideal location for tourism facilities with its sunny climate, sandy beaches and warm Indian Ocean water. Rising sea-levels will lead to reduced beach widths, damage to tourism infrastructure, and arguably be the single biggest factor in the shrinkage and/or collapse of the beach tourism industry.

Beach and shoreline erosion arising from rising sea-levels will lead to the loss of valuable public and private land and property. Private land owners are often the most negatively affected as many have invested large sums of money purchasing prime and expensive seaside properties. The options for the affected property owners to protect their properties are limited and difficult in an environment where little is known of the likely quantum and rate of shoreline regression. Where man decides to fortify the shoreline to reduce erosion damage and protect the land and property, the costs associated with this will negatively influence the economy. For local government this may mean less money to spend on developmental issues.

South African local authorities have been restructured in recent years with local government now covering the whole land surface of South Africa. This has created a situation where local authorities have inherited new areas and increased functions as municipal boundaries have changed. In many cases, this has stretched municipal capacity to the limit. Currently no direct authority is vested in local government for coastal management although indirectly many functions of local government directly affect the coast and coastal zone.

9.3 Climate change impacts

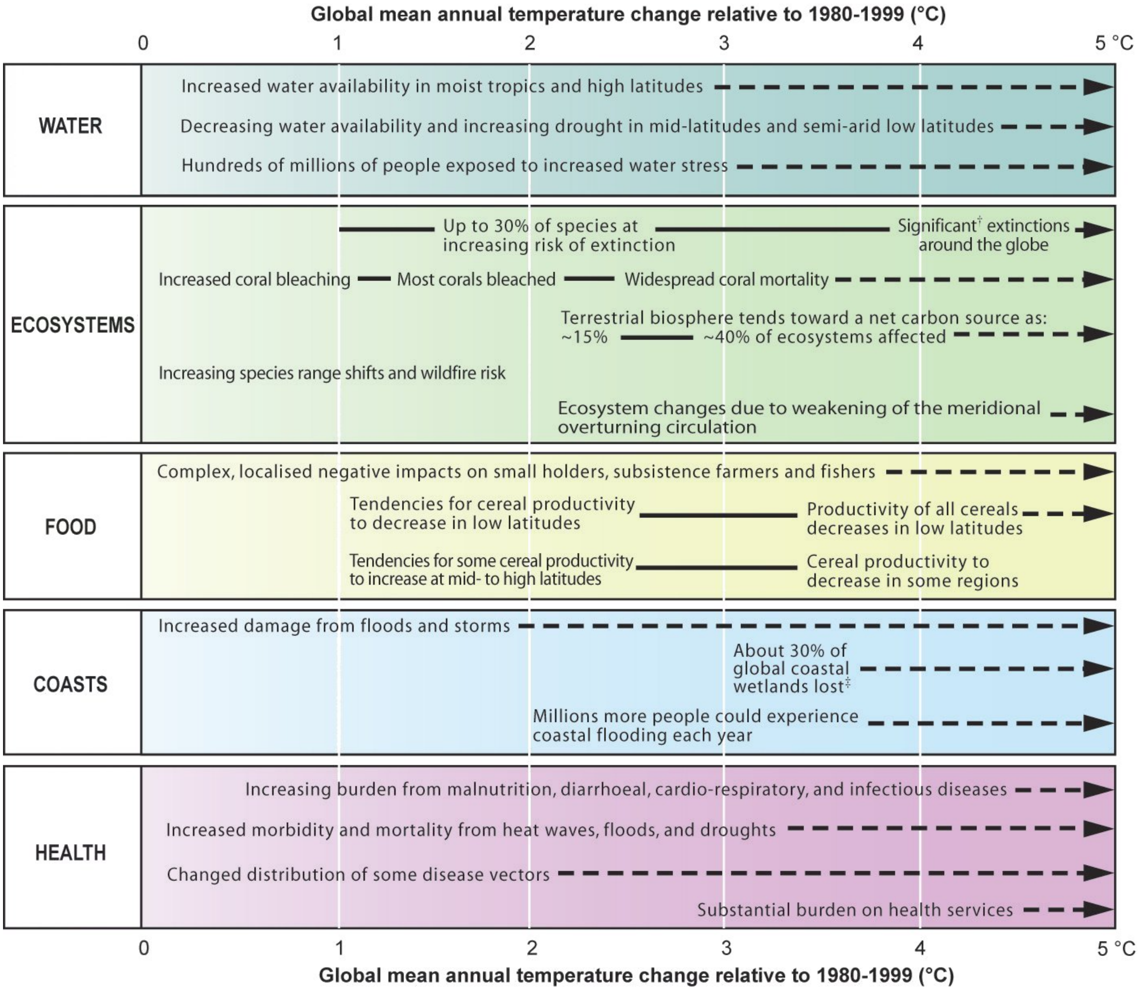
Climate change and its likely effects on our environment has become an ever-increasing point of discussion amongst built environment professionals. This has been constantly in the news and more particularly recently when the Intergovernmental Panel on Climate Change (IPCC) released their latest report (IPCC, 2007). The Panel has identified several factors, which are likely to be areas, which will adversely affect the coastlines of the world as, can be seen in Figure 9.1 below. Sea-level rise resulting from thermal expansion of the oceans and increased storminess of the oceans are two of the key impacts to which we are likely to be exposed.

9.3.1 Sea-level rise

One of the impacts of global warming is sea-level rise, which is driven by the following factors:

Melting of the polar ice caps and glaciers
Thermal expansion of the oceans
Increased break up of the Antarctic and Greenland ice sheets.

Global sea-level is estimated to be increasing over the 1993 to 2003 period at a rate of +3.1 ± 0.7 mm per year (Cazenave and Neren, 2004). However, the distribution of sea-level rise is not going to be uniform over the surface of the oceans (Bindoff *et al.*, 2007). It is therefore important that each region identify the extent of sea-level rise, which is likely to occur locally. Little work on sea-level rise has taken place to date along the east coast of South Africa; however, recently the author has been examining the tide gauge records in Durban. Over the 1970 to 2003 period, the results from this investigation yield that sea-level rose at a rate of +2.7 ± 0.05 mm per year (Mather, Unpublished data). Projected sea-level rise from the work



† Significant is defined here as more than 40%.
‡ Based on average rate of sea level rise of 4.2 mm/year from 2000 to 2080.

Figure 9.1: Predicted impacts from different temperature increases. (IPCC, 2007).

undertaken by the IPCC yields a range of projected increases from 1980-1999 to 2090-2099 to be in the range of 0.18-0.59 m (Bindoff *et al.*, 2007). The Southern oceans have exhibited a weaker rate of sea-level rise than the global oceans (Park 2007) and therefore for planning purposes a figure of 3mm per year, assuming that an A1B scenario is the most probable, should be factored into municipal plans from now onwards.

9.3.2 Increased storminess

An increasing frequency of more extreme storms and cyclones is predicted in the coming years because of the mid-latitude westerly winds strengthening since the 1960s. The IPCC considers it likely that future cyclones will be strengthened by increasing tropical sea surface temperatures resulting in more intense events with higher wind speeds and heavier rainfall (IPCC 2007). According to Theron (2007), quoting Hewitson (2006) South Africa is likely to experience an increase in average wind speed throughout the year caused by stronger prevailing winds.

The effect of just a 10% increase in wind speed on the coastal environment creates an order of magnitude increase of other coastal processes. This 10% increase in wind speed is predicted to result in a 26% increase in wave heights and potential increasing longshore transport rates by between 40% and 100% (Theron, 2007). Actual changes will be co-determined by many other factors, including local factors, such as, sediment availability, wave transformation, etc. These impacts are likely to affect the shoreline particularly in areas weakened by previous erosion or low lying areas relative to sea level such as the Isipingo area in Durban (eThekwini Municipality, 2006).

9.4 The March 2007 coastal erosion event

9.4.1 Background

This extreme wave event, generated by a low-pressure system off the coast, occurred at a time when the maximum gravitation forces exerted by the Sun and Moon were also at their 18.6 year peak. This combination resulted in exceptionally high waves on top of a raised sea level causing widespread damage along the entire KwaZulu-Natal coast on the 19 and 20 March 2007. The Saros equinox spring tide had been identified as early as September 2006 as a possible period of vulnerability from increased erosion for the Durban coastline and in particular for properties located north of Durban along Eastmoor Crescent, La Lucia (Mather 2006). However, nobody was prepared for the full impacts of this event.

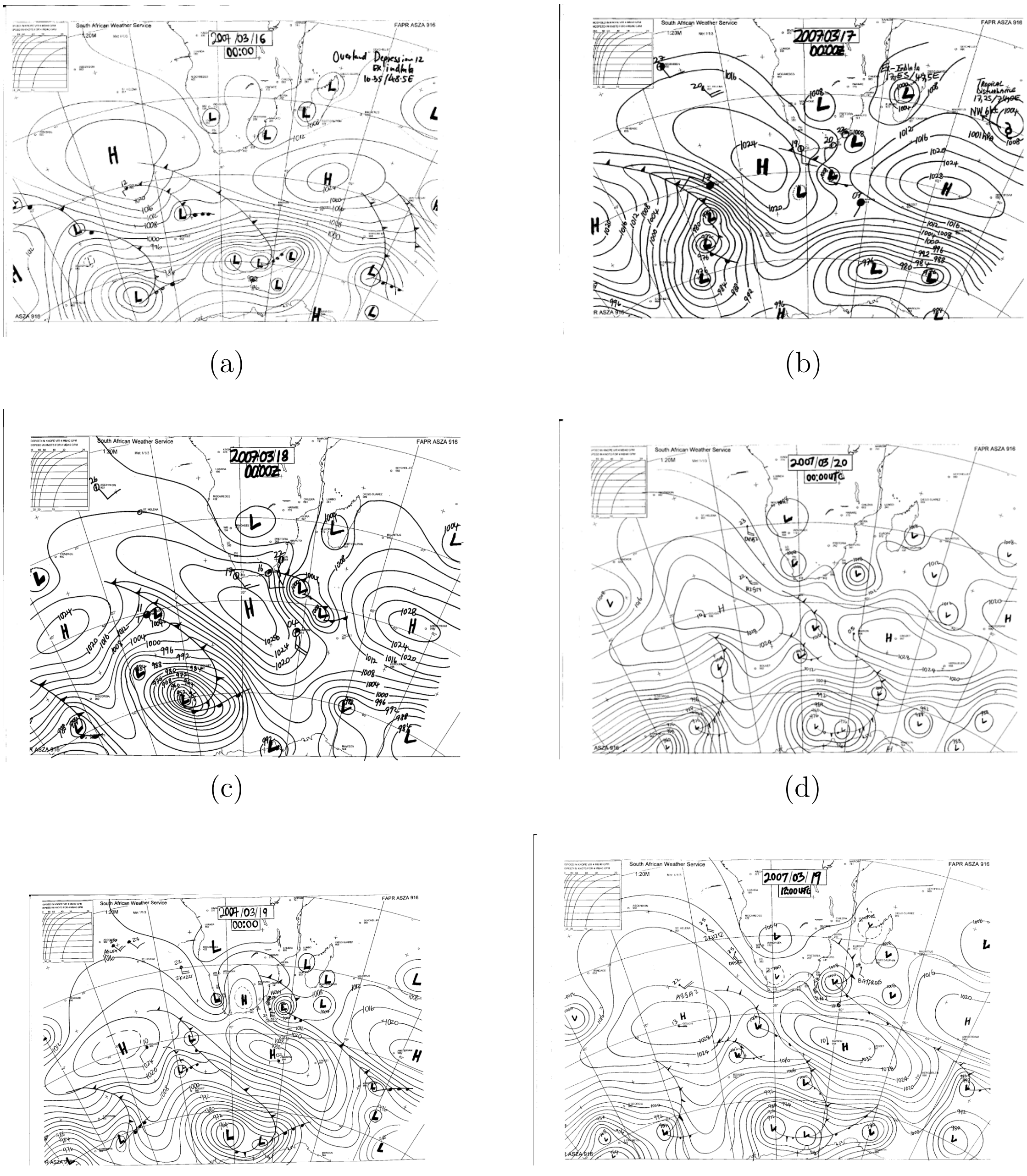
Sea conditions prior to the event had been unseasonable, with an unsettled sea, with 2 to 3m swells running. The prevailing sea conditions prior to March had been influenced by three tropical cyclones (Dora, Favio and Gamede) located east of Durban. Of these, only Cyclone Dora and Gamede were significant. Cyclone Dora, which later combined with a well-developed cold front to the south, induced swells in the 2-3m range and impacted Durban on 11 to 13 February. Cyclone Gamede arrived several weeks later as this storm tracked westward towards Madagascar on 26 February, turned southward on 28 February and eventually stalled in the south Indian Ocean from 1 to 6 March. Despite being downgraded from a cyclone to an extra tropical depression cyclone Gamede was responsible for the first calls of concern from residents as it generated 2 to 4m swells from 1 to 5 March. This event caused local inundation and minor erosion along Durbans golden mile (the beachfront strip from the harbour entrance to the Umgeni river mouth) when these swells coincided with the spring high tides on 3 to 4 March. Minor erosion damage was also recorded up and down the KwaZulu-Natal coast.

9.4.2 The storm of 19-20 March 2007

The storm started as a frontal low, which passed south along the coast of South Africa on 16 March (Figure 9.2a). The frontal low intensified and rapidly developed into a cut-off low south-east of East London on 17 and 18 March (Figure 9.2b and c). From the dense isohyets around this low, it can clearly be seen to intensify to a peak on the 19 March (Figure 9.2d) where it remained trapped between two high-pressure cells until the 20 March. The system started to weaken by midday on the 19 March (Figure 9.2e) and was almost back to normal by 20 March (Figure 9.2f).

The central pressure of this low-pressure cell dropped to below 996 hPa. The strong pressure gradient between the low and high cells generated strong and consistent winds, which were recorded between 40 knots (21m/s) and 45 knots (23 m/s) along the coast. As the system was trapped in position this allowed the wind to generate some impressive waves over the fetch length of 450 kms straight at the coastline of KwaZulu-Natal. The Acoustic Doppler Current Profiler normally used to record wave heights in Durban was out of commission during this event. Recorded wave heights for the event are therefore confined to the CSIR wave-rider buoy located off Richards Bay in 30 m of water depth.

This recorded a significant wave height (H_{m0}), defined as the average of the top third waves recorded, of 8.5 m, with a period 16 seconds from the south-east to south-south-east, measured at the peak of the storm at 05h00 on 19 March (Rossouw M, pers. comm.). The maximum wave height was recorded at 14 m (Rossouw M, pers. comm.). At the same time, the Highest Astronomical Tide (HAT) occurred which happens only once in 18.6 years. This would have elevated water levels by approximately 20cm more than the normal springtide levels and when, synchronised with the wave event magnified this combination for the worse. Fortunately, the wave event very quickly dissipated and by the evening of the 20 March, the swells had reduced to less then 3 m.



(a) (b)

(c) (d)

(e) (f)

Figure 9.2: Synoptic chart for (a) 16 March 2007 (b) 17 March 2007 (c) 18 March 2007 (d) 19 March 2007 and (e) 12H00 19 March 2007 and (f) 20 March 2007. (All the synoptic charts are courtesy of the South African Weather Service).

Figure 9.3: Santorini complex showing infilling and exposed sea protection works. Location approximately 20 kms north of Durban. (Photo: S. Bundy).

9.4.3 The probability of reoccurence

The debate regarding the return period of this event continues as this paper is being written. Although the direction of the storm corresponded to the general wave direction, the data is not considered sufficient for an accurate statistical extreme analysis to determine the return period for this event. If we look to similar previous extreme events then Cyclone Imboa on the 18 Feb 1984 with an H_{m0} of 8 - 9m would qualify. So would the low-pressure system off East London on the 13 June 1997 with an H_{m0} of 9.3m. This starts to indicate that this type of extreme event is more likely to occur every 10 to 12 years along the East coast. Observations on site reveal a similar picture. Erosion of the beaches exposed previously constructed sea protection works in several locations. The example in Figure 9.3 is that of the Santorini complex north of Ballito, which on closer examination shows previous protection works. The lower portion of the Santorini complex was constructed in about 1990 (Bundy S, pers comm.) and therefore is not older than 17 years. It is clear that this magnitude of erosion has occurred before and fairly recently. The only conclusion we can make is that this type and scale of event is likely to be more frequent then we think, particularly in the light of climate change.

9.4.4 The Aftermath

For many municipalities, the scenes, which presented themselves after the storm event, were shocking and infrastructure that had weathered previous storms were destroyed. Senior staff kept repeating that they had never before experienced this scale of devastation. Resources were quickly reallocated to evaluate the damage

Figure 9.4: Erosion at Umkomaas from the 2007 storm showing the erosion of the previous sea defense, carpark and access road. (Photo: A. Mather).

and identify emergency work, which needed to be implemented immediately. The initial focus was to identify those situations where an emergency existed that could be corrected by implementation of measures under section 30 of the National Environment Management Act (NEMA) (NEMA, 2006). An emergency in this instance, was defined as actions to protect lives, protect property and reduce risks to the environment, for example a washed away sewer pump station now discharging effluent to the marine environment.

The cost of repairs to municipal infrastructure was initially estimated to be in the order of R150 million. However this figure is rising as prices are received from contractors and could reach R400 million for the coastline of KwaZulu-Natal (Figure 9.4 ,Figure 9.5 and Figure 9.6).

9.5 Municipal readiness and response to the event

Each municipality drew up lists of damaged infrastructure and started looking at costs and potential funding. Some municipalities were prepared to rearrange their own budgets to get the damage repaired but others were not willing or able to do this and appealed to the National Government to declare a disaster area thereby hoping to free up national funds to undertake rehabilitation work. By the middle of June 2007, no disaster declaration had occurred and as a result, no money has been forthcoming from national government. Most municipalities have undertaken some work constrained by their existing budgets and some have been able to undertake the majority of the work.

For example, the beaches of Ballito, within the Kwadukuza Municipality, are still

Figure 9.5: Erosion along the base of the Bluff from the 2007 storm showing the undermining of the old rail line along the toe of the Bluff and the current access road. (Photo: A. Mather).

Figure 9.6: Erosion in Ballito from the 2007 storm showing the damaged beach facilities/toilet block and loss of sediment from this beach. (Photo: A. Mather).

in a state, that precludes them from opening. Apart from the obvious erosion of the shoreline and loss of public infrastructure, the amount of debris washed into the sea and now situated below the water surface is a major cause for concern. Despite extensive diving of the area, some of the beaches remain closed for these reasons. At the start of June 2007, seven of Ballito's seventeen beaches had been opened to the public. By the 20 June 2007, this increased to nine with officials unsure when the balance of the beaches will be reopened. eThekwini Municipal beaches were opened fairly soon after the event however several of the Blue Flag beaches have not been able to fly the flag due to these beaches not meeting the international Blue Flag criteria in all respects.

9.6 Current and future legal framework for coastal management

9.6.1 Sea Shore Act(1935)

This Act was specifically enacted to declare the State President to be the owner of the seashore and the sea, to provide for the granting of rights in respect of this land and to deal with alienation of this land. It is the oldest piece of environmental legislation currently on the statue books. The Act is not aligned to the issues of coastal management in the 21st century, is due to be repealed shortly, and therefore will not be discussed in any more detail.

9.6.2 White paper on sustainable coastal management (2000)

The white paper on sustainable coastal management was in a sense, ground-breaking in that for the first time, extensive public consultation on a scale not seen before, crafted a coherent, comprehensive and forward thinking policy framework for coastal management in South Africa. The principles underpinning the policy are very powerful and embody the essence of this policy. These are:

"National asset - The coast must be retained as a national asset, with public rights to access and benefit from the many opportunities provided by coastal resources.

Economic development - Coastal economic development opportunities must be optimised to meet societys need and to promote the wellbeing of coastal communities.

Social equity - Coastal management efforts must ensure that all people, including future generations, enjoy the rights of human dignity, equality and freedom.

Ecological integrity - The diversity, health and productivity of coastal ecosystems must be maintained and, when appropriate, rehabilitated.

Holism - The coastal zone must be treated as a distinctive and indivisible system, recognising the interrelationships between coastal users and ecosystems and between the land, sea and air.

Risk aversion and precaution - Coastal management efforts must adopt a risk-averse and precautionary approach under conditions of uncertainty.

Accountability and responsibility - Coastal management is a shared responsibility. All people must be held responsible for the consequences of their actions, including financial responsibility for negative impacts.

Duty of care - All people and organisations must act with due care to avoid negative impacts on coastal environment and coastal resources. "
DEAT 2000.

One of the shortfall of this policy was that the principles are very broad and open to different interpretation. The aim was to use this as a basis for new coastal management legislation, namely the Integrated Coastal Management Bill that will be discussed shortly.

9.6.3 Environmental impact assessment regulations (NEMA, 2006)

These regulations published in 2006 included activities, which were identified in terms of the National Environment Management Act (NEMA) (NEMA, 1998) which requires environmental approval before the activity can commence. Some of the relevant activities relating to the coastal zone are:

"Construction or earth moving activities in the sea or within 100 m of the HWM in respect of:
Facilities for the storage of materials and the maintenance of vessels
Fixed or floating jetties and slipways
Tidal pools
Embankments
Stabilising walls
Buildings
Infrastructure

The prevention of the free movement of sand, including erosion and accretion, by means of planting vegetation, placing synthetic material on dunes and exposed sand surfaces within a distance of 100m inland of the HWM.
The removal or damaging of indigenous vegetation of more then 10 square metres

within a distance of 100 m inland of the HWM

The excavating, moving, removal, depositing or compacting of soil, sand, rock or rubble covering an area exceeding 10 square metres in the sea or within a distance of 100m inland of the HWM.
Construction of earth moving activities in the sea or within 100m inland of the HWM including the construction and earth moving activities associated with:
Facilities associated with the arrival and departure of vessels and the handling of cargo Piers
Inter- and sub-tidal structures for entrapment of sand
Breakwater structures
Rock revetments and other stabilizing structures
Coastal marinas
Coastal harbours
Structures for draining
Underwater channels "
(NEMA, 1998)

The legislation also provides for an application for responses relating to emergencies. Typically, these are issues like chemical spills, which require the immediate intervention of the parties concerned to reduce the negative impacts to the environment. This is commonly referred to as a Section 30 application and importantly is subject to the retrospective approval of the Department of Agriculture and Environmental Affairs (DAEA).

9.6.4 The Integrated Coastal Management Bill (2006)

Some six years after the finalisation of the white paper on sustainable coastal management did the public get to see the Integrated Coastal Management Bill (DEAT, 2006). The Bill focuses on regulating human activity within the coastal zone. The coastal zone is defined in a new way in this Bill and is separated into the following areas:

Coastal access land land specifically set aside for the public to access the coastline and coastal public property

Coastal public property common property owned by the people of South Africa

Coastal buffer zone the area directly inland of the coastal public property, which comprises privately owned land, 100 m wide in the case of urban areas and 1000 m wide in the case of rural areas.

It is premature to discuss this in length, save to say that the coastal buffer zone will be the new battlefield of the future and it is therefore critical that the new Act and subsequent regulations make it easier for both public and private landowners to understand their obligations and rights.

9.7 Principles of sustainable coastal management and restoration

Within the current legal framework of coastal management and arising from this storm event, it became clear that the situation along our coastline was changing and that something was needed to provide the bridge between the different sets of legislation. In formulating, a strategy to address the repairs of the damaged infrastructure a set of local principles was developed by the Kwadukuza Municipality Tidal Wave Damage Professional Team on which the author sits as an advisor (Kwadukuza Municipality, unpublished data). These principles were developed to provide the level of detail to not only the municipality but to the numerous landowners whom were seeking direction. These local principles interpret the principles from the white paper on sustainable coastal management (DEAT, 2000) and provide the thread from policy to implementation.

9.7.1 Principle 1: Low gradient sandy coastlines are the most vulnerable to erosion

While the coastline of KwaZulu-Natal is dominated by sandy shorelines, there are sections of shorelines that can be classified as rocky. These rocky shorelines experienced some minor erosion but emerged unscathed from this erosion event. However, sandy coastlines, particularly those with low gradient coastlines, were severely affected. Because of this severe erosion, it is likely that the coastline will take many years to return to its former condition. The low gradient sandy shorelines will need to be carefully dealt with given their propensity to retreat by up to 40 m in width under storm conditions.

9.7.2 Principle 2: Managed Coastal retreat

Current international best practice in the face of sea-level rise is a managed coastal retreat. Managed coastal retreat will combat the increasing risk of coastal erosion and damage because of sea-level rise. The removal of structures and movement back inland provides a wider space for the fluctuation of the shoreline to occur will reduce the risk of infrastructural damage and ultimately prevent regular repeated loss of this infrastructure thus underpinning the concept of sustainability. Shoreline Management Plans (SMP) provide a framework in which different approaches (do nothing, hold the existing line, advance the existing line or retreat) can be considered for each section of coastline. A retreat strategy for most of the coastline is the most sustainable option. However, there are sections of coastline, which have been built up, and form part of the municipalities economic and tourism assets and these will need careful evaluation of the pros and cons of not retreating.

9.7.3 Principle 3: Sand has been lost, so sand should be replaced

The storm has removed beach sand therefore; the best replacement material is beach sand provided the grain size matches the receiving beaches sand grain size. This might sound obvious but as has been evidenced by well meaning efforts of people trying to protect their properties, many have taken to dumping various types of material in the eroded beach with little regard to the effects of this action.

Two examples of inappropriate replacement materials are Berea Red sand and builder's rubble. Berea Red sand consists of ancient marine deposits, which have accumulated inland, and along the Berea ridge in Durban approximately 1.2 million years before present (B.P.)(Francis T, pers. comm.). Berea sand is coated with ferric gels such as goethite and limonite with 5 to 8% clay aggregates pasted in the interstices (Francis T, pers. comm.) which gives this sand its distinctive colour. The median grain size (d_{50}) of typical beach sand along the open KwaZulu-Natal coastline is 0.350mm (Mather, unpublished data). Berea Red sand is normally finer than the current beach sand with a d_{50} of 0.250 mm and if placed onto the beach and into the nearshore zones of KwaZulu-Natal's high wave energy coastline, is rapidly eroded.

Builder's rubble is equally problematic for different reasons. It is not a material which occurs natural in the marine environment. When this material erode from its placement and is distributed along the beach it contaminates the beaches reducing their attractiveness to recreational users. The change from what was a natural sandy beach to a beach covered in half-bricks and pieces of concrete creates a potential liability for walkers, swimmers and can result in damage to launching craft. The rubble will lie dormant in the sand matrix, only to be exposed repeatedly during periods of erosion often giving the impression of additional dumping in the beach zone.

9.7.4 Principle 4: Soft coastal systems need "soft engineering" solutions

9.7.4.1 Onshore

The optimum erosion buffer is a natural dune cordon system. These should be established wherever additional protection is required. Property owners should be encouraged to re-establish and rehabilitate the dune systems between their properties and the sea. Where replication of the natural dune cordon is problematic, the use of soft-engineered, artificial vegetated dunes can be considered. Replaced sand can be stored within geofabric bags angled back up the erosion slope preventing further sand loss at the toe of the dunes and allowing some wave run up over the sloping structure thereby reducing the wave energy.

9.7.4.2 Offshore

Offshore protection measures can also be considered but by their very nature are generally more expensive to undertake. An example is beach re-nourishment that involves dredging sediment off shore and distributing it along the shoreline. This has been widely used in the United States to address eroding beaches. A further approach is the construction of offshore structures such as artificial reefs, which act to break up wave energy before it hits the shoreline, effectively reducing the erosive power of the waves in moving sediment in the cross-shore and long-shore directions. These interventions need to be carefully researched by experts, as these structures can be highly problematic as they can cause unexpected local and down-drift effects. In practice, a combination of these measures should be considered together.

9.7.5 Principle 5: Hard engineering should only be used as a last resort

Hard engineering should only be employed as a last resort as this causes local erosion and down-drift erosion. Hard engineering in this case is defined as any structure that is constructed from hard materials not likely to be commonly found in the beach zone. Examples of this are concrete sea walls, steel trench sheeting and contiguous augered pile walls. Hard vertical barriers are the worst performers in terms of reducing wave energy at the interface. The high-energy wave comes into full contact with the vertical face and reflects back into oncoming waves creating turbulence, which caused a loss of sediment at the toe of the sea wall. While the structure can be designed to withstand this, the effects are that the loss of sand at the toe is not replaced as easily as a similar stretch of beach without a sea wall. This leads to a locally sand starved environment preventing the full recovery of the beach and its associated sand dunes because the material is usually transported offshore or down-drift and not recovered.

9.7.6 Principle 6: Interventions are coordinated

The local authority should not undertake to provide any sea defence system for private property owners. However, the local authority has a duty of care to ensure that whatever is proposed is sustainable and that each property owner is not left to his or her own devices to construct a patchwork of different protection systems. Local authorities should encourage a coordinated or co-operative approach by affected property owners. Private property owners should remain obliged to maintain any defence system they establish. They should also be held liable for any failure, particularly where such failure may affect other properties or persons.

9.8 Results

Because of the criticisms received from business and the public regarding a lack of urgency by the public sector in responding to this disaster, the author undertook a survey of municipal officials, provincial officials, Non Governmental Organisations, ratepayer bodies and consultants involved in coastal management in KwaZulu-Natal. Ninety-two questionnaires were emailed out and twenty-eight of the original group returned their questionnaires. Three additional unsolicited questionnaires were received making up a total sample of thirty-one (34%). The 31 returns were distributed as follows; 10 from Municipalities (8 from the eThekwini Municipality), 3 from the KZN Provincial department and 18 from NGO/consultants. The number of returns from the eThekwini Municipality biased the municipal group. Therefore, this may not always reflect the views of all municipalities. The results are shown in Tables 9.8, 9.8 and 9.8 below.

Table 9.1: Results of questionaires sent to municipalities.

Questions to Municipalities	**Yes** %	**No** %	**Don't know** %
Within your municipal IDP is there a specific work programme to address climate change and particularly sea level rise and coastal erosion?	50	40	10
Do you think your municipality understands the likely impacts of sea level rise and increased storm activity on your coastline?	70	30	
Does your municipality have dedicated resources for coastal management?	100[1]		
If **not** do you think they should have?			
Does your municipality have plans to address the impacts of sea level rise and coastal erosion?	60	20	20
Have you heard of Shoreline Management Plans (SMP's)?	70	30	
If **yes**, is your municipality implementing SMP's?	50	13	37
Have you heard of Coastal Management Plans (CMP's)?	100		
If **yes**, is your municipality implementing CMP's?	80	10	10
After the March 2007 coastal erosion events do you think your municipality was able to manage the reconstruction afterwards?	75		25
Do you think your municipality has a better understanding of what to plan for into the future?	60	20	20

[1] eThekwini municipality response

Table 9.2: Results of questionaires sent to provincial officials.

Questions to Provinces	**Majority Yes** %	**Majority No** %	**Don't know** %
Within municipal IDP are there specific work programmes to address climate change and particularly sea level rise and coastal erosion?	33	67	
Do you think municipalities understands the likely impacts of sea level rise and increased storm activity on your coastline?	67	33	
Do municipalities have dedicated resources for coastal management?		100	
If **not** do you think they should have?	100		
Do municipalities have plans to address the impacts of sea level rise and coastal erosion?	67	33	
Have you heard of Shoreline Management Plans (SMP's)?	67	33	
If **yes**, are municipalities implementing SMP's?		100	
Have you heard of Coastal Management Plans (CMP's)?	100		
If **yes**, are municipalities implementing CMP's?	67	33	
After the March 2007 coastal erosion events do you think municipalities were able to manage the reconstruction afterwards?	33	67	
Do you think your municipality has a better understanding of what to plan for into the future?	67		33

Table 9.3: Results of questionaires sent to NGO's and consultants.

Questions to NGO's and consultants	**Majority Yes** %	**Majority No** %	**Don't know** %
Within municipal IDP are there specific work programmes to address climate change and particularly sea level rise and coastal erosion?		88	12
Do you think municipalities understands the likely impacts of sea level rise and increased storm activity on your coastline?	6	88	6
Do municipalities have dedicated resources for coastal management?	24	59	17
If **not** do you think they should have?	100		
Do municipalities have plans to address the impacts of sea level rise and coastal erosion?		88	12
Have you heard of Shoreline Management Plans (SMP's)?	47	47	6
If **yes**, are municipalities implementing SMP's?		55	45
Have you heard of Coastal Management Plans (CMP's)?	83	17	
If **yes**, are municipalities implementing CMP's?	20	53	17
After the March 2007 coastal erosion events do you think municipalities were able to manage the reconstruction afterwards?	6	76	18
Do you think your municipality has a better understanding of what to plan for into the future?	59	35	6

Some key findings of the study were:

88% of the NGO's and 67% of the Provincial group responded that the majority of municipalities did not have a climate change programme in their IDP.

Asked if municipalities understood the effects of coastal erosion and sea-level rise on their coastline, 87% of the municipal group responded positively in sharp contrast to the NGO's with 88% responding negatively.

100% of respondents thought that municipalities should have dedicated coastal management capacity given the demands that the new legislation is likely to bring.

In planning to address the impacts of coastal erosion and sea-level rise, the municipal group responded positively with 60% with 22% unaware of these plans. Of the Provincial group, 67% of respondents thought that the majority of municipalities had plans in contrast to the NGO group in which 88% of respondents said the majority of municipalities did not.

Shoreline Management Plans (SMP's) are not well understood with 70% for municipal, 67% for provincial and 47% for NGO's and consultants.

All groups, 100% for municipal and provincial and 83% for NGO's and consultants, had a better understanding of coastal Management Plans (CMPs)

The municipal group with 75% of respondents feeling that they had successfully managed the disaster and reconstruction afterwards. 33% of Province officials responded that they felt that municipalities had handled the situation satisfactory, in sharp contrast to the perception of the NGO's at 6%.

Asked if respondents felt that municipalities now had a better understanding of what to plan for in the future, the municipality group responded with 60% positive. 67% of the Provincial group thought that municipalities had a better understanding while 59% of NGO respondents thought so too.

9.9 Discussion

Climate change is unquestionably happening in our region and this change places great demands on all of us. Governments are at the forefront of adaptation and mitigation strategies and in the interest of the country will need to deliver the goods. To make a meaningful impact it is incumbent on all levels of government to play their part in the actions required to address these impacts. The public are looking to and demanding that government initiate a programme to address the impacts of climate change and of relevance for this paper are the effects of coastal erosion and sea-level rise. The coastal erosion, which occurred in March, has only heightened this issue amongst stakeholders. The magnitude of this erosion event was significant in that it affected many hundreds of kilometres of the KwaZulu-Natal coastline. The experts may debate the frequency of this event for some time but as Theron (2007) has highlighted, this scale of storm is most probably going to become a more regular event in the future.

The amount of sand lost off the visible beach is difficult to quantify. However based on surveyed cross-sections taken before and after the event along the eThekwini municipal coastline (approximately 100 kms) approximately 4 000 000 m^3 of sand was eroded (Mather, Unpublished data). Contrast this with the net long-shore sediment transport rate at Durban of 460 000 m^3 per year (Mather *et al.*, 2003) and one can start to appreciate the enormous power of the storm. Simplistically, this equates to about 9 years of sediment supply moving off the beach into the nearshore zone where it formed an offshore bar. Fortunately, some of this sand is now returning to the beach but the sea is unlikely to return the original volume as some of this would have moved into deeper water where it will not be reworked into the beach zone by normal wave conditions. The beaches will therefore remain in this depleted state for some time until new sediment from the river systems is introduced.

The protracted change in coastal legislation from the Sea Shores Act of 1935 to a proposed Integrated Coastal Management Act has resulted in the coastline being indirectly managed through other environmental legislation in a less then optimal way. In the absence of a new Act, which was one of the key conclusions of the white paper on sustainable coastal management, the other environmental legislation is the only means of regulating activities in the coastal zone. For example, the NEMA regulations requiring activities within 100 m of the HWM to undergo a scoping assessment was taken from an early draft of the Integrated Coastal Management Bill. In the changing legal landscape for coastal management, many municipalities are out of touch with the relevant legislation and still feel they are able to undertake certain actions and activities with no regard to the law. Difficulties in understanding the different laws and regulations applicable to the coast have resulted in a degree of confusion as to what to do to comply with the law. Many Municipalities feel that they are required to undertake onerous measures to comply with these laws and regulations in the face of their mandate to deliver services to communities.

Many private landowners have repeatedly asked for direction and assistance, to no avail after the March event. In the face of this confusing situation, some private landowners have taken the opportunity to undertake whatever remedy they thought might be appropriate without reference to any of the Authorities. Many landowners have nevertheless complied with the requirements of Section 30 of NEMA but, being unsure of the requirements, have instead of undertaking the works and then making the application, have sent in their Section 30 applications with proposals of what they intend to do. In amongst the private individuals, Authorities and municipal groupings entered the insurance companies. This resulted in the four groups not only being confused as to what and how to address the erosion effects, but actively contributed to divergent views on what should be done.

The insurance companies were prepared to pay to rebuild the lost structures however; the private landowners were caught between the authorities and the insurers if they went ahead with repairs. There was no guarantee that the authorities would accept the repairs and therefore the landowner could be instructed to remove the intervention. If this happened, the insurance companies had made it clear to the insured that they would not pay a second time. This resulted in many landowners preparing and submitting a Section 30 NEMA application and then waiting to obtain an approval despite the fact that this is not what the Section 30 application is designed to provide. This put the DAEA in a difficult legal predicament as to whether they approve these or not. Approval effectively sanctions the proposed measures without an assessment, effectively negating DAEA's power to instruct the removal of these structures at a later stage. By refusing the application, they open themselves up to possible claims for damages. Fortunately, it would appear that the DAEA is able to provide a qualified response to these applications but by the middle of June, the response had not been forthcoming. This situation could easily have been avoided had the Integrated Coastal Management Act been in force giving officials access to new tools to apply.

In an effort to address the concerns of the landowners and to give the Municipality some guidance, the principles of sustainable coastal management and restoration were developed as outlined above. These principles provide a framework in which different types of interventions can be evaluated and, when first presented to the public, at which event it received a standing ovation (Bundy S, pers. comm.). These principles are underpinned by the concepts of environmental, social and economic sustainability. These principles can be easily applied to erosion events like the March coastal erosion event. Perhaps the biggest challenge in implementing these principles is the mindset, which is, that this event is rare and will not reoccur in the near future. While none of us have a crystal ball, it is conceivable that this event is likely to reoccur in the next 10 years and when it does the destruction is likely to be similar to or even more than the previous event if the rate of development remains unchecked.

Historically, Municipalities have sought to replace damaged infrastructure and facilities in their original positions and have convinced themselves that by strengthening the structure all will be fine. The case is not entirely hopeless, the eThekwini Municipality has, post this storm, identified facilities that will not be reconstructed in their original positions. If the demand for the facilities is still strong then alternative positions for these facilities will be sought in less vulnerable locations. The typical facilities are inappropriately located car parks, roads, walkways and other municipal infrastructure. This change in thinking is a strong, positive sign and is to be encouraged in other Municipalities.

In assessing the municipal IDP's, it became clear that apart from the eThekwini Municipality, no other Municipality has incorporated a climate change programme into their IDP. There are various reasons for this and these are best summed up by comments made at the Western Cape Climate Change Seminar held in Kirstenbosch in February 2006 where a representative of the Cape Town Municipality stated that the challenges for Cape Town (and in fact for almost all) municipalities are:

Climate change mitigation aspects have not yet been addressed
The City planning function does not yet reflect climate change in their planning
There is a lack of capacity in local government
There is a lack of awareness among local government officials
There are financial, economic, institutional and legal barriers to be overcome

The municipality has limited resources.

He went on to highlight the key risk areas from a municipal perspective as:

- a lack of awareness and capacity,
- climate change was not seen as a concern in the context of development demands,
- a lack of clear understanding from the leadership.

(DEA DP, 2006).

Another notable point was the perceptions between the Authorities and the Non Governmental Organisation's in assessing the capacity and response of municipalities to the storm event. A sizable portion i.e. 64% of Municipal and Provincial Authorities felt that they had handled the situation well in sharp contrast to the 6% of Non Governmental Organisation's respondents. All groups responded well to the questions regarding CMP's but were less responsive to the questions about SMP's. This is almost certainly due to the extensive publicity of the Integrated Coastal Management Bill, which incorporates CMP's as part of the requirements of government. The desirability of having a SMP is as great as a CMP and it is hoped that this will be incorporated into revisions of the Bill and will be able to provide a framework to manage shoreline changes into the future. As to municipalities having plans to address the impacts of sea-level rise and coastal erosion, the responses were overwhelming that virtually no municipalities have considered this seriously to date and it is an area that municipalities can easily address. Tools such as coastal setback lines, based on the potential erosion line using projected sea-level and storm activity as a basis, are frankly just good planning. Whilst this may become a requirement in the Integrated Coastal Management Act there really is no excuse for municipalities to start these right away. However, a recurring comment in the returned questionnaires was the question of the capacity and ability of government to address the challenges of coastal erosion and sea-level rise. A sample of comments received was:

"*I think there is still a lack of willingness by Local Government to commit to anything that is going to cost money, this includes long-term/ short-term plans for managing weather patterns and coastal conditions*".

"*The ... municipalities along the coastline do not seem to have the initiative to be pro-active and in fact seem unable to deal with the problems like the recent storm events very well, even in a reactive way*".

"*They now are better informed after the March event, but seem to have gone back into thinking that this is a once-off event and will never happen again*".

"*Lack of success by municipalities in facilitating participation in terms of land owner's impacted...* ".

The perception of the public is clearly that municipalities are not performing at a level, which inspires confidence in their abilities to address these issues. It is this challenge that needs to be addressed and it will take strong leadership by those in the field on coastal management to turn the tide. Role models are clearly needed at this stage and what we need is for some municipalities to show the way, admittedly perhaps at the risk of some failures, to improve the tools and systems for others to follow. A respondent echoed this approach:

> "*... our only hope for the long-term sustainability of our coastline is for ... capacitated municipalities to lead the way, work out with the necessary expertise exactly what is needed, what is available, and then drive this at a Provincial level, so that Province, possibly through the Provincial Coastal Committee and Regional Coastal Committee ... get this information implemented along the coastline through the various municipalities*".

To address this gap in the demand for better knowledge and to have in place a system which all stakeholders can buy into and understand it is proposed that a mini conference be held over two days to cover the physical aspects of the erosion event on day one followed by the legal and process issues on day two. This will allow all interested parties to hear expert input first hand. The second component envisaged is the writing up of a user manual on addressing coastal erosion in a sustainable manner, which can be distributed to all stakeholders so that in future events they will know their rights and obligations as well as empowering the community to be in a position to help and regulate them.

9.10 Conclusion

Based on the analysis presented in this paper municipalities are clearly not succeeding in addressing the issues of coastal erosion and sea-level rise. Even within the eThekwini Municipality, which is seen as one of the larger, more capacitated municipalities, there is a struggle to communicating its plans and coastal vision to its own staff resulting in negative perceptions of the readiness of the municipality. The problems and potential impacts of coastal erosion and sea-level rise appear to be just another issue, way down on municipal priority lists. With the predicted increases in sea-level rise and storminess in our region, it is important that municipalities are ready to respond to this. This would appear to be easier said than done, as the capacity issues facing municipalities are very real.

The response to the March 2007 coastal erosion event has exposed weaknesses amongst the coastal municipalities particularly in KwaZulu-Natal, which will require addressing. These weaknesses are in all likelihood also present in all other coastal municipalities around South Africa. To address this it is recommended that a conference be held focussing specifically on this event and that a practical manual be drawn up based on the lessons learnt from around the country. This manual will assist coastal managers, coastal regulators and the community, around South Africa, in improving their responses to future events of this kind.

In conclusion, the challenge to address coastal erosion and sea-level rise rests firmly with government and particularly local government as the authority charged with development at the local level. Perhaps the new legislation will be the incentive to put in place better systems and management of the coastal zone. However, until then the challenge to all of us in local government is to raise awareness of these issues and provide the leadership to overcome the challenges, which lie ahead.

9.11 Acknowledgements

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Epilogue to Chapter 9

In Chapter 9 the assessment of the government and in particular the municipal capacity, as the level of government closest to the people, to deal with coastal storm events was discussed. What emerged from a detailed questionaire was that municipalities do not have the capacity to respond to coastal erosion with perhaps the exception of the large metropolitans. Many municipalities do not have any capacity to deal with a crisis situation let alone plan proactively for future sea level rise and coastal erosion impacts. Almost all municipalities do not incorporate climate change into their Integrated Development Plan's (a legal requirement of all municipalities to achieve better and more holistic planning).

Prologue to Chapter 10

This lack of capacity at municipal level is a real problem on the ground when there is a need to determine and manage the possible physical impacts of future storm events and sea level rise. What is needed is some framework to inform municipalities of the risks of coastal erosion and sea level rise. Therefore there is a need to develop scenarios of future sea level change in the region. These scenarios need to be integrated with a wave run up model, such as the one presented in Chapter 7 which was specifically developed for this region. The combination of future sea level rise scenarios and wave run up modeling can be used to identify sites within the region which are most vulnerable to shoreline changes in the future. As the shoreline in the Southern and Eastern African coastline is vast it was decided to focus on a specific area to present the approach. Thereafter to take these findings and apply these to the broader Southern and Eastern African region, providing some generic lessons to those areas outside the eThekwini municipal area untill the rest of the region can have a similar detailed evaluation undertaken.

The purpose of Chapter 10 is then to bring together the research work completed in this thesis by examining in detail the eThekwini municipal area as a case study, applying the various sea level rise scenarios and modeling wave run-up and in so doing determining what the likely future impacts of sea level rise and coastal erosion could be. The findings from the eThekwini municipal area will be extended to the rest of the Southern and Eastern African coastline by providing some generic lessons and advice concerning the likely impacts which will serve as a preliminary assessment until the rest of the region can have a similar detailed evaluation undertaken.

This Chapter includes the thematically linked, journal paper, which has been invited and submitted to Water as a research paper titled:

Mather, A.A. A Southern African perspective on managing sea level rise and coastal storms: A case study of the Durban coastline.

The submitted journal publication has been reproduced in full in the Appendix.

Chapter 10

A SOUTHERN AFRICAN PERSPECTIVE ON FLOODING BY SEA LEVEL RISE AND COASTAL STORM SURGE: A CASE STUDY OF THE DURBAN COASTLINE

10.1 Introduction

In recent years, much work has been done on global climate change and the likely impacts that may arise from this change (IPCC, 1996; IPCC, 2001; Stern, 2006; IPCC, 2007). However, relatively little research on climate change has been undertaken for the African continent to date, with the exception of South Africa. Climate change impacts are likely to manifest in many different ways. In this paper, however, the focus is on coastal flooding hazards, now and under future sea-level rise (SLR) along the Southern African shoreline. In South Africa, amid increased awareness and concern regarding climate change and SLR, several government agencies have commissioned research in these areas. Studies of SLR in Durban (Mather, 2007) and SLR in Namibia and South Africa (Mather *et al.* 2009), regional impacts of climate change in the Western Cape (Midgley *et al.* 2005) have recently been completed. Two of South Africa's major coastal cities, Durban (CSIR, 2006; Golder Associates, 2007, 2008a and b, 2009; eThekwini, 2009; Mather, 2009) and Cape Town (LaquaR, 2008) have embarked on studies to understand and address these impacts. Research institutions are now also contributing (Hewitson, 2006; Theron, 2008; Harris, 2008).

Outside of South Africa there has been even less work undertaken although Mozambique has initiated discussions and projects on SLR (Brundrit, pers. comm.

2008; Theron, pers. comm. 2009). While this new impetus is encouraging, the mitigative and adaptive ability of governments, regions, cities and communities in Africa to proactively manage the impacts of climate change has been a concern in international circles (Jevrejeva, 2008). This concern arises due to the high mitigation and adaptive costs that are likely to be incurred. The region is financially poor by world standards and very little funding is likely to be available for widespread interventions making the challenge of dealing with climate change and SLR even more difficult. In reality, there is limited scope for mitigation of climate change and therefore efforts must be concentrated on adaptive measures. In order to adapt for the future, it is important to understand the quantum of the possible threats because without this the risk is that maladaptation will occur.

10.2 Problem Statement

The southern and eastern coastline of Africa (Figure 10.1), comprising South Africa, Mozambique, Tanzania, Kenya and the islands of Seychelles, British Indian Ocean Territories, Rodrigues Island, Reunion, Madagascar and Mauritius, is regularly affected by cyclonic and other significant weather events which have the ability to unleash large wave events along the coast. The impacts of climate change and sea level rise are likely to exacerbate the existing problems of coastal flooding and erosion. Much of this stretch of coastline comprises sandy beaches backed by flat low coastal plains and in some case coral reefs, which is already vulnerable to flooding and erosion in extreme wave events. Progressive sea level rise will worsen the situation but it is the episodic wave events, occurring with very little warning, that results in significant flooding and erosion. In order to plan for these hazards some baseline data are needed. The reality is that countries in this region do not have spare funds to generate this data and so it is unlikely that in the foreseeable future data collection will meet first world standards.

Having said that there does exist some sources of data available for the region. Historical data on cyclone events is available from agencies such as Meteo France. Tide gauge coverage is more problematic as there is inadequate spatial coverage of tide gauge sites in the region and of those stations which have tide level data, they are for relatively short duration preventing high confidence sea-level change trends from being calculated (Woodworth *et al.*, 2007). Changes in the coastline position over time is almost complete absense except for one or two isolated areas where either shoreline monitoring was undertaken or historical set of aerial photography exists which can be used. This lack of coastal erosion and shoreline change data along this stretch of coast makes it difficult to understand historical changes and plan for the future and unfortunately this is unlikely to change given the funding limitations of most African countries.

Therefore under these circumstances it is essential that a simple, practical and easily applied approach of identifying the coastal flooding hazard zone be developed.

Figure 10.1: Map of the Southern and Eastern Africa coastline showing the study area in dark grey.

The approach must not only be simple to apply but it must also be conservative enough to help coastal managers identify the flooding and erosion hazard zones. The objective of this paper is to demonstrate this by developing an approach that meets these requirements and using it to inform the extent of the coastal flooding hazard zone. The Southern and Eastern African coastline stretching from Mombasa to Cape Town (excluding the island states) is over 6000 km in length, a distance too great to look at in detail in this paper. In order to work with a manageable coastline length the Durban coastline (±100 km) was chosen as a case study see Figure 10.2.

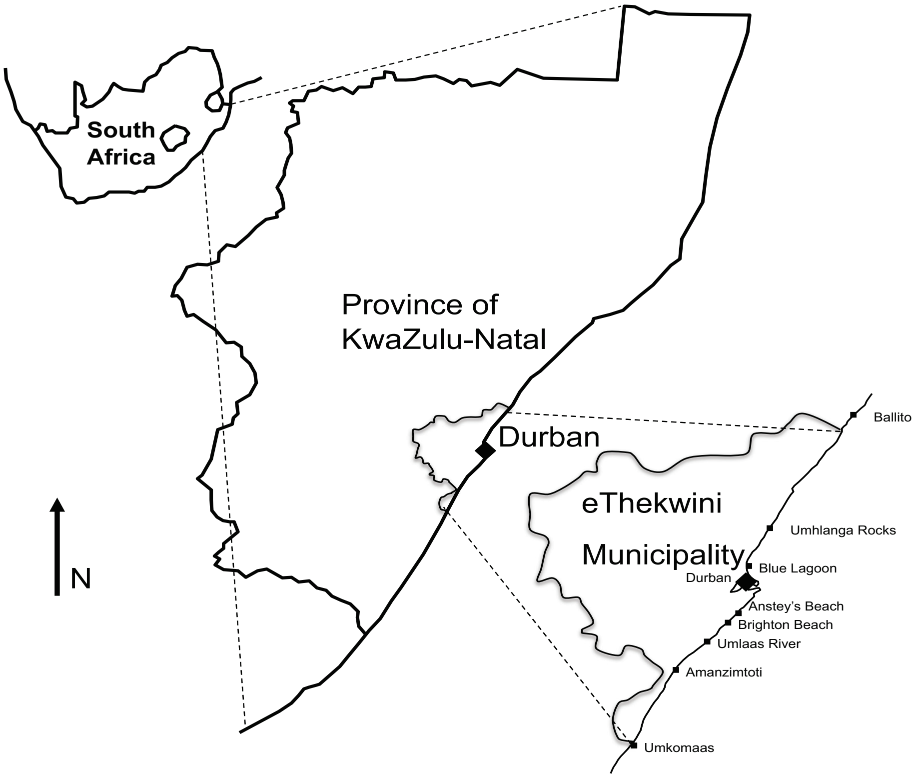


Figure 10.2: The extent of the eThekwini Municipality study area.

10.3 Coastal Flooding, Erosion and Wave Hazards in the Region

10.3.1 Cyclones

The Southern and Eastern African coastline is intermittently impacted by extreme swells associated with tropical cyclones (which are also referred to as hurricanes in the North Atlantic and typhoons in the western Pacific Oceans) and cut-off low pressure systems.

In the eastern Indian Ocean, cyclones generally form to the east of Madagascar. Most of the time they move in a west-south-westerly direction towards the African continent. Some make their way across Madagascar into the Mozambique Channel, while others move southward. The majority of tropical cyclones track back in a south-easterly direction, away from the mainland, and back towards the Indian Ocean. It is these cyclones which turn south-easterly and sometimes remain semi-stationary south of Madagascar that are the ones that cause the biggest swells in the region. Occasionally tropical cyclones do make landfall and can devastate the coastal zone in its path. One such event, Tropical Cyclone Domoina occurred in January 1984 and made landfall near Maputo, Mozambique causing extensive wind and rainfall damage. Tropical cyclones typically occur in the summer months but are most frequent in January, February and March as the tides lead up to the equinox as shown in Table 10.1 after (Kovacs *et al.*, 1985). The various cyclone tracks can be seen in Figure 10.3.

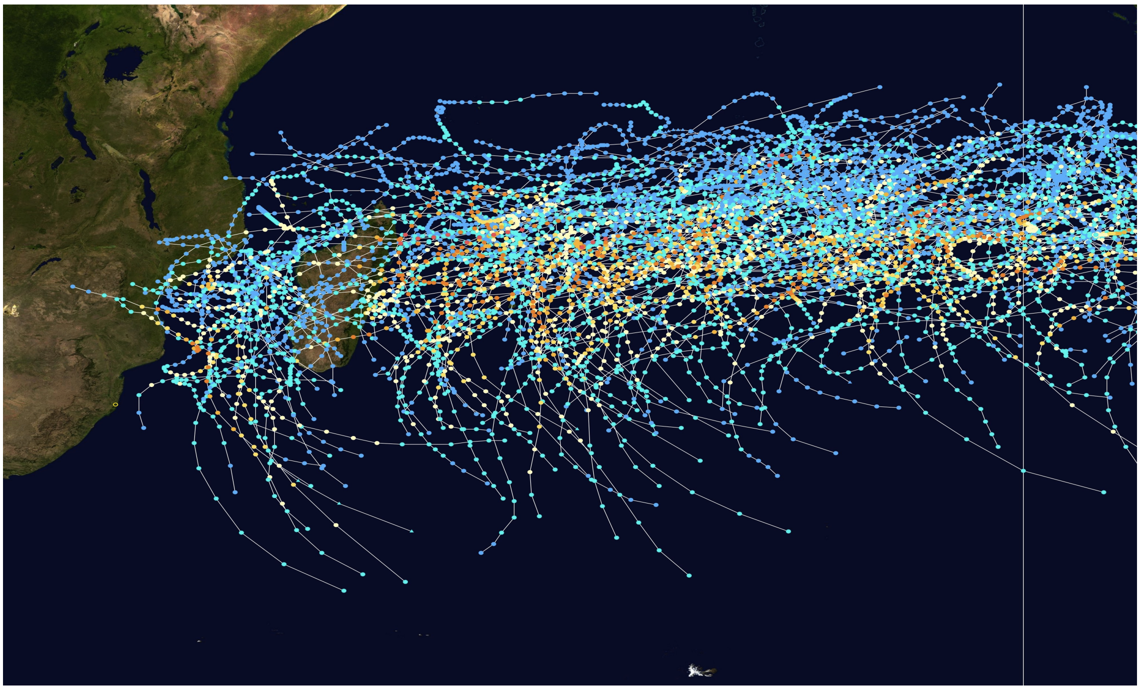


Figure 10.3: Cyclone tracks for the years 1980 to 2005 in South-west Indian Ocean (Wikipedia Commons).

In contrast cutoff lows, are generated in the Southern Oceans when an anticyclonic disruption occurs as a result of strong upper ridge advancing south-eastwards and separating a cold upper air pool. They are characterised by a convex shaped surface high pressure system along the southern Cape coast (Taljaard, 1985). The formation of cut-off lows over land are not uncommon, however, these rarely result in high seas. An intense cyclonic mid-latitude system is often referred to as an extra-tropical or mid-latitude cyclone, and is normally associated with a cold front which follows a strong ridge of the Atlantic high pressure system (Alexander, 2000). Cold fronts are often preceded by coastal lows, which are typically responsible for the south-westerly winds along the east coast of Southern Africa (Tyson and Preston-Whyte, 2000). Well formed cold fronts can generate significant swell and the passage of this type of system can results in gale force winds and high seas (Alexander, 2000). When these weather systems coincide with spring high tides they set the scene for exceptional flooding and erosion.

Table 10.1: Monthly frequency of tropical cyclones since 1848 in the SW Indian Ocean based on 934 events (after Kovacs *et al.*, 1985).

Month	**Percentage**
Sept	1
Oct	2
Nov	3
Dec	13
Jan	30
Feb	26
March	17
April	6
May	2

10.3.2 The March 2007 storm in KwaZulu-Natal, South Africa

10.3.2.1 Conditions preceding the storm

Sea conditions had been unusual in the months leading up to this event as the region had been affected by three cyclonic events, Dora, Favio and Gumede. Cyclone Dora which combined with a well developed cold front to the south of the country resulted in 2-3 m swells and impacted the KwaZulu-Natal coastline from 11th to 13th February 2007. Cyclone Favio, which generated 185 km/h winds within 37 km of the centre and significant wave heights above 14 m (Meteo France, 2008), moved from the south of Madagascar, through the Mozambique Channel and made landfall in Mozambique The cyclone generated high seas in Mozambique and heavy rainfall in south-eastern Zimbabwe and southern Malawi. However it did not produce large wave heights along the KwaZulu-Natal coastline (Hunter, 2007). Cyclone Gamede closely followed and although downgraded from a tropical cyclone to an extra tropical depression, remained relatively stationary between the 2nd and the 5th

March and created localised flooding along the KwaZulu-Natal coastline. Cyclone Gamede also deplete the beaches of their buffer of sand as the waves moved sand from the beaches into deeper water.

10.3.2.2 Condition during the storm

The weather system responsible for the March sea storm started as a frontal low, which passed south along the coast of South Africa on 16th March 2007 (see Figure 9.2a to f). The frontal low intensified and rapidly developed into a cut-off low south-east of East London on 17th and 18th March. It intensified to a peak on the 19th March, where it remained trapped between two high-pressure cells until the 20th March. The cut-off low started to weaken by midday on the 19th March and conditions had almost returned to normal by 20th March (Mather, 2008). The central pressure of this cell dropped to below 986 hPa at its peak. The strong pressure gradient generated strong and consistent winds. Wind speeds started picking up on the 17th March with recorded hourly wind speed rising to 10.9 m/s (peak 10 min speed of 18.5 m/s at 24H00). On the 18th March, the recorded hourly wind speed peaked at 11.9 m/s (peak 10 min speed 22.1 m/s (43 knots) at 14H10) and then subsided over the course of the 19th March (South African Weather Service, 2008). As the system was trapped in position this allowed the wind to generate some impressive waves straight at the coastline of KwaZulu-Natal for approximately 48 hours. Wave heights at Richards Bay, approximately 180 kms north of Durban reached a significant wave height (H_{m0}) of 8.5 m, with a peak single wave height of 14 m. The event was felt along a long stretch of coastline from Maputo (25° 58” S, 32° 34” E), Mozambique (Corniche E, pers. comm 2007) to Port Elizabeth (33° 58” S, 25° 38” E). Fortunately, the wave event very quickly dissipated and by the evening of 20th March, the significant wave height had reduced to less than 3 m (Mather, 2008).

10.3.2.3 Tide, storm surge and wave run-up levels.

The Highest Astronomical Tide of the Year (HATOY) at 2.284 m above MSL (2 cms less then the Highest Astronomical Tide (HAT) of 2.30 m) was predicted to occur on the 19th March 2007 at 04H32 South African Standard Time (SAST). This event had already been forecast as having the potential to create widespread erosion should it coincide with a large wave event (Mather, 2007). The South African Navy tide gauge in Durban recorded a peak storm surge of 70 cms (3 min average). Wave run-up levels recorded along the beaches ranged between +4 m and +10.5 m above MSL (Mather *et al.*, 2011). The highest levels were recorded in open coastal locations where the bathymetry dropped off sharply.

10.3.2.4 Impact of the storm

The storm resulted in wide scale destruction of private and public infrastructure and homes along 400 km of coastline was estimated at around US$100 million (Mather, 2008). Several homes where completely lost or damaged beyond economic repair and damaged sewer reticulation poured raw sewage into the sea for several months after the event resulting in a bathing ban along many of the popular swimming beaches.

10.4 The likelihood and magnitude of future storm events and sea level rise by 2100

The future threat of similar large destructive wave events has been accepted. Therefore the attention has turned to developing a planning framework around these events. The goal is to reduce the flooding and erosion hazard associated with these events. With a coastline that has significant coastal development already in place the task is made more difficult by the social and economic considerations associated with such decisions (Polomé *et al.*, 2005). Kay and Alder (1999) have defined a hazard as an event or process with potential harm to people, property and the environment. Kay and Alder's definition seperates the concept of risk (likelihood of occurrence with no human consequences) from the concept of a hazard (likelihood of occurrence with human consequences). It is becoming clearer that this hazard will increase as more human development is located in the coastal zone and may also increase with ongoing climate change in the region (Theron, 2007).

10.4.1 Past and future storm activity

The March 2007 event while significant was by no means unusual. Events of similar magnitude have occurred in the recent past. On the 13th June 1997, a cut-off low system off the coast of East London, South Africa created similar conditions to this storm. Significant wave heights of 9.3 m were only marginally higher but the effects were of similar erosion and loss of property. Cyclone Imboa occurred in mid February 1984, off the coast of Maputo, Mozambique creating high winds and resulting in significant wave heights of between 8 and 9 m. During 1970 a wave event caused erosion and damage along the Durban coastline. In late May 1966, a sea storm, with a significant wave height of approximately 8.5 m, stripped the sand off the beaches along the coastline south of Durban, South Africa revealing a Quaternary fossil bed (Jukes, 1976). As has been previously pointed out wave events along this stretch of coast are driven by the wind generated from cyclonic and cutoff low events. To generate the most erosive waves two factors must coincide. Firstly, high sustained winds blowing onshore and secondly, a suitably long fetch (the distance over which the wind can blow and in so doing, creating waves). Using the physical layout of the regional coastline as a starting point potential maximum wave height using either fetch distances or wind speeds can be estimated. On that basis the potential maximum significant wave height along the South African, Mozambique, Tanzanian and Kenyan coastlines have been calculated using the Coastal Engineering Manual nomograms II-2-23 and II-2-25 (CEM, 2002) and are shown in Table 10.2.

Table 10.2: Potential maximum significant wave heights in the region.

Coastal Segment	**Duration limited** (m)	**Fetch limited** (m)	**Max regional wave height** (m)
Cape Town (South Africa) to Mossel Bay (South Africa)	10	10	10
Mossel Bay (South Africa) to Lake Poelela (Mozambique)	9	9	9
Lake Poelela (Mozambique) to Ruvuma Bay (Mozambique)	9	8	8
Ruvuma Bay (Mozambique) to Mombasa (Kenya)	10	10	10

The wind speeds and fetch lengths in the Mozambique Channel are restricted by the proximity of Madagascar to the Mozambique coastline effectively capping the maximum wave heights to 8 m (see Table 2). When these results are compared to other data, the results are similar. The Voluntary Observing Ships (VOS) observed wave height data from 1960-1999, yields only 0.1% of a total of 17168 records exceeded 9.0 m at the southern tip of Madagascar (CSIR, 2000). Reduced wave heights in the Mozambique Channel have been reported by Theron (2007).

10.4.2 Sea Level rise by 2100

Various authors have used a variety of different factors and methods to predict future sea level rise. The use of global climate change models (IPCC, 2007), a temperature/rise in sea level relationship (Rahmstorf, 2007), ice melt yield (Meier *et al.*, 2007) and quadratic equation projections (Church and White, 2006; Jevrejeva *et al.*, 2008) are a few of the methods employed. Predicted rates and magnitude of future global sea level rise are still hotly debated but there is agreement that these will rise. Several countries have adopted sea level rise scenarios based on the work of the IPCC (2007) and others notably post 2007. For example, Germany has taken 1 m of sea level rise as the upper bound of potential sea level rise by 2100 (Schubert *et al.*, 2006). The Dutch, with their extreme vulnerability to the impacts of sea level rise, have adopted a maximum sea level rise excluding settlement of 1.1 m by 2100 (Delta Commission, 2008) and California have adopted a maximum of 1.4 m by 2100 (Heberger *et al.*, 2009).

Recent sea-level analysis in the region has shown that there is variation in the rate of sea-level change in the region (Mather *et al.*, 2009). Virtually all tide gauges show a rise with the exception of Zanzibar at -3.6 mm per year (Chapter 6). For this particular case study the observed sea-level rise trend at Durban is +2.7±0.05

mm per year (Mather 2007) and for the eastern region of South Africa to be +2.74 mm per year (Mather *et al.*, 2009).

However in order to model the effects of any sea-level rise several sea-level rise scenarios were chosen. These scenarios have been determined as follows:

Scenario 1: 300 mm based on current linear sea-level rise to 2100
Scenario 2: 600 mm based on doubling of the current sea-level rise rate to 2100
Scenario 3: 1000 mm based on an accelerated ice melt scenario.

The last scenario was included as recent literature has pointed to accelerated ice melt (Meier *et al.*, 2007).

10.4.3 High Water Mark and wave run-up position

An important factor in determining the hazard zone is the extent of wave run-up along the shoreline. Traditionally the coastline has a legally defined measure of wave run up, the High Water Mark. Generally, these high water marks are a combination of a high tide level and storm wave run up. In most instances they are delineated following actual events, i.e. a land surveyor coordinates the position of the debris line and this is declared the high water mark. These high water marks however are not helpful in identifying the hazard zone as they generally do not account for extreme waves in the order of 8 to 10 m. As waves approaching a shoreline their shape and height changes, as wave energy is lost to friction on the ocean floor.

This can also causes a change in wave direction depending on the incident wave angle to the coastline. As the waves make their way inshore, the wave height increase until the wave breaks before reforming as a lower wave which proceeds inshore. The surf zone (the area where the waves break) accounts for the majority of the loss of wave energy (Stockdon, 2006). The wave then reaches the beach and the remaining wave energy is converted to potential energy in the form of run-up the slope of the beach (Hunt 1959). The run-up of the wave provides the energy needed to rework the beach slope, erode the dunes (Sallenger, 2000; Ruggiero *et al.*, 2004) and endanger any manmade structures in its path.

Planning for coastal impacts requires an understanding of the likelihood and extent of water/wave action and sea-level rise along the coast, which then provides a context in which coastal hazards can be quantified. Intuitively one understands that the closer a structure is located to the sea then higher the risk of likely damage. The magnitude of wave run-up across and up the beach slope is therefore critical in understanding the extent of the potential coastal hazard zone for large wave events. However, the identification of this zone varies along the coastline depending on numerous factors relating to the beach, beach material, wave regime, wave direction and underwater bathymetry.

Rising sea levels have the effect of raising the Still Water Level (SWL) along the coastline and allowing more wave energy to move closer inshore. As Mather *et al.* (2011) (Chapter 7) have pointed out the best of these international models do not predict the observed wave run-up very well along this coastline and therefore a new local model was developed for the region. This model will be used as the basis of the predicted wave run-up heights in this paper.

10.5 High Water Mark and Flooding Hazard delineation Model: Case study of the Durban Coastline

10.5.1 The approach

The approach consists of two separate parts, the firstly to calculate the amount of wave run-up along the shoreline based on the off-shore wave, bathymetry and the state of the tide and secondly to determine of the extent of retreat of the coastline under differing sea-level rise scenarios. For this retreat of the shoreline the Bruun's model (Bruun, 1962) was selected due to its ease of application and simple input data.

10.5.2 The input data

The coastline was flown at a high resolution, accuracy to ±10 cms, and once rectification of the imagery had been completed a digital terrain model (DTM) was constructed. The wave run-up model requires information on the offshore wave height H_{m0}, tidal level at the time of storm, and distance to the depth of closure which along this coast is approximately the -15m depth contour. Data for the model was obtained for wave heights (CSIR), tide levels (South African Navy) and the -15m bathymetric contour from Admiralty charts (South African Navy). The model can be run with any combination of these variables and for varying conditions i.e. a wave height of 10 m at HAT. For the case study a particular set of variables were chosen based on the requirements to map the High Water Mark and not to map the most likely regional maximum wave height from Table 10.2. Model runs assumed the state of the tide as at Mean High Water Springs (MHWS) tide at a level equal to 2.01 m Chart Datum (CD) combined with a 1:10 year storm wave height (H_{m0}=7.1 m)(M. Rossouw pers comm.) for 300 mm, 600 mm and 1000 mm.

10.5.3 GIS procedures and data presentation

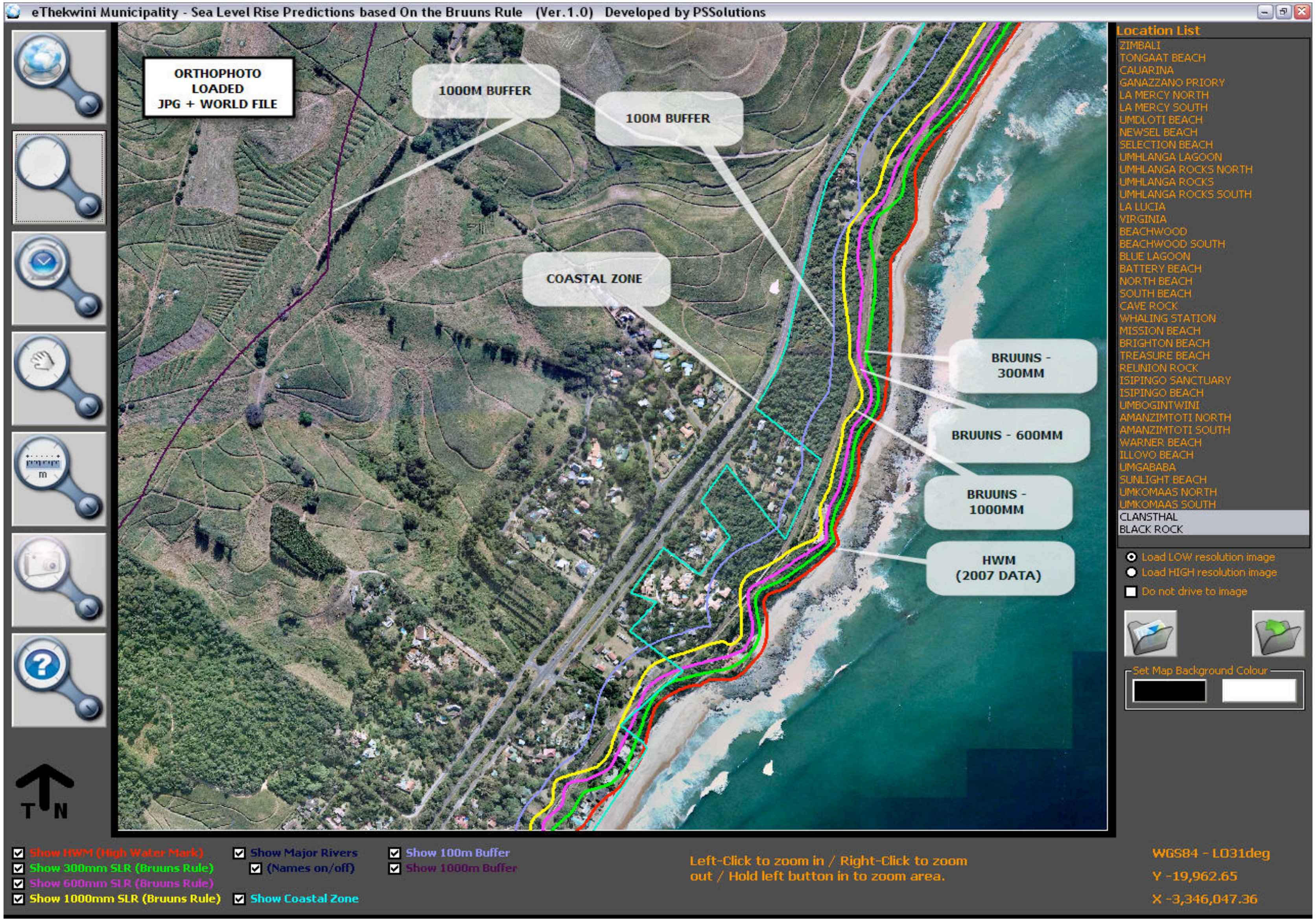
The DTM was imported into a Computer Aided Design (CAD) application as a triangulated irregular network (TIN). Added to this data were the -15m (below sea level) depth contour line and the +0m contour line. From these data a series of section lines perpendicular to the -15m depth contour line were generated and extended until they intersected the +0m contour line. These section lines were generated at approximately 5 m intervals along the entire 100 kms of coastline. Using custom software, which runs inside the CAD environment, the wave run-up model was applied using the information for each and every section line. This produced a point height which was placed along the transect line where it intersected with the terrain module gradually building up a string of point which were then joined to form the respective line.

From this the amount of beach retreat was calculated using the Bruun's model algorithm (Bruun, 1962). The study coastline was sectioned at 5m intervals. The wave run-up model provided the elevation level of maximum wave run-up at each point. The regressed HWM position was then determined from the DTM. This retreated maximum wave run-up prediction was then used to determine the slip failure of any dune structure that existed inland of this. The slip failure angles were determined by previous data (eThekwini Municipality, unpublished data). This slip failure zone was plotted on the sections and the top of the slip failure zone was determined. Once each and every cross-section had been analysed a line joining the entire respective model run results was created and shown as a line on the aerial imagery.

10.5.4 Presentation of the model results

Often the results of GIS based models are only accessible to a limited group who have the correct software and have the technical skills to work with the applications. To address this, the final output was created using Flash technology that can be compiled in such a way that no external or third party software is needed to run the application. This freeware application can be distributed on DVD to any interested party to install on their personal computers. This portability has made this information accessible to many more people than through traditional GIS platforms. A screen shot of the viewer is shown in Figure 10.4.

All four scenarios were plotted against the aerial photography backdrop yielding the positions of the current HWM (red) and future HWM with SLR of 300 mm (green), 600 mm (purple) and 1000mm (yellow). A sample of the visual output is shown in Figures 10.5 and 10.6 . The viewer provides an accessible tool for planners, engineers and the public to view the potential sea level rise impact scenario along the coastline. This viewer has been used in public meetings to work through a range of potential responses which may be considered in the various locations of the coastline. The viewer has also been made available to the public to work with in the comfort of their own homes prior to the discussion enabling them to critically examine their areas and to allow them to formulate a better understanding of the likely impacts in their areas.



eThekwini Municipality - Sea Level Rise Predictions based On the Bruuns Rule (Ver.1.0) Developed by PSSolutions

● Load LOW resolution image
○ Load HIGH resolution image
☐ Do not drive to image

☑ Show HWM (High Water Mark)
☑ Show 300mm SLR (Bruuns Rule)
☑ Show 600mm SLR (Bruuns Rule)
☑ Show 1000mm SLR (Bruuns Rule)
☑ Show Major Rivers
☑ (Names on/off)
☑ Show Coastal Zone
☑ Show 100m Buffer
☑ Show 1000m Buffer

Left-Click to zoom in / Right-Click to zoom out / Hold left button in to zoom area.

WGS84 - LO31deg
Y -19,962.65
X -3,346,047.36

Figure 10.4: Viewer interface (PSSolutions).

Figure 10.5: Sample of the output from the viewer (PSSolutions).

Figure 10.6: Sea level rise impacts on the central beachfront at the Point (PSSolutions).

10.6 Impacts and responses to sea level rise and erosion in the study area

The study highlighted several areas along the coast which were vulnerable to coastal erosion under rising sea levels.

10.6.1 Flat sandy beaches

The study area has limited areas of flat sandy beaches however, where these exist the majority have been developed into recreational areas supported by development in the form of hotels, commercial and other development at the back of beach. A typical example of this is the seven kilometre central beachfront in Durban which has since the 1920's become the main beach tourism area of the municipality. This area is one of the most impacted areas in the study area as the urban development has been placed close to the shoreline as well as the fact that portion of this coastline had been reclaimed from the sea in the last century. The entire stretch will be subject to impacts even with the lowest scenario of sea level rise considered (300mm). As an example the newly (2003) constructed Ushaka Marine World constructed at a cost of US$ 100 million is shown in Figure 10.7 in the block north west of the sea water intake pier. The 300mm SLR scenario (green line) impacts the entire promenade, a portion of the water park pools, the entrance kiosks and two entire restaurant blocks. The 600mm SLR scenario (purple line) impacts the water slides, a portion of the ship which houses the balance of the restaurants and the start of the shopping area. The 1 m SLR scenario affects 50% of the site, eroding the seal enclosure, the balance of the ship, most of the water slides and 20% of the shopping complex.

To reduce these impacts the strategy proposed is a combination of soft engineering (to be discussed in greater detail in Chapter 9) and renourishment. The areas directly seaward of the structures at risk have been protected by a defence system comprising a buried geofabric bag retaining wall (Figure 10.8) covered in an artificial dune with vegetation planted on top (Figure 10.9).

In addition to the geobag protection a renourishment programme has also taken place. The first 500 000 m^3 of sand was dredged offshore and deposited into this area during 2010 resulting in a widening of the beach zone of over 50 m. Over the 2010/2011 season this has been distributed northwards resulting in an average beach widening of approximately 20 m. This renourishment will be repeated as and when required to offset the erosion due to sea level rise until the off shore sand reserves are depleted or until this renourishment can no longer hold back the sea.

10.6.2 Steep dune slopes

There are several large primary dune systems, which dominate sections of the study area. The most well known of these are the red dunes, or the Berea Red formation, which exists along the coast from just south of Durban to beyond Maputo,

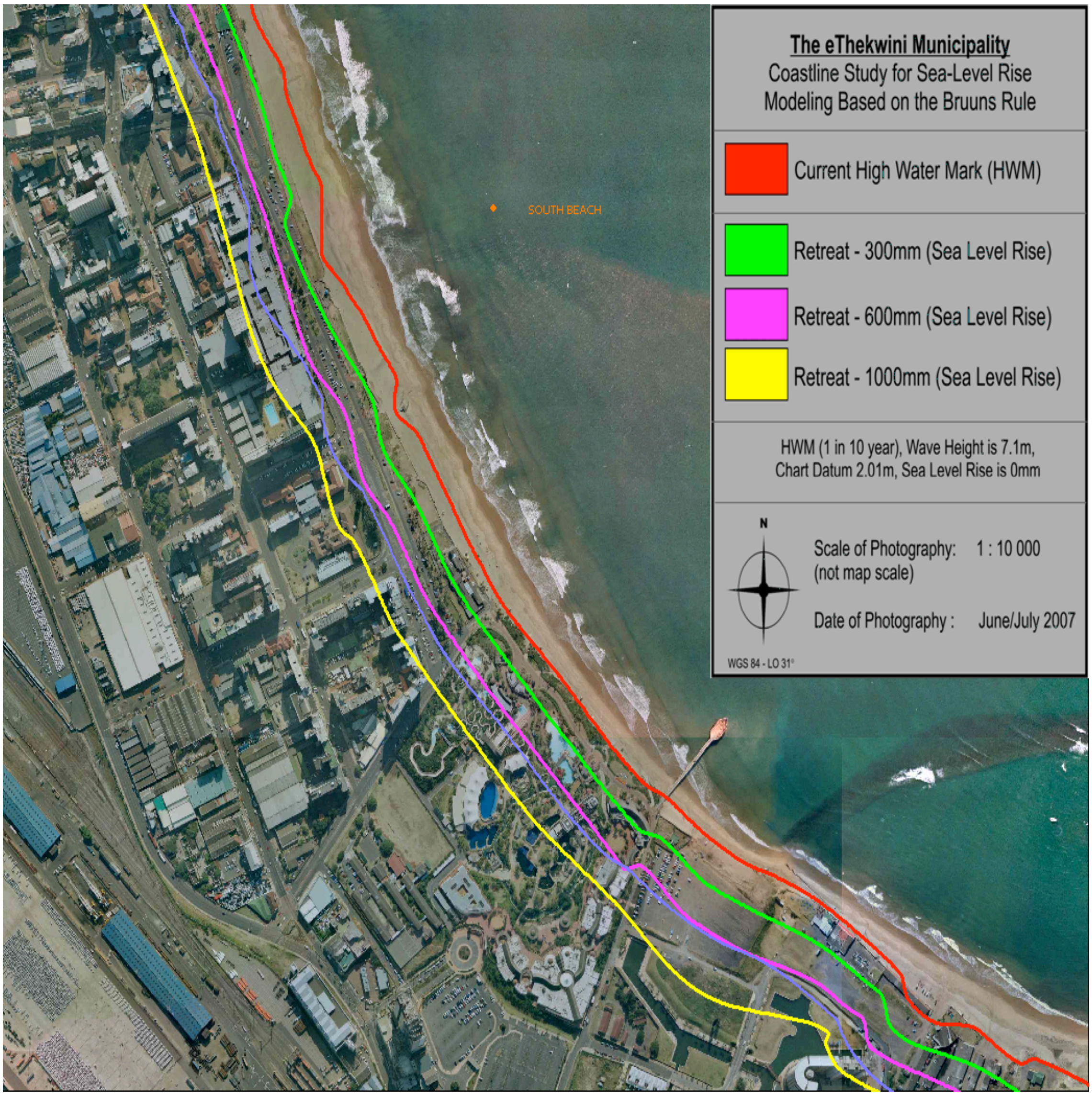


Figure 10.7: Sea level rise impacts on Ushaka Marine World at the Point. Ushaka Marine World is located west of the sea water intake pier (PSSolutions).

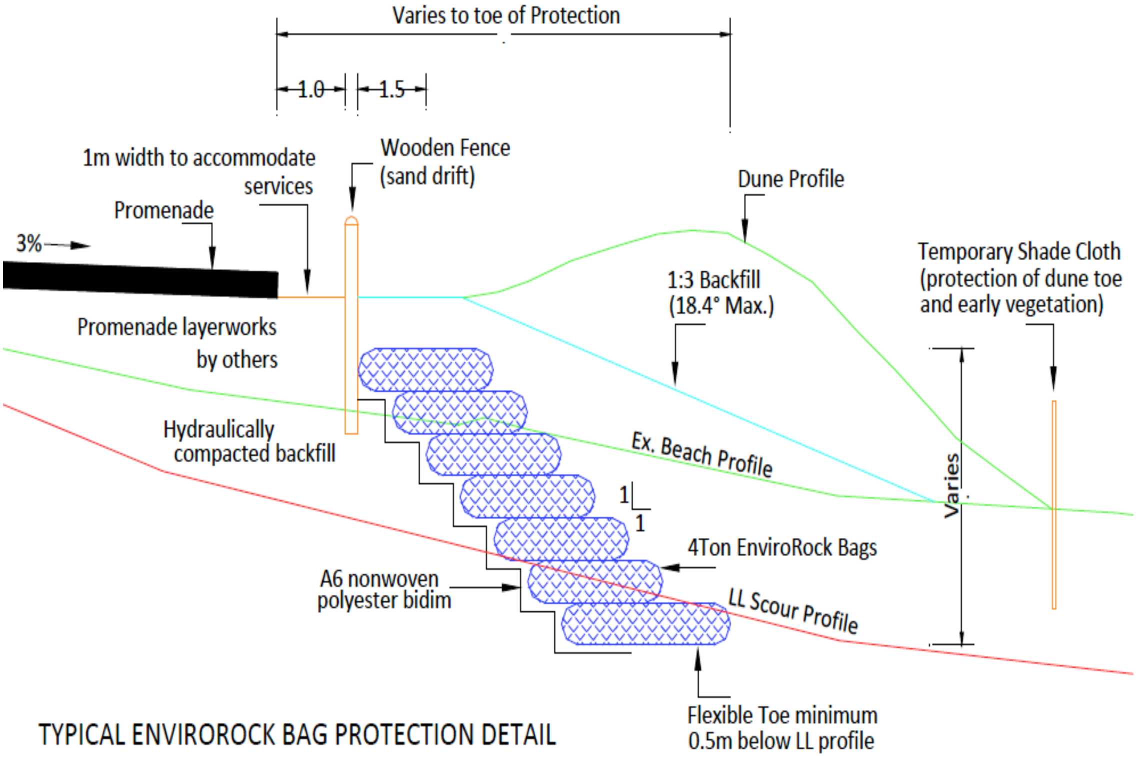


Figure 10.8: Geobags placed in front of the Ushaka Marine World at the Point (Photo: M Pauselli).

Figure 10.9: Dune re-establishment in front of Ushaka Marine World at the Point (Photo: M Pauselli).

Mozambique. These ancient dunes, formed around 182 000 years ago, are aeolianite deposits of fine quartz grains coated with clay containing ferric oxide giving the sand its distinctive red colour. These dunes have been eroded back since the last sea level low stand approximately 18 000 years ago (Ramsay and Cooper, 2002). As these are unconsolidated sand dunes or bluffs they are unstable. Up until the present time these unstable slopes have been identified, demarcated and development precluded from the slip area using coastal set back lines.

With rising sea levels the slip failure zone will migrate inland. Just a 300 mm rise in sea levels is sufficient to endanger existing development. Figure 10.10 shows the main sewerage treatment works (60 Ml/day) which services the Central Business District of Durban and it can be seen that a sea level rise of 300 mm will affect the main sewer pipeline around the tip of the Bluff. Adaptation in this case has been to protect the incoming sewer pipeline which is exposed along the front of the dune face with an engineering solution. This will reduce the risk of failure of the line in the interim. However what is also evident is that the platform adjacent to the beach which houses the plant will be directly affected and therefore the municipality is proposing to relocate the works inland and out of the high risk zone to the inland side of the dune with a pipeline through the dune and to the sea outfall.

Figure 10.11 shows the same dune formation but further south where the existing coastal forest is at risk of slipping into the sea under the scenario of 1000 mm of sea level rise. Under these circumstance there is little one can do given the fact that urban development prevents the natural system from retreating inland. Adaptation responses here cannot be justified on an economic grounds and therefore we are probably going to see the loss of coastal forest in this area.

10.6.3 Beaches facing the open coast

This category is by far the most common situation along the study area. The high energy wave environment along the sandy coastline has formed long straight open beaches stretching sometimes for tens of kilometre's between rocky outcrops. Under rising sea levels these shorelines will retreat, albeit to a lesser amount then the flat sandy shoreline discussed in section 10.6.1. These beaches are predominately backed by residential development. Typical of this situation is the coastline south of Umhlanga Rocks where a mix of large individual homes and residential complexes have been constructed (Figure 10.12). Many of these developments fall seawards of the set back line and a common adaptation response here has been to install a geofabric bag defence similar to Figure 10.8. The major difference here is that the defence costs have been to the individual home owner whereas the Ushaka Marine World defence system was borne by the municipality. The coastal management legislation in South Africa specifically states in Clause 15(1) that:

> "*No person, owner or occupier of land adjacent to the seashore or other coastal public property capable of erosion or accretion may require any organ of state or any*

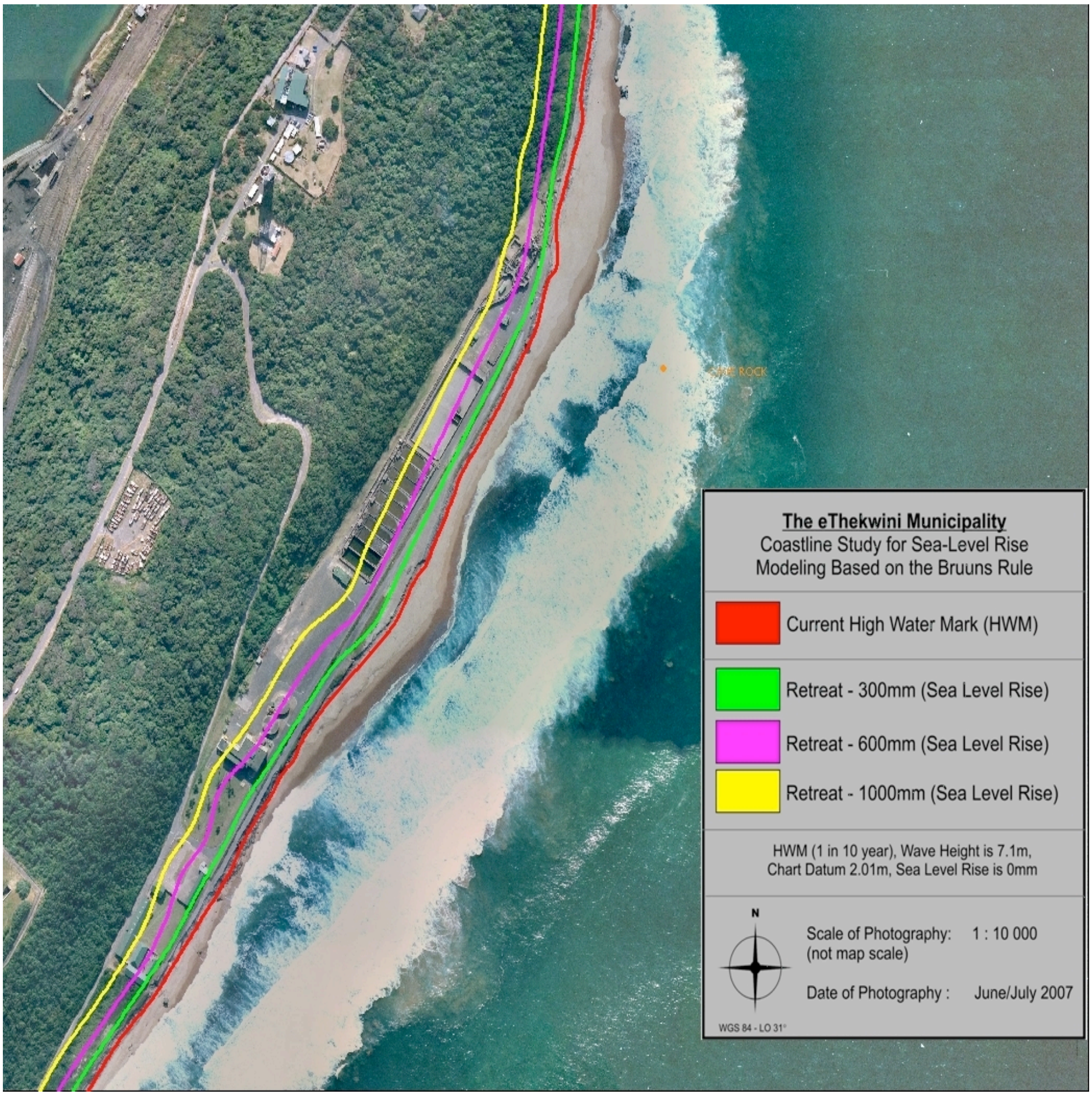


Figure 10.10: Sea level rise impacts on the central waste water treatment works on the Bluff (PSSolutions).

Figure 10.11: Slip failure of oversteep dunes on the Bluff (PSSolutions).

other person to take measures to prevent the erosion or accretion of the seashore or such other coastal public property, or of land adjacent to coastal public property, unless the erosion is caused by an international act or omission of that organ of state or other person".
ICM (2008).

In these cases the individual residents will need to foot the bill for their defences subject to the approval of the type of defence with the local authorities. This has yet to be challenged in court and given the far reaching financial implications of this clause it is anticipated that this will be challenged at some time in the future.

10.6.4 Topographically constrained beaches

There are a number of pocket or topographically constrained beaches which have rocky headlands either side of them, typical of this type of situation is the beach at Clanstal shown in Figure 10.13. Note the defence system under construction in the centre of the embayment.

Here the beaches retreat at a greater amount in the centre of the beach tapering down either side to the rocky headlands. These beaches will experience additional erosion from the additional wave run-up induced by a increased water level from SLR. Here the adaptation response will be similar to that discussed in Section 10.6.3.

10.7 Assessment of the regional shorelines

The implications for sea level rise along the sandy Southern and Eastern African shoreline will have far reaching effects extending beyond just inundation and coastal erosion. In this paper the focus is however on the primary impacts as they relate to the typical types of shoreline present. The management response to SLR will need to be developed from this assessment based on each locality where infrastructural responses/interventions may be considered. This detailed investigation at each site is beyond the scope of this paper, however, some generic evaluation is possible using the study area and the broad categorisation of beach types.

10.7.1 Rocky shorelines

Rocky shorelines are present along the Southern and Eastern African coastline particularly in the Western and Eastern Cape regions of South Africa. By their very nature these shorelines are relatively stable and are not subject to erosion to the extent that sandy shorelines are. The main impacts of rising sea levels will be the increase in wave run-up levels higher than present resulting in loss of vegetation at these locations.

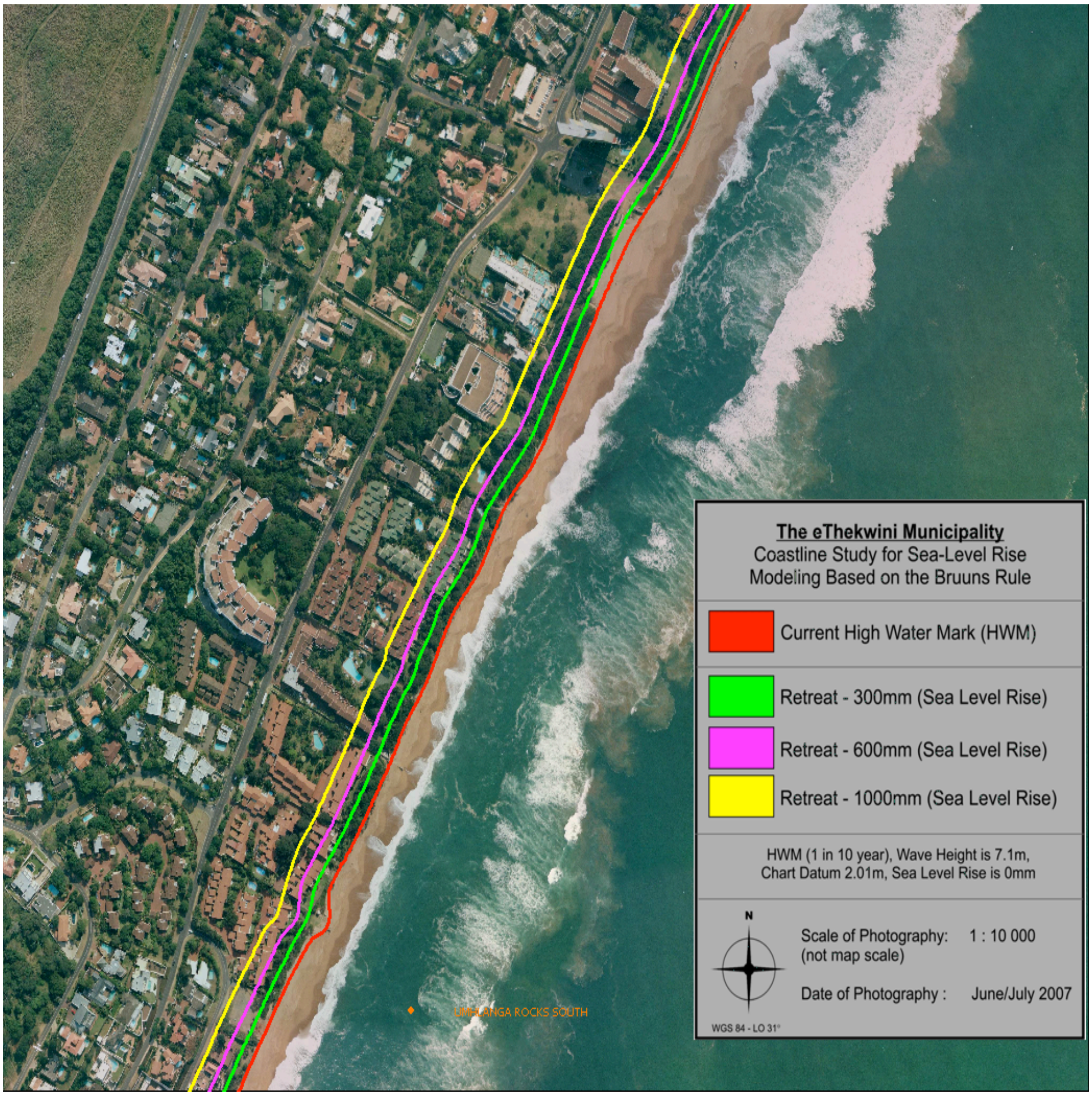


Figure 10.12: Sea level rise impacts on Umhlanga area (PSSolutions).

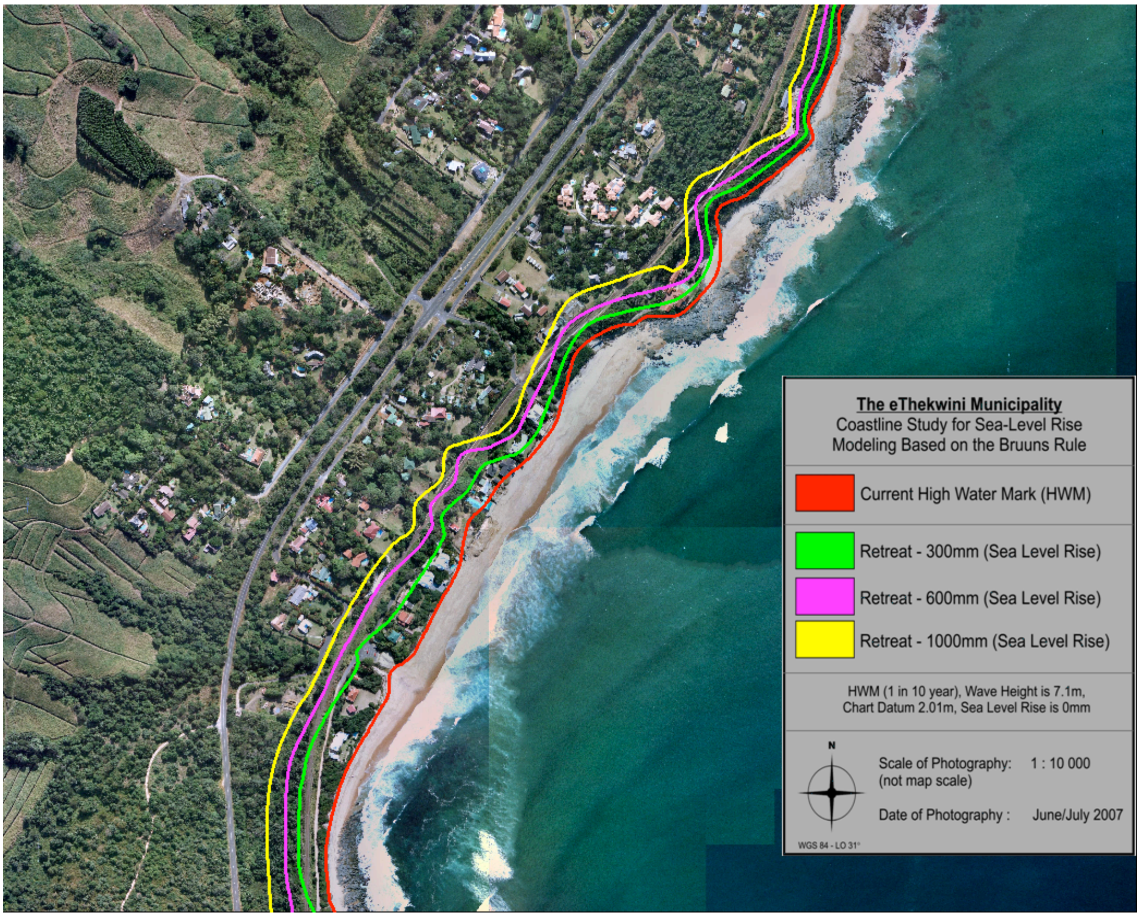


Figure 10.13: Sea level rise impacts at Clanstal (PSSolutions).

10.7.2 Undeveloped natural sandy shorelines

This type of shoreline exists in limited areas in South Africa but is more widespread in Mozambique, Tanzania and Kenya. Like rocky shores this type is least likely to present a hazard to humans simply because they are undeveloped. Small increases in sea level result in significant advance of the high water mark. Typically these areas were inundated in the previous high stands of sea level around 6000 years ago (Ramsay and Cooper, 2002). Typical of this type of coastline is the coastline of Mozambique with a wide continental shelf where large portions of the flat, low elevation coastal plains are river deltas. There is sufficient land for the sea to retreat naturally with little impact on humans.

From an adaptation point of view these areas need to be allowed to naturally respond to rising sea levels and perhaps the only management interventions should be to actively prevent new settlement in the potential flooding and erosion zone. A development set back line should be formulated with various sea level rise scenarios so that the authorities can manage development as well as prevent additional development in high-risk areas. This development set back lines must be of sufficient distance from the existing shoreline to cover the risk zone. From previous experience in the region, often these set back lines are underestimated and are of insufficient width to perform their function. This will lead to problems with development sited too close to the coast in the future (Harris, 2008). However if these development set back lines are properly determined they have the ability to reduce risk so that the economic investments in the developments are fully realised before the developments are lost or are required to be relocated.

10.7.3 Beachfronts and Coastal Development

Beachfronts are significant local and regional economic generators and are very often constructed with significant back of beach amenities and infrastructure. The extent of these facilities has evolved over several decades and cannot simply be moved overnight. It is along this coastal type where the largest impacts will be experienced. Many beachfronts already have some form of sea defence in place protecting infrastructure and it is often this infrastructure that is the first to be damaged by heavy seas. Unfortunately, as is the case for many urban beachfronts, there is no longer any room to maneuver; development is so intense there are limited options for retreat. The adaptation response must be tailored to suit each location and its respective circumstances. For example, without any adaptation interventions the beachfront at Durban, South Africa (shown in Figure 10.7) will result in the loss of significant development and infrastructure such as the Ushaka Marine World (the fifth largest aquarium in the world when it was completed in 2003) and to roads, coastal structures and tourism amenities.

In the short term it is possible to maintain the shoreline by providing additional sand from dredge sites offshore to replace and offset the increased erosion and beach reduction caused by sea level rise. The economic costs of this option will determine when this intervention is no longer viable. In the medium term, the decision to defend will need to be taken, retreat will probably not be possible. The nature of the coastline will then change permanently with sea walls replacing the once sandy beaches along 'Durban's golden mile'. Other less developed beachfronts may not be so fortunate and may find that the renourishment option is too expensive and will need to move directly to a defend position. On a positive side the development in these less developed beachfronts will be less intense and it may be possible to retreat some distance inland, effectively putting off the inevitable defend option.

10.7.4 Estuaries and Mangroves

Estuaries, often with associated mangrove stands, are highly productive systems (Forbes and Demetriades, 2009; Perissinotto *et al.*, 2010) and form part of coastal ecosystems that are amongst the most threatened ecosystems in the world (Millennium Ecosystem Assessment, 2005). Their functioning is controlled by two main drivers:

(1) fresh water river flows and

(2) the marine processes of tides, waves, sedimentation and accretion.

Some estuaries remain permanently open to the sea, some open and close depending on which factor is dominating and some remain permanently closed relying on seepage to the sea. At the best of times these systems are delicately balanced and any changes to their normal functioning, such as artificial mouth breaching, reduces the productive window while insufficient breaching results in the accumulation of pollutants particularly in urban estuaries, often leading to low oxygen and fish kills (Perissinotto *et al.*, 2010).

Against this background estuaries will be impacted by sea-level rise in two ways. Firstly, as the sand bar across the estuary mouth migrates inland this has the potential to fill out the estuary basin with marine sediment. This in turn will reduce the available water volume and thereby reducing the efficacy of the estuary to provide a fish nursery for marine species. Secondly, raised water levels will allow more wave energy into the mouths of estuaries and will start to negatively affect the mangrove stands that may have formed within the estuary, disrupting the nutrients which many organisms rely on to survive. This has a knock on effect through the food chain. Along this coastline mangroves do not survive when exposed to direct wave action and so when this occurs the mangroves will start to die off. The current problems of the accumulation of pollutants particularly in urban estuaries will be exacerbated by more frequent mouth closure.

Management actions, particularly in natural systems, are often not successful and so it is suggested that efforts be made to increase the resilience of estuaries by addressing pollution issues such as discharges from waste water treatment works. The estuary would need to be protected from being confined by a ring of urban development preventing the natural expansion of the estuary habitat as sea levels rise. A buffer zone is required and this will need to be set in place and actively managed to prevent encroachments into this area (Perissinotto *et al.*, 2010). In order to set in place some guidelines for the buffer which includes a sea level rise component it is suggested that a contour of say +8 m above MSL or some defined horizontal distance from the +5 m above MSL contour be set in place based on the topography of each estuary.

10.7.5 Harbours

The main Southern African harbours are located along the east shoreline of Africa, ie. Cape Town, Port Elizabeth, Coega, East London, Durban (the largest container port in Africa and 3rd in the southern hemisphere) serving as a major import/export hub for the Southern African region, Richards Bay (largest coal export terminal in the southern hemisphere exporting approximately 100 million tons per annum), Maputo, Beira, Nacala , Dar Es Salaam and Mombasa. This string of ports provides for the flow of goods into and out of Southern and Central Africa. It is expected that a small rise in sea levels could be handled within the design capacity of the current harbours. However, should sea level rise by around 1 m this will start to lead to problems. The extra water depth will result in an increase in wave energy both outside and inside the harbour. Impacts outside the harbour are like to be wave overtopping of the entrance breakwaters with loss of some of the structure leading to increased maintenance costs and additional capital costs to redesign the harbour entrance works. Within harbours, the extra water depth will result in less freeboard along the quayside resulting in more frequent wave wash/overspray onto the working area increasing down time and loss of productivity. With the increased wave energy, ships moored alongside the quays will not be sufficiently stable for the offloading of cargoes. This will result is longer offloading times, longer ship turn-around times, inefficiency at the berth side and extra costs. Management interventions could be the fortifying of the entrance breakwater structure to reduce the increased wave energy and changes to reduce the additional wave energy penetration which affects moored ship stability at berth. In the extreme scenario of several meters of sea level rise this will inundate the harbours preventing them from operating and transporting goods.

10.7.6 Armour or fortified coastlines

Shorelines that have previously been fortified using sea wall of other defence system will not be immune from attack. Increases in water depth as a result of sea level rise will allow increased wave energy to penetrate closer inshore. This increased wave energy could exceed the original design condition, the structure subjected to more wave energy then it is capable of withholding will result in partial or full failure of the structure. Adaptation to sea level rise would be to check the design parameters of existing critical infrastructure where failure could result in severe financial, social and environmental costs. New infrastructure adaptation is easier as these additional wave forces can be designed into the structure before construction.

10.8 Conclusion

The results of this paper show that the zone of high risk down to the High Water Mark within the coastal zone can be relatively easily described and mapped. This provides the basic information that decision makers require when planning any new and existing activity within the coastal zone. The results show that different portions of the coastline will experience differing degrees of impacts by sea level rise and while it is relatively straight forward to predict the impacts of sea level rise it is more complicated to decide what adaptation responses are sustainable and which will avoid maladaptation.

10.9 Acknowledgements

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Epilogue to Chapter 10

In Chapter 10 the research developed in this thesis was brought together to analysis what the potential physical impacts of future sea level rise along the Southern and Eastern African shoreline. The approach was to use a detailed case study in order to determine the typical types of impacts at the different types of shorelines. The case study revealed that the shoreline types that are most likely to be impacted are the flat sand shorelines where beach regression due to sea level rise will be greatest and secondly along the steep sandy dune system common along portion of these coastlines.

Using this approach demonstrated within the study case area it is possible to extend this approach in a cost effective manner to the rest of the Southern and Eastern African shoreline enabling other coastal managers to benefit with this new information. This is but the first step as ultimately the adaptation measures to future sea level rise will be more than just a function of the identified physical impacts and will need to be matched by strong management, financing and capacitated governments.

Chapter 11

CONCLUSION

11.1 Relevance of this research work in the regional and global context

Research on the impacts of climate change, sea level rise and consequently coastal erosion has occupied the minds of many researchers over the last two decades. The focus has been predominately along the coastlines of countries in the Northern Hemisphere. This is to some degree understandable as the number of institutions and researchers in the Northern Hemisphere far outweighs the Southern Hemisphere. As a result the African continent has not attracted much research. This does not mean that research has not been carried out to date as limited studies have taken place recently and there are a number of studies which are now rather dated that were undertaken over two decades ago.

The need to provide recent up to date data and research in the region has been acknowledged (Woodworth *et al.* 2007). The research in this thesis will serve a number of regional objectives namely,

(1) it will provide a basis to determine the research gaps which exist currently,
(2) the identification of problems with the current tide gauge station network and data issues,
(3) providing the basis on which data problems should be addressed,
(4) providing information on the state of sea level changes in the region and,
(5) providing the input into a range of planning interventions required for planning and adaptation to sea level rise and coastal erosion.

At a global level this research also provides a number of important contributions namely,

(1) to provide the most up to date research for the studies of global sea level rise. For example, Church and White (2011) where they selected the most accurate global

tide gauge stations and which only five of the thirteen examined here were utilised, (2) to provide new data in a region which is poorly covered by tide gauges in the global context and
(3) to provide sea level changes which are accurate and of high confidence which are needed to calibrate the satellite altimeter data (Mitchum, 1998).

11.2 Have the questions, aims and actions been answered in this thesis?

At the start of this thesis several questions were posed and the answers to those questions can now be provided.

Question 1. Have there been recent historical changes of sea level along the Southern and Eastern African coastline and,
Question 2. If so, what is the rate and direction of sea level change?

This study has shown that there have been changes in sea levels around the Southern and Eastern African coastline however the quantum of this change varies spatially throughout this region. In Chapter 4 the first tide gauge station in the region at Durban was analysed and this tide gauge station exhibited a relative sea level rise of +2.7±0.05 mm per year between 1970 and 2003 after extensive work had to be undertaken to correct the data from this tide gauge.

The assessment of tide gauge stations was extended to the rest of South Africa and Namibia in Chapter 5 where it was shown that generally all tide gauges show a rising trend over the period from 1957 to 2007. The only tide gauge station showing falling relative sea levels was that of Mossel Bay at −0.40 ± 0.19 mm per year (1958-2007). The Mossel Bay tide gauge station was reanalysed in Chapter 6 and now shows a relative sea level rise of +0.33 ± 0.35 mm per year (1958-2009) as a result of changes made to the data by the PSMSL. The tide gauge station at Knysna previously reflected a rate of relative sea level rise of +1.27 ± 0.50 (1960-2007) and now shows an increase in relative sea level rise to +1.81 ± 0.54 mm per year (1960-2009). The East London station has also changed dramatically with an increase in relative sea level rise from +0.17 ± 0.05 (1967-2007) to +2.30 ± 0.93 (1967-2009) mm per year. The tide gauge station of Durban remains an anomaly with a relative sea level rise of +1.11 ± 0.58 mm per year (1971-2009) from the PSMSL records in contrast to that calculated in Chapter 4 of +2.70 ± 0.05 (1970-2003).

In Chapter 6 the analysis of tide gauges was extended to the remainder of the study area covering the Mozambique, Tanzania, Kenya and western Indian Ocean islands of the Seychelles, British Indian Ocean Territory, Rodrigues, Reunion and Mauritius. The results also show a general increase in relative sea levels with the exception of Zanzibar which yielded a relative sea level change of −3.64 ± 1.62 mm per year.

Question 3. What factors are influencing these sea level changes?

The main factors affecting the extent of sea level changes in the Southern and Eastern African coastline can now be given as (1) Barometric pressure changes and (2) vertical crustal movements (3) thermal expansion due to incresing water temperatures.

The assessment of barometric pressure changes was confined to the Namibian and South African coastline due to the unavailability of barometric pressure data outside of this region. In Chapter 5 the impacts of changing barometric pressure was applied to the relative sea level trends and the conclusion reached was that rising barometric pressure was suppressing rising sea levels along the eastern South African coastline, having no impacts of sea level changes in the southern South African coastline and raising sea levels on the western South African and Namibian coastline as barometric pressure was dropping. Rising sea surface temperatures in the Agulhas and Benguela currents are increasing sea levels throughout the region.

In Chapters 5 and 6 vertical crust movements were assessed in the region and although there are limited GPS stations there were some interesting results. All the African mainland countries, South Africa, Namibia, Mozambique, Tanzania and Kenya as well as the most easterly island in the study area, the British Indian Ocean Territory, yielded rising ground levels. In contrast, the western Indian Ocean islands of Reunion, Mauritius, Rodrigues Island and the Seychelles yield falling ground levels. The impact of the vertical crustal movement on relative sea level change was in all but one case smaller then the relative sea level change and only the tide gauge in the Seychelles provides a reversal in the sea level trend.

Question 4. How should these future sea level changes be managed?

As was seen in Chapters 4, 5 and 6 the amount of sea level change varies within the study area but it is generally rising at all stations. Rising sea levels will result in changes to the shoreline but these will differ depending on the type of coastline. However society will need to make some hard decisions with regard to its future management of the coastline in the light of rising sea levels and coastal erosion. The author has proposed, in Chapter 8, that the use of a risk-based approach which seeks to balance the needs of society for access the coast while taking some precautions against rising sea levels is the way forward. This approach permits inexpensive and easily replaced infrastructure to be placed in the higher risk zone while strategic infrastructure what would result in widespread negative impacts be located in the lowest risk zone. Detailed assessment of the entire coastline were beyond the scope of this study however using a detailed case study a number of lessons and recommendations on managing the different types of coastline were discussed in Chapter 10.

Within this study the aims were:-

Aim 1. To determine the most accurate measured rates of sea level change along the Southern and Eastern African coastline.

In Chapters 4, 5 and 6 a detailed analysis of the regional tide gauge stations was presented. Many problems particularly with the South African tide gauge stations were discussed. Several corrections to the data were identified and in some cases a number of data problems where recorded without any obvious solution. The South African Navy's Hydrographic office has taken some of these data issues into account in the re-publication of several of the affected tide gauge records most notably the tide gauge stations of Mossel Bay which now shows a positive relative sea level rise of +0.33 ± 0.35 mm per year (1958-2009), Knysna which previously reflected a rate of relative sea level rise of +1.27 ± 0.50 (1960-2007) and has now been corrected to show an increase in relative sea level rise of +1.81 ± 0.54 mm per year (1960-2009) and East London which has also been reworked now yields an increase in relative sea level rise from +0.17 ± 0.05 (1967-2007) to +2.30 ± 0.93 (1967-2009) mm per year.

The tide gauge station at Durban, despite all the research work undertaken in this thesis, remains an enigma with a relative sea level rise of +1.11 ± 0.58 mm per year (1971-2009) (PSMSL, 2011) in contrast to the result calculated after extensive correction to the data of +2.70 ± 0.05 mm per year (1970-2003) (Mather, 2007) and the surrounding tide gauge results of Port Elizabeth (+2.52 ± 0.77 mm per year) and East London (+2.30 ± 0.93 mm per year) in Chapter 6.

Aim 2. To predict future changes in sea level for the remainder of this century

Predicting future sea levels is difficult as is evidenced by a large number of researchers using a range of different approaches to determine this over varying time scales. In this research the focus was on physically based projection methods and in Chapter 8 two methodologies where used. The temperature/sea level rise relationship developed by Rahmstorf (2007) and the tide gauge projection used by a number of authors (i.e. Church and White, 2006) however these were modified by the author for application in this region. The modified Rahmstorf (2007) approach yielded predicted sea levels ranging from 117 mm (1° C) to 702 mm (6 ° C) (Table 8.4). The tide gauge projection approach was also modified by using the local linear trend (those derivided in this study) and including a global acceleration rate from Church and White (2006) and Jevrejeva *et al.* (2008). This yielded 358 mm using a modified Church and White (2006) approach and 338 mm using a modified Jevrejeva *et al.* (2008) approach (Table 8.5). Given the range of predictions it was decided to use scenarios of 300 mm, 600 mm and 1000 mm and to assess the impacts of these three scenarios only.

Aim 3. To develop a management model to allow society to anticipate these physical changes

In order to know what to plan for under future sea level rise it is important to first determine what these impacts are likely to be. The impacts are not simply an assessment of an increased water depth in the ocean but the combined impacts of higher water level, increased inshore wave energy as a result of high water levels and the erodability of the land adjacent to the shoreline. In Chapter 10 the key regional variables were determined and then this approach was demonstrated by the use of a detailed case study of the Durban coastline. The resultant predicted impacts were mapped in a freeware GIS viewer which is available to the public. A copy is contained in the back cover of this thesis.

Aim 4. To explain why this research is of relevance in the global sea level rise context

The importance of this study was discussed earlier in Chapter 11, Section 11.1 as to how this study contributes to regional and global objectives.

Aim 5. To assess constraints to the management of shoreline change

Two main areas of constraint to the management of shoreline change were identified in this study. The first constraint is the lack of understanding of what sea level rise and coastal erosion could mean physically on the ground. The second constraint is the capacity and skills within the government sectors to respond to these potential changes. These two constraints where discussed in Chapters 8, 9 and 10 where it was concluded that local government is generally not well prepared and that the physical impacts have not been mapped on the ground making it even more difficult to intervene in the absence of an assessment to identify potential impacts.

These aims were achieved by the 10 actions:

Action 1. To analyse all available tidal gauge records for all suitable gauge stations on the Southern and Eastern African coastline and,

Action 2. To determine the most reliable and accurate tide gauge data and

Action 3. To compute sea-level trends along the Southern and Eastern African coastline

All the available tide gauge stations in the study area were analysed (21 in total), but unfortunately 3 tide gauge stations had too short a period of data available and these had to be set aside. However, a total of eighteen tide gauge stations were used to derive sea level change trends in Chapters 4, 5 and 6.

Action 4. To determine which factors are influencing this change and to what extent they aggravate or mitigate sea-level change

The main factors found to be affecting the extent of sea level changes in the Southern and Eastern African coastline are:-

1. Barometric pressure changes. This was discussed in Chapter 5.

2. Vertical crustal movements.

This was discussed in Chapters 5 and 6.

Action 5. From these results develop scenarios of sea level change in the region for the remainder of this century

This was discussed in Chapter 8 where two methodologies where used based on a modified Rahmstorf (2007) and the modified tide gauge projection used Church and White (2006) and Jevrejeva *et al.*(2008). Three scenarios were developed from these analyses namely, 300 mm, 600 mm and 1000 mm of future sea level rise by the year 2100 and these three scenarios to assess the impacts of sea level rise in Chapter 8.

Action 6. Through a review of management models of wave run up and shoreline change develop a model suitable for use in the region

The wave run up model review as well as the novel approach used to develope a new wave run up model was described in Chapter 7. The results of this show that this new model is simpler to apply, requires less data and provides better results for wave run up in this region.

Action 7. To determine sites within the region which are most vulnerable to shoreline changes in the future

This was discussed in Chapter 10 where a case study of the Durban coastline was undertaken and extended to cover similar types of coastline types within the region.

Action 8. To review the legal framework for coastal management

This objective was discussed in Chapters 8 and 9 where the focus was on South Africa's recently promulgated Integrated Coastal Management Act.

Action 9. To assess the capacity of local government to manage sea level rise and coastal erosion

This was carried out in Chapter 9 where it was found that generally the municipalities are not prepared for future sea level rise and coastal erosion.

Action 10. To set the results within the global context

This was discussed in Chapters 2, 10 and 11, (Section 11.1). The sea level changes in the region generally accord with the published global sea level change results.

11.3 General Conclusion

Sea-levels are on the rise along the Southern and Eastern coastline of Africa. However, the rate of rise varies driven by local factors particularly vertical crustal movements and to a lesser extent changing barometric pressure. The rising seas will have the effect of increased coastal erosion and beach regression in the region. Hardest hit will be the sandy exposed beaches. However, the rate of sea-level rise in itself is not the only issue. Sandy coastlines are particularly vulnerable to erosion when the combined impacts of sea-level and coastal storms occur simultaneously. Modeling the impacts of extreme or in fact normal storms combined with raised sea levels has shown that the coastline will respond differently depending on the coastal profile.

Determining the extent of vulnerability of the coastline, and in turn the hazard zone, which has to be managed has been a first step in informing the management of the coastline. Extreme wave run-up modeling provides the first indication of the extent of the hazard zone. This provides the platform on which the magnitude of possible coastline changes can be predicted. Managing the differing scenarios of rising sea-levels and consequential coastal erosion is now a key concern of coastal communities. The extent of these possible impacts can allow the proper and coherent decisions as to what possible interventions could be applied to each location. Consideration of a managed retreat, a do nothing or defend the line is vital in determining what it means in managing future changes. This is important to pre-determine the range of possible interventions prior to the the occurence requiring intervention. The decision as to what steps will be taken needs to be decided early so that the public and authorities are aware of the respective actions required when problems develops.

The implementation of coastal management will in the main rest on the shoulders of local government. This level of government being closest to the people will be at the forefront of the challenges, which lie ahead. The research here has shown that the majority of municipalities are unprepared for proactive coastal management. The research has recommended the establishment of dedicated coastal management resources within each local authority. This capacity must be supported by the appropriate financial and human resources if they are to be successful. The capacities of local authorities are but only one part of the picture. For successful coastal management the legal framework has to be in place to guide, direct and manage.

In South Africa's case the country has been slow in developing dedicated legislation for coastal management. This however is in the process of changing as the country embarked on a process of revising its coastal legislation in the 1990's and after many years of work the Integrated Coastal Management Act was signed into law on the 11 February 2009. The commencement of this Act will have wide implications for how the coastal will be managed. The new law will have implications for property rights of coastal landowners, authorities and requires the improved management at all levels from Local to National government. The new legislation introduces a wide range of new concepts such as a new definition of the coastal zone and the establishment of development setback lines. The hopes of all involved in coastal management rides high that this new legislation will provide a defining moment in South Africa's management of the coastline.

11.4 Future research work

The current spatial distribution of regional tide gauge stations is distorted in that the majority of tide gauges are located along the South African coastline. Outside of South Africa the region has a limited number of tide gauges in operation. The expansion of additional tide gauge stations is an important step in being able to determine the rate of sea-level rise across the region. It is recommended that some of these new tide gauge stations be located with GPS stations so that the extent of vertical crustal movement can be determined.

In the last decade, satellite observations have become a useful tool in determining the rates of sea-level rise around the world. As the satellite data lengthens this information can be used, in the absence of tide gauge stations, to determine the relative changes of eustatic and relative sea-level rise in the region. This approach will still require tide gauges to confirm the results of the satellite analyses. For the short to medium term a combination of tide gauge and satellite altimeter data will need to be used to determine the rates of sea-level rise in the region.

While this research has provided new and updated information regarding sea-level rise, coastal erosion and possible management implications, the bulk of the focus has been on the South Africa. Beyond the South African coastline, there is a need to develop the data and infrastructure to a similar level. Specifically the focus for future work should be on data collection, research, capacity building and improved management of our coastlines if we are ever going to proactively manage sea level rise and coastal erosion.

I wish to end off this thesis with a quote from a friend who said:

"In the long term, the sea will always win. It is up to us how big we want to make the fight"
Linda R. Harris, 2008.

11.5 References

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Linear and nonlinear sea-level changes at Durban, South Africa

A.A. Mather*

The tide record between 1970 and 2003 for Durban, South Africa, is analysed to determine the extent of recent linear and nonlinear sea-level trends in the light of predicted global sea-level rise. Given the stability of the adjacent land mass, Durban is ideally suited to test global sea-level change. The linear trends of monthly mean sea level revealed a sea-level rise of 2.7 ± 0.05 mm/yr and the yearly mean sea-level trend revealed a rise of 2.4 ± 0.29 mm/yr. Nonlinear trends varied between –1 mm and +8 mm/yr. These findings are similar to recently published results of global sea-level rise calculations over the last ten years derived from worldwide tide gauge and TOPEX/Poseidon altimeter measurements, which range between 2.4 and 3.2 mm/yr.

The need to determine trends in sea-level change

There is growing worldwide awareness of the effects of climate change induced by human actions on our planet and, particularly, of the global effect of sea-level rise on coastal cities, towns and subsistence communities that rely on the sea for income and food. Urban settlements have expanded rapidly over the last thirty years, especially in developing countries, making more people vulnerable to this risk.[1]

Sandy beaches, which make up 34% of the world's coastline,[2] form an integral part of most coastal cities' tourism potential. Tourism is an important economic activity in KwaZulu-Natal, and Durban's beaches constitute the province's most important tourist attraction, with 73% of domestic tourists visiting them.[3] Rising sea levels will reduce the surface area of beaches, and the consequent damage to tourism infrastructure will impact adversely on the local tourism industry.

Coastal harbours are similarly vulnerable. Durban plans to double its container port capacity over the next few years.[4] Port and harbour development is costly and developers plan for use of this infrastructure for up to a century or more.

Measurement of sea-level change has been in progress for decades, with the main focus on the northern hemisphere. Data from tide gauges have traditionally been used for this purpose. In the late 1990s, however, the use of satellite data became more prominent, chiefly because of poor geographical coverage by tide gauges, the influence of tide gauge records by land movement and the superior accuracy provided by satellite data. Historically, the analysis of sea-level trends has been undertaken using linear regression techniques, but more recently nonlinear analysis has been introduced.[5]

This paper examines current rates of sea-level rise for Durban and surrounding coastal areas based on the tidal records of the South African Navy's tide gauge located near the harbour entrance (31°00′E, 29°49′S) (Fig. A in supplementary material online). No such analysis has been done to date for Durban nor for any major coastal city on the east coast of Africa. The results are compared with published global sea-level changes.

Methods and results

The tide data used for this analysis were sourced from the South African Navy's Hydrographic Office. The most reliable records between 1970 and 2003 were selected and were received as hourly observed tide levels in Chart Datum (CD). The navy data were found to be unusable in their existing form. There are two other data records for Durban, one held by the British Oceanographic Data Centre (BODC) and the other by the Permanent Service for Mean Sea-level. These were evaluated and found also to contain several anomalies despite originating from a single tide recorder. This required a re-analysis of these data, to rectify and remove dubious records.[6]

The barometric data used in this study were obtained from the South African Weather Service, received as hourly recordings from the Durban International Airport weather station. Recorded tide data are influenced by meteorological effects. Compensation requires the extraction of the influence of barometric pressure, commonly referred to as 'inverted barometer' effects,[7] as these can mask the true sea-level change. Correlation coefficients were established between changes in apparent sea levels, using the Durban tide gauge and changes in barometric pressure. These were –8.7 mm per hPa for annual readings and –5.9 mm per hPa for monthly readings (Mather, manuscript in preparation) and were applied to the data. The longer the period of analysis, the closer the correlation tended to the theoretical relationship of –9.9 mm per hPa.

Two different levels of analysis were undertaken. In the first method, using annual records, the data were analysed according to Pugh.[8] This entailed refining the data, applying a weighting factor to account for discarded data, introducing a barometric correction and, finally, applying linear regression to the refined, weighted annual change. The second method used was similar to the first except for the omission of weighting factors, using monthly rather than annual change and the application of a barometric compensation of –5.7 mm per hPa, rather than the –8.7 mm per hPa used in the first method. Nonlinear trends for monthly mean sea levels were calculated using CATMV, a computer program developed by the Gistat group (www.gistatgroup.com), based on the singular spectrum analysis (SSA) method.[9,10]

Results

The linear analysis of monthly mean sea levels (MMSL) yielded a rate of sea-level rise of 2.7 ± 0.05 mm/yr at the 95% confidence level (Fig. 1). The linear analysis of yearly mean sea level (YMSL) yielded a sea-level rise of 2.4 ± 0.29 mm/yr (Fig. 2). Nonlinear trends (Fig. 3) show changes similar to the linear trends. On examination of the moving annual average trends (Fig. 4), however, it is possible to distinguish different phases. These range from approximately –1 mm/yr to +8 mm/yr. Only two periods show a negative trend, these being in 1972 and 1992. The two negative trends are of small magnitude, –1.1 mm/yr and –0.6 mm/yr, respectively. A positive trend is evident in the rest of the series, with the highest value of +8.4 mm/yr recorded in 2002.

Discussion

Sea-level trends around the world have shown varying amounts of sea-level variation, depending on the location and geological history of the site. Emery and Aubrey[11] evaluated 587 gauges with records longer than ten years and identified only 36 that originate from stable coastlines. Only three of these sites were from southern Africa and all were situated on the west coast. As the southern part of the African continent is founded

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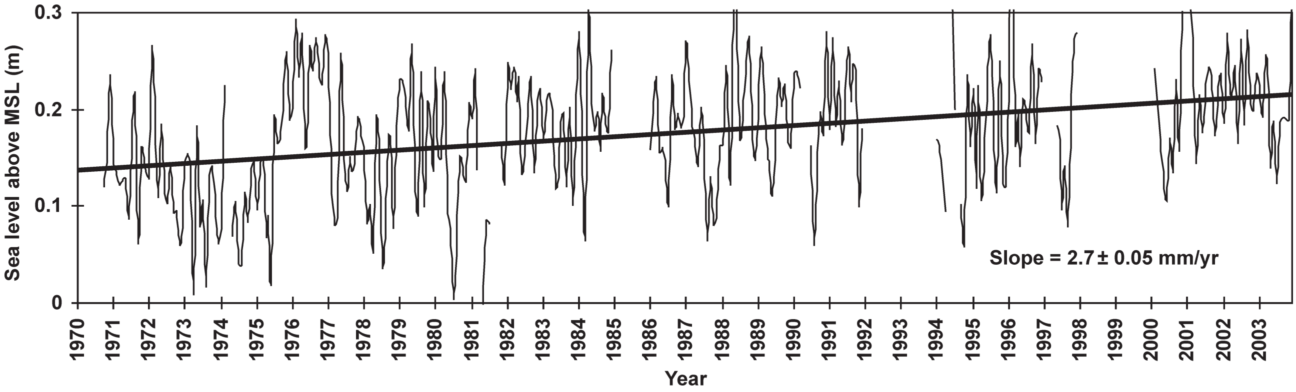

Fig. 1. Monthly sea-level changes at Durban and derived linear trend.

on a stable cratonic base, this makes the land mass around Durban tectonically stable.[12] This obviates the need to correct for many of the other influences that pervade the tidal records, notably subsidence and post-glacial rebound. Durban is, therefore, one of relatively few sites in the world that can be used directly to assess global sea-level change.

Little recent research has been conducted in South Africa on rates of sea-level change calculated from tide gauge data. In 1984, Brundrit[13] focused on sea-level changes only on the west coast of South Africa, and Hughes *et al.*[14] examined changes on the west and Cape coasts with respect to sea-level measurements in the global context of sea level. Brundrit[15] examined the tide gauge data at Lüderitz, Port Nolloth, Simon's Town and Mossel Bay, deriving trends from these sites. He omitted the east coast entirely, however. Except for the work of Cooper[12,16,17] and Hughes,[18] who used estimates of sea-level change to model coastal impacts, even fewer sea-level studies have been undertaken specifically for Durban.

A comparison of our results with this previous work was made. Cooper,[16] quoting Hughes (pers. comm.), refers to Durban's tide record as showing 'little upward trend' and ascribes this to possible instrument error, land movement and/or other factors. This paper examines this particular period of the Durban record, and analysis clearly shows an upward trend. This anomaly may be attributable to previous workers' use of the British Oceanographic Data Centre record for Durban, which shows a downward trend, and not the official tide record from the South African Navy. The BODC record originates from the University of Cape Town via the University of Hawaii. The work of Cooper[12,16] included a regional estimation of the effects that a 1-m sea-level rise could have on the KwaZulu-Natal coastline. This figure was chosen presumably as it reflected the upper limit of sea-level rise predictions at that time. All other previous work has been based on scenarios and none of the authors derived the actual sea-level rise for the east coast from tide data. Thus the data from this study are vital for future work.

The approach adopted in this study, based on MMSL and YMSL data from the available records, provides good correlation with more sophisticated analyses. Pugh[8] points out that: 'This method is used by many authorities because it requires little mathematical insight, yet produces values close to that obtained by more elaborate tide-elimination techniques (Rossiter, 1958).'

It is important to note that calculations based on mean monthly sea level almost always yield different answers to those based on yearly mean sea-level calculations. Time series plots of YMSL values appear to be smoother than those of MMSL values. As there are 12 times more data points in the mmSL record, however, this effectively increases the sample size of MMSL plots, leading to a smaller standard error of the regression coefficient.

Linear regression analysis is a relatively easy and popular tool whereby sea-level trends can be obtained. This method has its defects, however. Regressional analysis is sensitive to the starting position of the analysis and, therefore, is inappropriate for periods of a decade or less, because of the multi-year cycles present in the tide record.[5,19] These cycles, if not properly accounted for in the analysis, mask longer-term trends in the data.

Nonlinear techniques, on the other hand, are more robust and not as sensitive to the start position. Two approaches considered for this analysis were the empirical mode distribution (EMD) [20,21] and singular spectral analysis (SSA).[9] Both are effective in decomposing time series into trends and residual frequencies, allowing better understanding of the latent trends in the data. As with most data series, however, gaps are common and are difficult to deal with. CATMV, which uses SSA, was chosen here, as this software has a superior method of filling in data gaps.[10]

The comparison of these results with worldwide figures is shown in Table 1. Over the last century, the trend is towards an

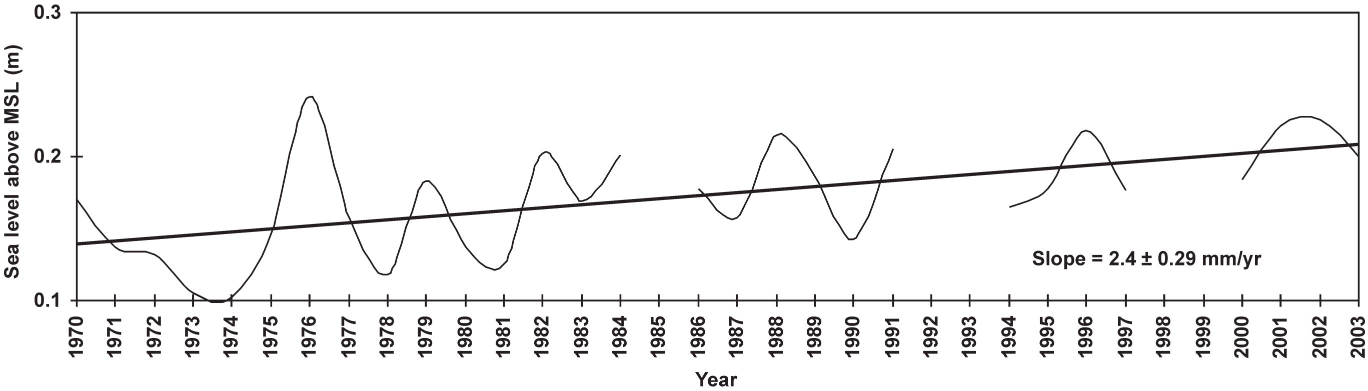

Fig. 2. Annual sea-level changes at Durban and derived linear trend.

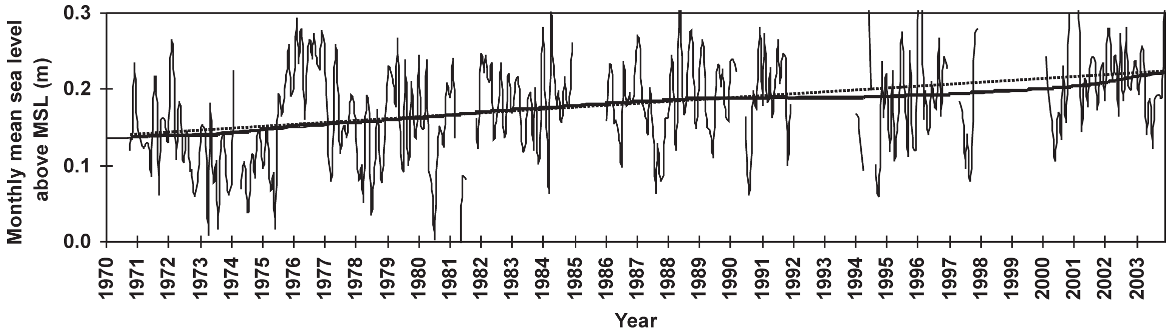

Fig. 3. Monthly sea-level changes at Durban and derived non-linear trend. The dotted line shows deviation from the linear trend.

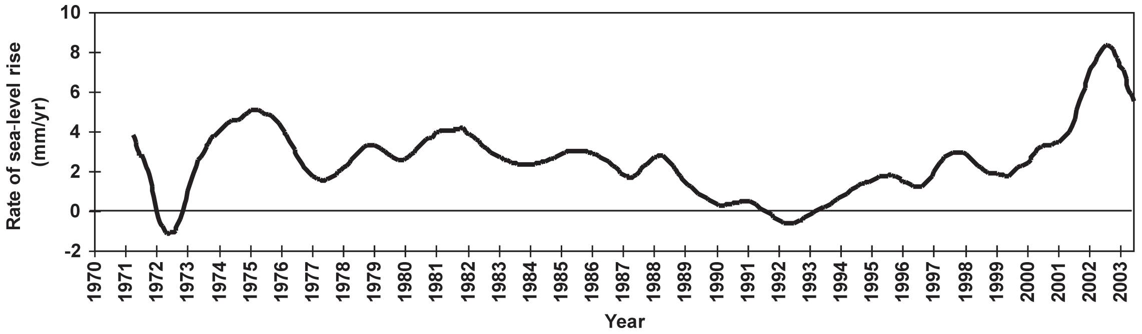

Fig. 4. Annual rate of sea-level change at Durban.

ever increasing rise-rate, which has led to speculation about future acceleration in rising sea levels. Church and White[43] have subsequently established evidence of an acceleration in the rate of sea-level rise from extended (1870–2004) tide gauge records. For this reason comparisons with other sea-level changes are confined to time periods relevant to this study. Church and White[43] examined the 1970–2003 period and obtained a global sea-level rise of 2.1 mm/yr. Many new analyses have been undertaken as a result of satellite altimeter data becoming available, Cabanes *et al.* [33] and Nerem and Mitchum [34] examined global sea-level rise for the period 1993–1998 and arrived at a figure of 3.2 ± 0.2 mm and 2.5 ± 1.3 mm/yr, respectively. Jevrejeva *et al.*[5] derived a figure of 2.4 ± 1.0 mm/yr for the period 1993–2000. More studies were undertaken as the satellite data extended over longer time periods. Cazenave and Nerem[41] and Leuliette *et al.*[42] examined sea-level change over the period 1993 to 2003 and published results of approximately 2.8 ± 0.4 and 3.1 ± 0.7 mm/yr. Bindoff *et al.*[44] updated the work of Cazenave and Nerem [41] and obtained a linear rate of sea-level rise of 3.0 mm/yr. All of these results are comparable and correlate well with the linear results of 2.7 ± 0.05 mm/yr obtained for Durban.

Nonlinear results show a constantly changing trend influenced by the multitude of different global changes at play. Analysis shows that, apart from one short period between 1972 and 1973, the major part of the record revealed an upward trend of varying degree. The period between 1972 and 1973 shows a downward trend of –2 mm/yr. The next period, which accounts for most of the time series, yields an almost uniform trend of +2.6 mm/yr.

A distinct advantage of nonlinear trends over linear trends is that discrete periods can be analysed against results obtained for comparable periods. A comparison for the period 1993–98 with the results obtained by Nerem and Michum[34] from satellite data of 2.5 ± 1.3 mm/yr indicates trends from this study of 1.9 mm/yr, which falls into the range provided by Nerem and Michum. Cazenave and Nerem[41] and Leuliette *et al.*[42] undertook a further study for the period 1993–2003, which yielded 2.8 ± 0.4 mm and 3.1 ± 0.7 mm/yr and, compared to the result of 3.0 mm/yr obtained in this study, showed excellent agreement with global nonlinear variations of sea levels.

Based on the comparisons above, the linear rate of sea-level rise derived for Durban of 2.7 ± 0.05 mm/yr would appear to be valid for use at Durban and the surrounding areas.

Table 1. Published information on global sea-level rise.

Reference	Year	Period of time considered	Average rate of sea-level rise ± s.d. (mm/yr)
Peltier[22]	1996	1920–1970	1.94 ± 0.6
Davis & Mitrovica[23]	1996	Unspecified	1.5 ± 0.3
Douglas[24]	1997	1880–1996	1.9 ± 0.1
Nerem *et al.*[25]	1997	1993–1997	2.1 ± 1.2
Viliblic[26]	1997	1807–1992	1.5–2.0
Lambeck *et al.*[27]	1998	1892–1991	1.1 ± 0.2
Mitchum[28]	1998	1993–1996	2.3 ±1.2
Cazenave *et al.*[29]	1998	1993–1997	1.4 ± 0.2
Woodworth[30]	1999	1900–1998	1.22 ± 0.25
Nerem[31]	1999	1993–1998	2.5 ±1.3
Peltier[32]	2001	20th century	1.84–1.91
Cabanes *et al.*[33]	2001	1993–1998	3.2 ± 0.2
Nerem & Mitchum[34]	2001	1993–1998	2.5 ±1.3
Proshutinsky *et al.*[35]	2001	1950–1990	1.8
Church *et al.*[36]	2001	20th century	1.0–2.0
Lambeck[37]	2002	1914–2002 1897–1990	1.16 1.65
Johansson[38]	2002	1993–2000	1.9 ± 0.2
Hunter *et al.*[39]	2003	1841–2002	1.0 ± 0.3
Church *et al.*[40]	2004	1950–2000	1.8 ± 0.3
Cazenave & Nerem[41]	2004	1993–2003	2.8 ± 0.4
Leuliette *et al.*[42]	2004	1993–2003	3.1 ± 0.7
Church & White[43]	2006	1870–2004 1900–2004 1970–2003	1.44 1.7 ± 0.3 2.1
Jevrejeva *et al.*[5]	2006	1993–2000 1920–1945	2.4 ± 1.0 2.5 ± 1.0
Bindoff *et al.*[44]	2007	1993–2003	3.0

Conclusion

The rate of sea-level rise of 2.7 ± 0.05 mm/yr for Durban and its adjacent coastline is consistent with previous worldwide research, clustering in a band between 2.4–3.2 mm/yr. These results are important in that they provide for the first time a locally measured rate of sea-level rise that can be used for strategic coastal planning, coastal management, and in the design of future port infrastructure and marine structures in the region.

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This article is accompanied by supplementary material online at www.sajs.co.za

Supplementary material to:

Mather A.A. (2007). Linear and nonlinear sea-level changes at Durban, South Africa. *S. Afr. J. Sci.* **103**, 509–512.

Fig. A. The location of the tide gauge in Durban harbour. [Source: eThekwini Municipality.]

Paper No: M-04

SEA LEVEL RISE FOR THE EAST COAST OF SOUTHERN AFRICA.

by

A.A Mather[1]

ABSTRACT

Sea level rise remains an ever growing threat to the world's coastal cities and ports. While much research has been undertaken particularly in the Northern hemisphere, the opposite is true of the Southern hemisphere and more particular on the African continent. The likely rates of sea level rise and it's effects along the South African coast has largely been neglected, although some older work was done over two decades ago.To address this gap in information, there is now considerable interest in bringing the region up to date so that this information can be used in planning for and adapting to these issues along the east coast of Southern Africa. The tide record between 1970 and 2003 for Durban, South Africa was analysed to determine the extent of current sea level trends in the light of predicted global sea level rise. Until recently the Durban tidal record length was not of sufficiently length to permit such an evaluation. Durban is ideally suited to test and reflect on global sea level change given its historical land stability. Tide gauge sea levels were barometrically corrected using derived corrections for Durban and then used as the basis of an analysis of Monthly Mean Sea Levels (MMSL) using monthly mean sea levels and Yearly Mean Sea Levels (YMSL) using annual mean sea levels.

Comparisons with the British Oceanographic Data Centre(BODC), the Permanent Service for Mean Sea Level (PSMSL) and the official South African record held by the South African Navy's Hydrographic office (SAN) yields several anomalies. These anomalies are identified and a suggested approach to addressing these is given in this paper. The MMSL calculations yielded a sea level rise of 2.7 ± 0.05 mm per year at a 95% confidence level and the YMSL calculations yielded a sea level rise of 2.4 ± 0.29 mm per year at a 95% confidence level. These results compare favorably with recently published results of global sea level rise calculations over the last 10 years ranging between 1.8 ± 0.3 mm per year and 2.8 ± 0.4 mm per year derived from worldwide tide gauge and TOPEX/Poseidon altimeter measurements. Comparisons with other South East African sea level records yields a range of sea level changes from approximately -3.64 to +3.43 mm per year. These trends are at odds with recent satellite sea level trends which shows that no negative sea level trends are evident. This new work on Durban's sea level rise provides corrections to the various data sets held by the Permanent Service for Mean Sea Level, the British Oceangraphic Data Centre and the South African Navy's Hydrographic Office. It also provides an up to date and valid figure that is able to be used along the east coast of Southern Africa where tide gauge data is suspect or non existant. This will enable the region's planners and engineers to plan for these changes in their work.

1. INTRODUCTION

In order to establish the extent of regional sea level change it was necessary to identify a suitable tide gauge site that was geologically stable, that had a reasonable length of record and one that would be representative of the region. The investigation into the selection of this gauge narrowed the choice down to the coastal city of Durban, which is located at 29º 53´ S and 31º 00´E along the eastern seaboard of South Africa shown in Figure 1.

Figure 1: Map of South Africa.

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1.1 The need for accurate tidal records for analysing sea level changes

The importance of a reliable and complete tidal record is critical for a variety of purposes. Coastal and Port engineers desire a correct record of tide influences in order to provide the proper selection of design criteria for maritime structures and port infrastructure. Coastal managers and planners need a dependable record to define areas that require special zonation and/or special building controls. For example, the demarcation of the High Water Mark, which is now, required in terms of the South African Environmental Impact Assessment Regulations 2006, to help identify potential erosion areas and development set back lines along the coastline.

Coastal policy makers and planners require a tide dataset that can be analysed to provide trends for the extent of sea level change in the region. In the light of concerns about global climate change, tidal records are becoming important indicators in monitoring the impacts of climate change around the world and can provide vital information to researchers in their efforts to assess the rate of change, the likely impacts of these changes and to give valuable input into future predictions (Proshutinsky *et al* 2001). An accurate tidal record is of great importance in this field of work as changes are normally in the order of millimetres per year (Pugh 1987).

1.2 Predicting sea level change from tidal gauge records

Prediction of sea level changes by Douglas (1991) from tide gauges around the world, using a record period of at least 50 years, showed that approximately 50% recorded rising sea levels and 50% showed receding sea levels. The majority of world tide gauges are located in the Northern Hemisphere and global estimates of sea level change are biased by this. Most of the world's tide gauges are located at the edge of continental plates, on river deltas or along coasts that are subject to post glacial rebound. This makes it difficult to isolate the relative sea-level change from other land surface changes, such as settlement although several authors have attempted to do so. Emery and Aubrey (1991) evaluated 587 gauges longer than 10 years from around the world and identified only 36 gauge records as originating from stable coastlines, of which three where from the south-western coast of Southern Africa. However no records of significant length were from the east coast of Southern Africa, even though it may be considered as geologically stable.

1.3 Aims and objectives of this study

This paper aims to establish a regional sea level rise rate for the east coast of Southern Africa, based on the Durban tide gauge, and to compare this with other tide gauge results in the region. The paper describes the analysis and some noteworthy observations of the tidal record for Durban, South Africa.

1.4 Background to this study

The South African Navy's Hydrographic Office records tidal data for all major South African ports including Durban. While the different stations have varing record lengths, the Durban tide gauge has reliable records that exist from 1970 to the end of 2003 when the gauge was decomissioned due to building works in the area (Farre 2006). For Durban, the unprocessed data, in the form of hourly recordings measured in Chart Datum (CD) from a single tidal gauge between 1970 and 2003, has been processed and published by three different organisations, namely the British Oceanographic Data Centre (BODC), the South African Navy's Hydrographic Office (SAN), and the Permanent Service for Mean Sea Level (PSMSL), the latter two data sets being similar but measured against two different datum (Chart Datum and Revised Local Reference (RLR). The BODC publishes tide gauge data received from the University of Hawaii after re-analysis of the original Durban data received from the University of Cape Town. All these organisations make the processed data available for planning and research organisations and it is these data sets which form the basis of the analysis in this paper. All three of the published Durban datasets contain gaps and in some instances have complete years missing. Although the published data sets are drawn from the same unprocessed gauge records, they contain clear differences.

During the course of this analysis the PSMSL revised its data set for Durban on the 7 August 2006 upon advice from the SAN. This new data set will also be exaimined. The objectives of this analysis is to analyse and evaluate the accuracy of the Durban tide record, to correct wherever errors in data have occurred and to produce a corrected and definitive tidal record which can be used with confidence in determining sea level changes along the east coast of South Africa.

2. MATERIALS AND METHODS

2.1 Sea level records

Analysis of a single 35-year dataset with readings taken every hour equates to a considerable amount of data, which needs careful evaluation. The Intergovernmental Oceanographic Commission (2002) provides several methods for analysing such data, which are briefly discussed below.

- ***Simple arithmetic mean values***

This approach is to simply average all the month records to produce a value for that month. This applies only when there are no gaps in the data. If this is applied to data with gaps the incomplete tidal cycles in the record biases the data. This method has limited applicability given the data gaps in the Durban record and is not considered in further analyses.

- ***Modified arithmetic mean values***

Another approach is a modified form of the above, which entails the following steps (Pugh 1987):

(i.) For any day that has incomplete hourly data records, the day's recordings are removed from the data calculations ;

(ii.) For each month (less the days eliminated above), a mean monthly tidal level value is calculated, eliminating the effect of low and high tides.

- ***Low-pass filtered mean values***

In order to eliminate the tidal aliasing inherent in the arithmetic mean value approach, the application of a low-pass filter can be applied which gives a smoothed daily noon value, which can then be averaged out over the month in question. There are several filters available designed for this purpose such as the Doodson filters, which uses 19, 72 and 168 h periods (Doodson and Warburg 1941).

- ***Chosen method of calculation***

Due to the simplicity and ease of application the modified arithmetic method was chosen here. It is important to note that, whereas the approach may seem to be simplistic it has been shown to provide a good correlation with more sophisticated analysis when used to provide weighted mean monthly values to calculate annual values (Pugh 1987).

To quote from Pugh (1987) on the accuracy *"This method is used by many authorities because it requires little mathematical insight, yet produces values close to that obtained by more elaborate tide-elimination techniques (Rossiter, 1958). The maximum contribution, due to aliasing of tidal changes, to a 30-day monthly mean-sea level is 0.055 per cent of the* $\boldsymbol{M_2}$ *amplitude, 0.267 per cent of the* $\boldsymbol{K_1}$ *amplitude, and 0.401 per cent of the* $\boldsymbol{O_1}$ *amplitude. Over a 365-day year the maximum* $\boldsymbol{M_2}$ *error is 0.035 per cent. The* $\boldsymbol{S_2}$ *component will of course average to zero over any period of complete days."*

Where M_2 is the principal semidiurnal lunar tide component, K_1 is the principal solar and lunar declination component, O_1 is the principal lunar declination component and S_2 is the principal semidiurnal solar tide component in the tide harmonic equation.

Recorded tide data is most often measured against a Chart Datum by Marine surveyors, which simply put is where the zero datum (Vertical axis = 0.000m) is equal to the lowest possible tide level, often referred to as the Lowest Astronomical Tide (LAT) which occurs once in every 18,6 years (South African Navy 2006). To correct this to a datum which can be used by Land surveyors it is necessary to correct these tide recordings to the corresponding Land Leveling Datum (LLD). These conversions are calculated and published by the Hydrographic Office of the South African Navy (SAN 2006).

2.2 Barometric pressure corrections

Barometric pressure over the ocean surface affects sea levels and as Pugh (1987) has indicated this varies from the theoretical relationship of -9.9mm/hPa in almost all instances and is dependent on local factors such as the bathymetry, tidal currents, etc. In order to established the respective relationship between sea level and barometric pressure for the Durban tide gauge station, departures from the recorded and predicted sea levels were correlated against barometric pressure reading obtained from the South African Weather Service from its Durban Airport site.

3. RESULTS

The results of the analysis of the different data holdings of each organisation are addressed separately below

3.1 Barometric pressure corrections

The analysis of monthly data gives a relationship of -5.9mm per hPa increase which accords well with the results obtained by Hoar and Wilson (1994) which indicate that Durban at 30ºS would record an IB coefficient in the order of -5.5 to -6.5mm per hPa. The annual relationship yields a relationship of -8.7 mm per hPa increase. This is just short of the theoretical value of -9.9mm per hPa increase but is of an acceptable order to apply as a correction for sea levels.

3.2 South African Navy data

The analysis yields a monthly sea level change record as shown in Figure 2. This yields a normal looking tidal record save for the sudden drop in 1992 and the acceleration to 2003.

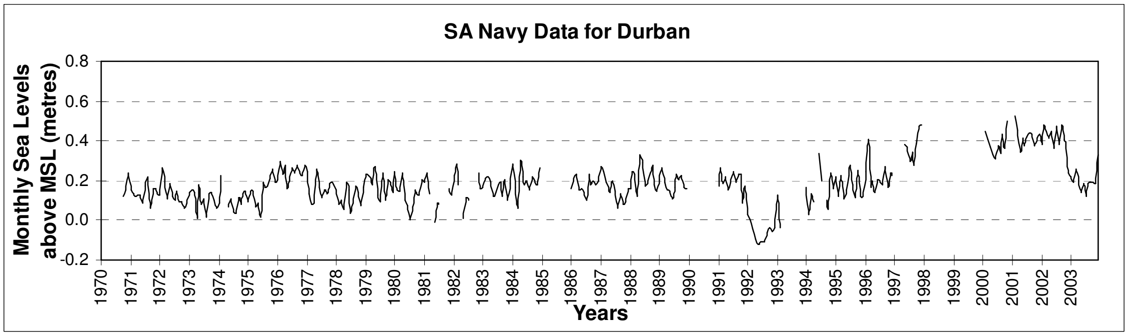


Figure 2: Monthly sea levels above MSL for Durban: South African Navy and PSMSL.

3.3 British Oceanographic Data Centre

Appling the same methodology as outlined for the South African Navy yielded a different curve as shown in Figure 3.

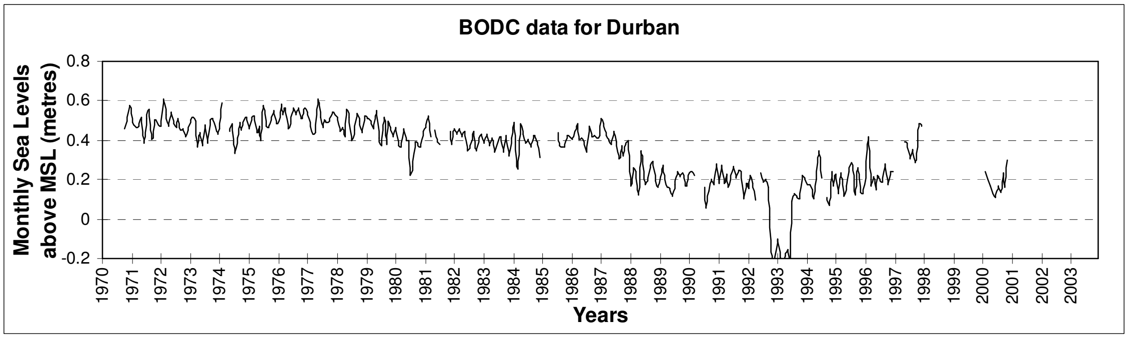


Figure 3: Monthly sea levels above MSL for Durban: British Oceanographic Data Centre.

When these two records are plotted together, it is clear that there are similar periods where data is identical and other areas where there is conflict (Figure 4).

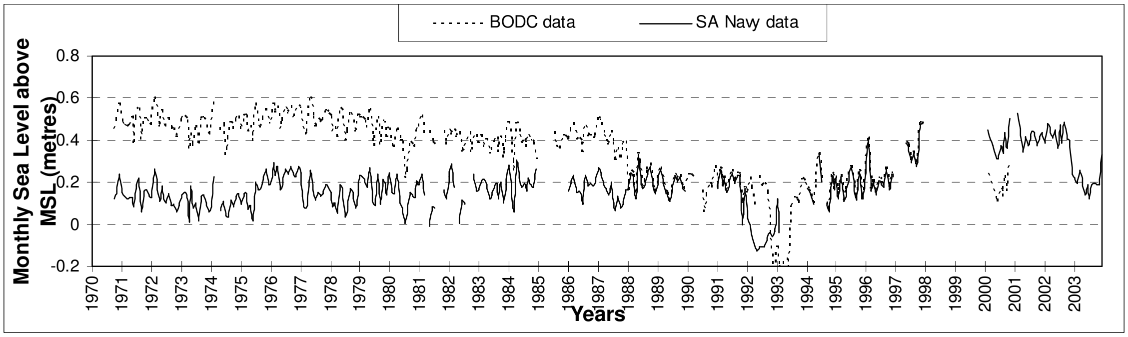


Figure 4: Monthly sea levels above MSL for Durban: BODC and SAN.

After extensive analysis of these two data sets, the following errors emerged from the analysis (Garland and Mather 2007).

- Durban average mean sea level is at +0.2m MSL (Hughes 1992) and any records which deviate substantially from this are incorrect for example the BODC record between 1970 to 1988 and 1992 to 1994.
- The duplication of annual records in two adjoining years due to human error. In the South African Navy record the years 1981 and 1982 were duplicated record for record but have now been rectified once this was brought to the their attention (Farre 2006 pers. comm).
- A datum error of +0.2m in the SAN record between 2000 and 2003 attributed to confusion relating to the different between average sea levels at +0.2m and 0.0m above Land Levelling Datum(LLD). The level of 0.0m LLD for Durban is not equivalent to the average of sea levels, which is at +0.2m LLD. The confusion is understandable as levels recorded in the LLD are commonly referred to as level against "Mean Sea Level".

These corrections are summarised in Table 1 below.

Period	Up to 31 Dec. 1978	1 Jan 1979 to 31 Dec. 1996	1 Jan 1997 to 31 Dec. 1997	1 Jan 1998 to 31 Dec. 2002	1 Jan 2003 onwards
Offset from CD to Leveling Datum (MSL)	-0.838m	-0.900m	-1.100m	-1.313m	-0.913m

Table 1: Revised offsets to convert Chart Datum tide recordings to Land Levelling Datum for Durban (Garland and Mather 2007).

Once these corrections are made, the revised data for Durban can be re-plotted and is shown in Figure 5 below.

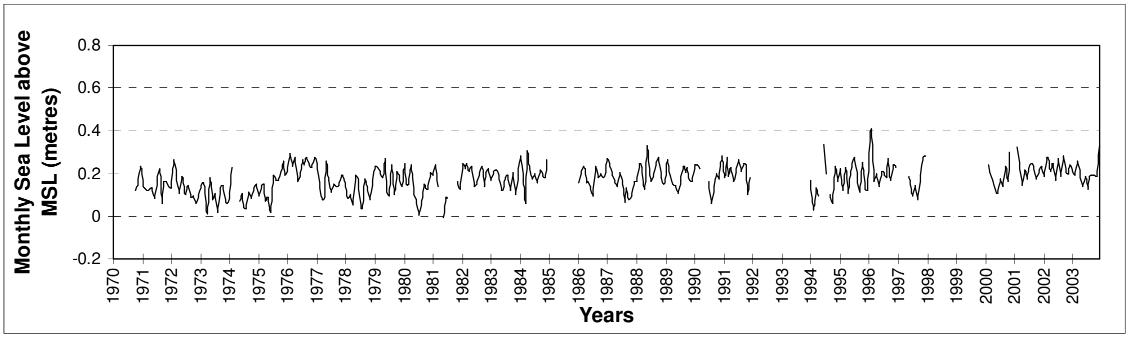


Figure 5: Monthly sea levels above MSL for Durban: Garland and Mather 2007

3.4 Permanent Service for Mean Sea Level

In August 2006, the PSMSL published a revised data set for Durban after receiving revise information from the SAN. This revised Durban data set is shown in Figure 6.

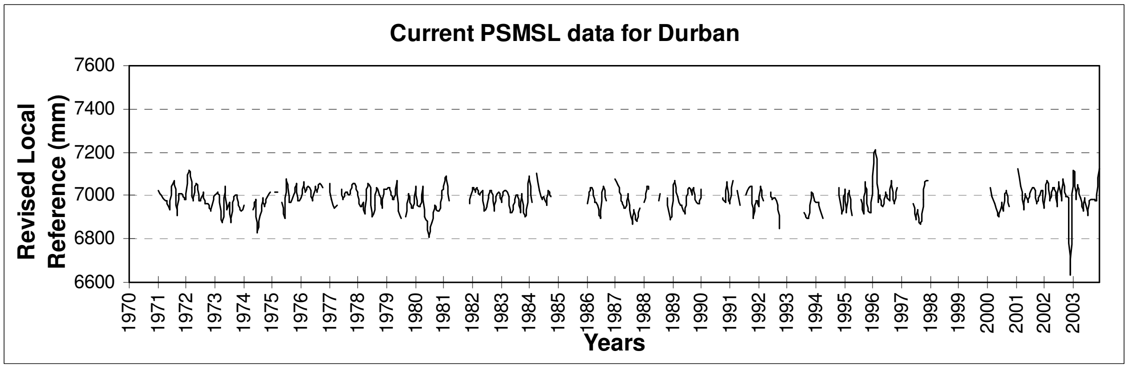


Figure 6: Monthly sea levels above MSL for Durban: PSMSL 2007.

To be able to compare these results directly with Garland and Mather 2007, it was necessary to offsetting the PSMSL results by subtracting 6805mm, effectively converting the PSMSL Revised Local Reference (RLR) data back to the datum used by the SAN for Durban. When the adjusted PSMSL and the data from Garland and Mather 2007 are compared, it is clear that there are differences in the data. The adjusted PSMSL data set confirms the validity of the corrections undertaken by Garland and Mather 2007 as there is now almost perfect match (within 10mm of each dataset) except for the period between 1970 and 1978 as can be seen in Figures 7 and 8. However, the period between 1970 and 1978 it would appears that data over this period has been raised by the PSMSL, when compared with the analysis of Garland and Mather 2007, in its conversion to RLR, by an amount varying between 50 and 70mm (Figure 8). While this is insignificant for naval charting purposes the effect is significant as previously pointed out that the effect of a few millimetres is sufficient to affect sea level rise calculations. What this correction does is to raise the early portion of the tidal record upwards and flatten the sea level curve to such an extent that when a linear regression of the data is undertaken the rate of sea level rise in Durban is effectively zero.

An alternative approach was to determine the sea level trends in the region, in the face of conflicting tide gauge trends, using satellite sea level monitoring for the region. Worldwide data from CLC/LEGOS was obtained and this is shown in Figure 9. What this clearly shows is that over the period 1992 to 2007 sea levels along the east coast of Southern Africa and particularly in Durban were not zero. It does show some variability along the east coast of Southern Africa but generally stays within a narrow band between 2 and 4mm per year.

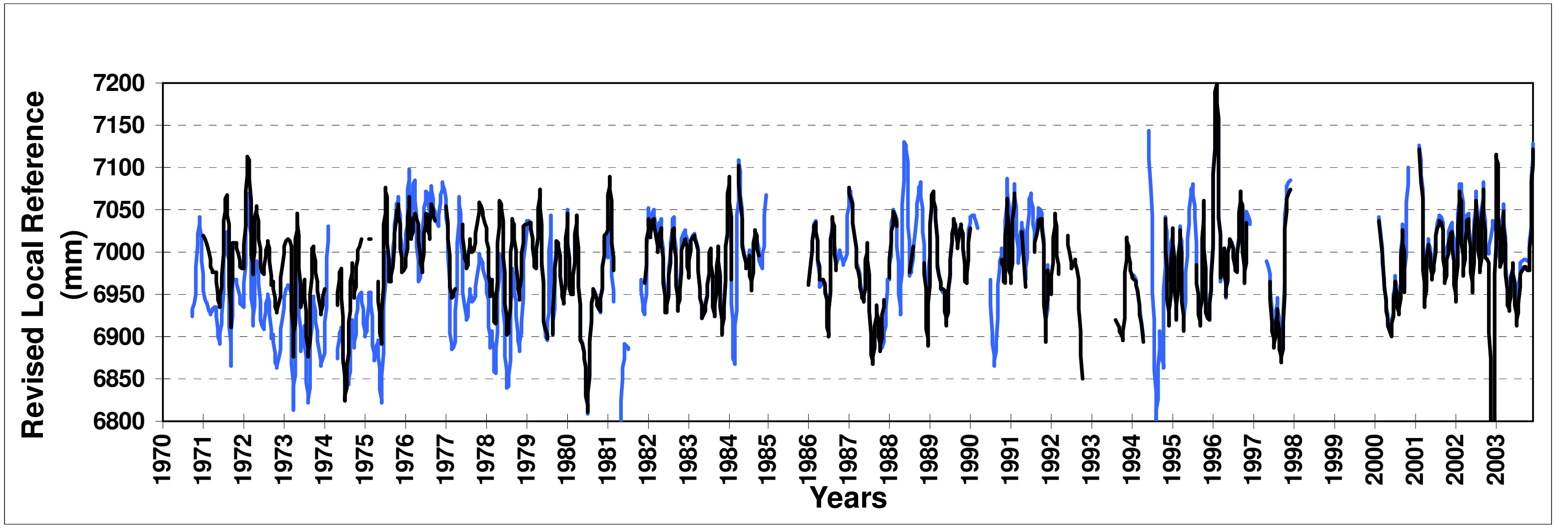


Figure 7: Monthly Sea levels for Durban: Garland and Mather 2007 (shown blue) and PSMSL (shown black).

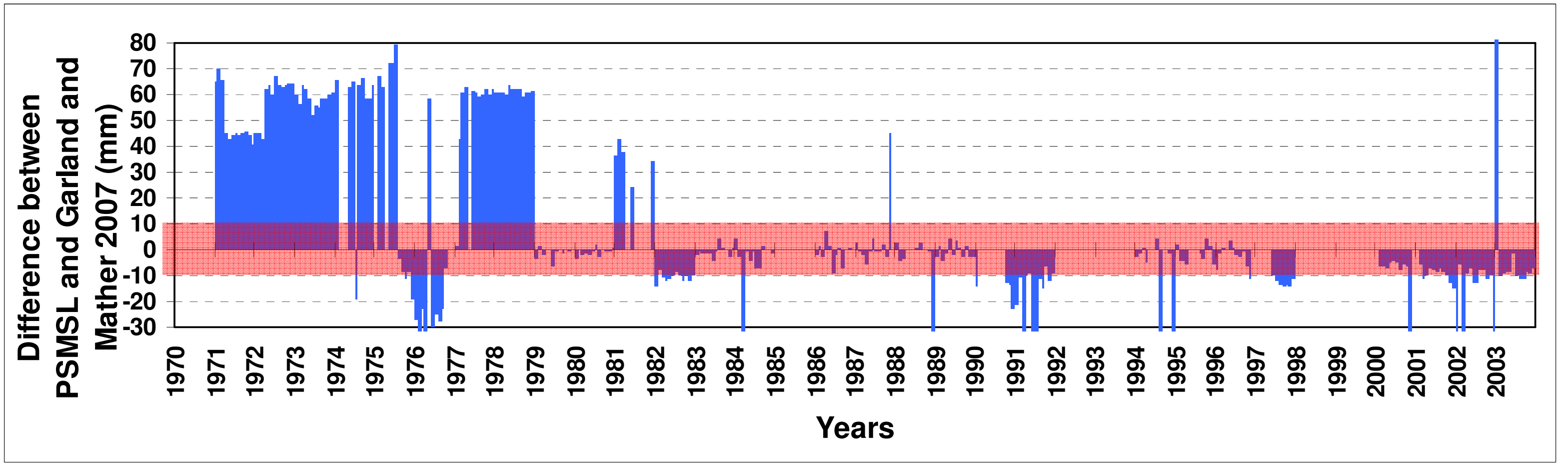
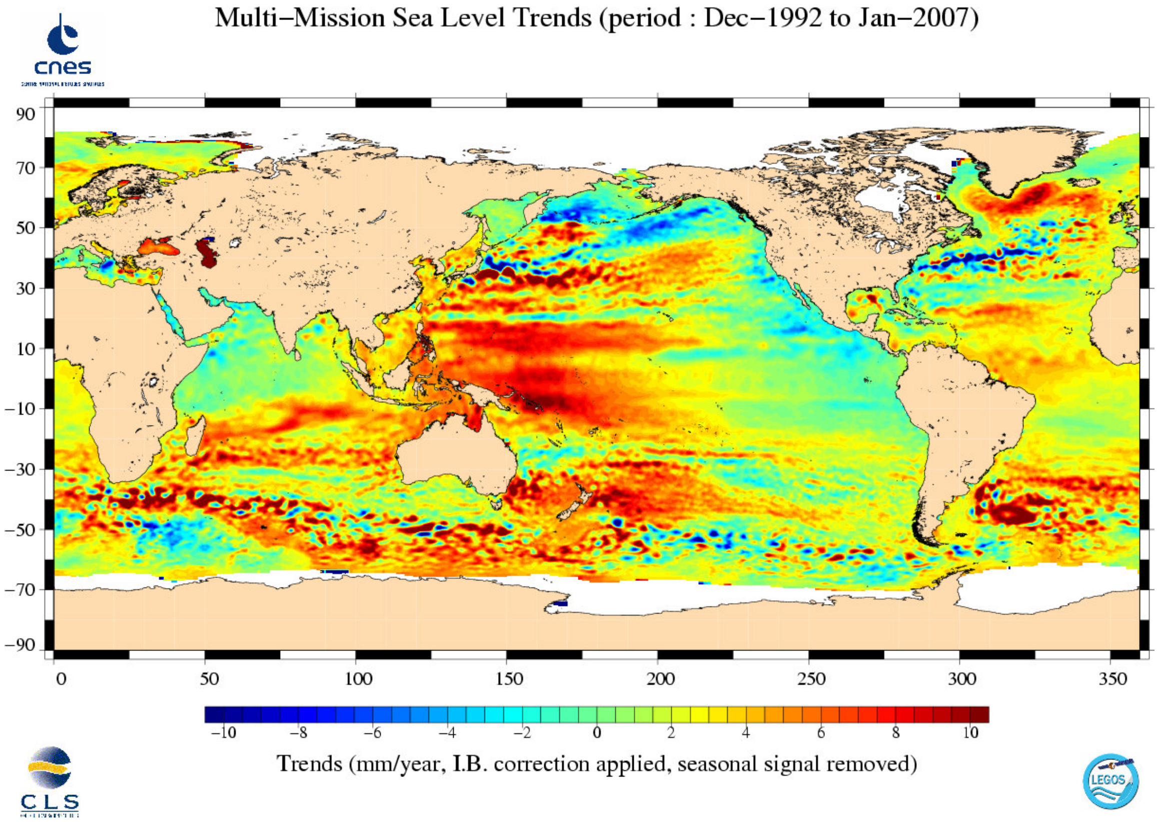


Figure 8: Differences between monthly sea levels for Durban: Garland and Mather 2007 and PSMSL 2006 (+/- 10mm band shown in light red).



Multi–Mission Sea Level Trends (period : Dec–1992 to Jan–2007)

Trends (mm/year, I.B. correction applied, seasonal signal removed)

Figure 9: Multi-mission sea level tends from satellite between Dec 1992 and Jan 2007.

4. DISCUSSION

The analysis of tide gauge data is often a difficult task given that there are a number of external influences, which can and do affect tide gauge sites. While this needs to be borne in mind when undertaking work in this field it is clear that with some careful thought the problems identified with the tide gauge errors can be addressed. This tide data held by the PSMSL appears to be that supplied by the SAN and then re-referenced against a revised local reference. The practise is quite acceptable as it now identifies the data as having been worked on as the revised datum given is around 7000 mm. However when the PSMSL results are compared (after offsetting them by 6805mm) to the corrected results from Garland and Mather 2007 it is clear that, although the majority of the two are within 10mm of each other, there is clearly a section in the early record which has been revised by the PSMSL. Ignoring for the moment the early raised section the PSMSL results are almost a perfect match to those obtained by Garland and Mather 2007. The question of the early section of the record presents an interesting question. The original and current SAN record for 1970 to 1978 has not been revised nor has any official notices been issued as to the accuracy and/or datum correction required to address this period. The PSMSL has however published Durban's revised local reference data for all to use. This is an issue, which will need to be resolved by the authorities concerned so that the same corrected data can be shown on all data holdings.

This result compares favourable to recent sea level results obtained by others as shown in Table 2 below.

Author	**Year of analysis**	**Number of stations**	**Period of time considered**	**Average rate of sea-level rise ± s.d. (mm/year)**
Gutenberg	1941	69	1807-1937	1.1
Polli	1952	110	1871-1940	1.1
Cailleux	1952	76	1885-1951	1.3
Valentin	1952	253	1807-1947	1.1
Lisitzin	1958	6	1807-1943	1.1
Fairbridge & Krebs	1962	unspecified	1860-1960	1.2
Kalinin & Klige	1978	126	1900-1964	1.5
Emery	1980	247	1850-1978	3.0
Gornitz et al.	1981	193	1880-1980	1.2
Barnett	1983	9	1903-1969	1.5
Barnett	1984	152	1881-1980	1.4
Barnett	1984	152	1930-1980	2.3
Pirazzoli	1986	229	1807-1984	indeterminable
Gornitz & Lebedeff	1987	130	1880-1982	0.9 – 1.2
Peltier & Tushingham	1989 and 1991	40	1920-1970	2.4±0.9
Pirazzoli	1989	58	1880-1980	0.52
Stewart	1989	152	1881-1980	indeterminable
Trupin & Wahr	1990	84	1900-1979	1.7±0.13
Douglas	1991	21	1880-1980	1.8±0.1
Emery & Aubrey	1991	517	1807-1986	indeterminable
Nakiboglu & Lambeck	1991			1.2±0.4
Shennan & Woodworth	1992	33	1901-1988	1.0 ± 0.15
Gröger & Plag	1993	854	1807-1992	indeterminable
Gornitz	1995			1.5±0.7
Mitrovitch & Davis	1995			1.4±0.4
Peltier	1996	16	1920-1970	1.94± 0.6
Davis & Mitrovitch	1996	unspecified	unspecified	1.5±0.3
Peltier & Jiang	1997			1.8±0.6
Douglas	1997			1.8±0.1
Viliblic	1997			1.5 to 2.0
Lambeck *et al.*	1998	56	1892-1991	1.1±0.2
Woodworth	1999			1.0
Peltier	2001			1.84 to 1.91
Nerem & Mitchum	2001	Satellite	1993-1998	2.5±1.3
Proshutinsky *et al.*	2001	60	1950-1990	1.8
Lambeck	2002			1.16 &1.65
Johannsson	2002			1.9±0.2
Hunter *et al.*	2003		160 years	1.0±0.3
Church *et al.*	2004	426	1950-2000	1.8±0.3
Cazenave & Nerem	2004	Satellite	1993-2003	2.8±0.4
Church & White	2006	Tide gauges and satellite	1870-2004 1900-2004 1970-2003	1.44 1.7±0.3 2.1
Jevrejeva, S. *et al.*	2006	Tide gauges	1920-1945	2.4±1.0 2.5±1.0
Bindoff *et al.*	2007	Satellite	1993-2003	3.0

Table 2: Results of worldwide sea level rise between 1941 and 2007.

What can be seen in Table 2 is that it is clear that sea level rise rates are on the increase in the 1940/50's a figure of just over 1mm per year was commonplace. The rate has now risen to a figure within the range of between 2.1 and 3.0 mm per year for the last few decades of record. Durban's rate of sea level rise has been calculated at 2.7mm per year which compares well with accepted global sea level rise calculation over similar periods.

The results of sea level change trends from tide records along the east coast of southern africa are rather scattered. Results obtained from the PSMSL (excepting Durban which is based on this paper) yield a scattering of results ranging from -3.64 to +3.43 mm per year (Table 3).

Station	**Country**	**Location**		**Rate of sea level rise mm/year**	**Period of analysis**
East London	South Africa	33º 00′ S	27º 54′ E	0.15	1967-2005
Port Elizabeth	South Africa	33º 58′ S	25º 38′ E	3.43	1978-2005
Durban*	South Africa	29º 53′ S	31º 00′ E	2.70	1970-2003
Maputo	Mozambique	25º 58′ S	32º 34′ E	0.63	1961-2001
Port Louis	Mauritius	20º 09′ S	57º 30′ E	-0.1	1986-2003
Zanzibar	Tanzania	06º 09′ S	39º 39′ E	-3.64	1984-2004
Mombasa	Kenya	04º 04′ S	55º 32′ E	1.10	1986-2001

Table 3: East coast tide gauge trends from the PSMSL (* except Durban).

The difficulty with tide gauges and therefore the evaluation is that they are subject to numerous physical factors and human errors which when looking at small changes in sea level over decades can be significant enough to make any results questionable. It is not in the scope of this paper to provide a comprehensive re-analysis of the other tide gauges shown in Table 3, however it is clear that these results would require further analysis before one could be confident of the actual rate of sea level change. In this case, it can be argued that, as Durban's data has been extensively analysised by the author it would be a resonable assumption to use the result from Durban as a acceptable first estimation of the sea level trends in the region based on the results obtained and plotted in Figure 10 below.

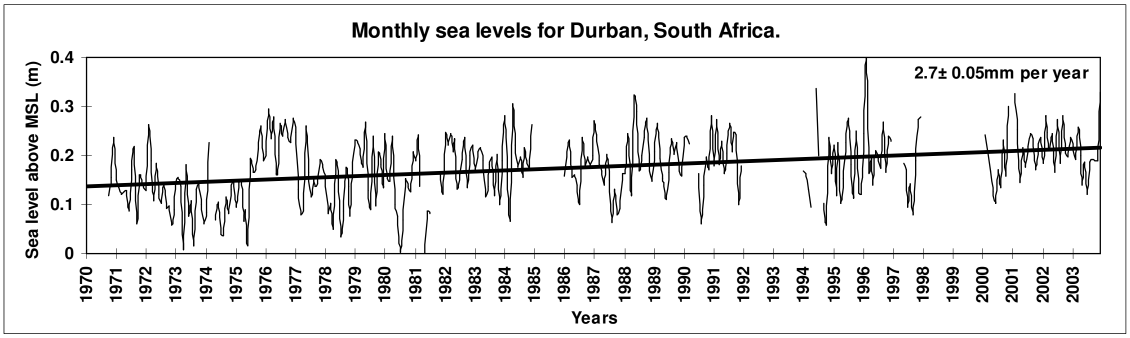


Figure 10: Mean monthly sea level record for Durban.

5. CONCLUSION

The Durban tide gauge data sets held by several authorities' are not in agreement with each other and therefore the results need to be carefully examined before any results can be accepted. The author has proposed a set of correction to the data held by the SAN and has questioned the recent RLR results of the PSMSL. In order to provide a more representative sea level rise trend in the region the author has reworked the available data into what is believed to be an acceptable figure for the region. The corrections given in this paper demonstrate that with careful thought, the data sets can be compared and the anomalies identified and corrected to the extent that the revised results are more representative of current sea level trends in the region. Data authorities need to examine their data holding in light of this paper so that future research can be based on more robust and secure data.

The results of the analysis of the Durban tide gauge yielded a rate of sea level rise of 2.7 ± 0.05 mm per year at a 95% confidence level using monthly mean sea levels and a sea level rise of 2.4 ± 0.29 mm per year at a 95% confidence level using annual mean sea levels. These results are comparable with global sea level rise results for similar lengths of record. The Durban result also compares favourable with recent satellite sea level trend results from the region. This result can be applied to the Ports of Port Elizabeth, East London, Richards Bay, Maputo, Beira, Nacala,Port Louis, Dar es Salam, Zanzibar and Mombasa. The rate of sea level rise of 2.7 ± 0.05 mm per year can be used with confidence as a regional rate of sea level and will provide planners and engineers with a better basis on which future and present port and coastal developments can be planned and evaluated in the region.

6. ACKNOWLEDGEMENTS

The author would like to extend his thanks to the South African Weather Service for access to barometric data for Durban, the South African Navy's Hydrographical Office for the Durban tide gauge data and the Permanent Service for Mean Sea Level rise for the tide data referred to in this paper.

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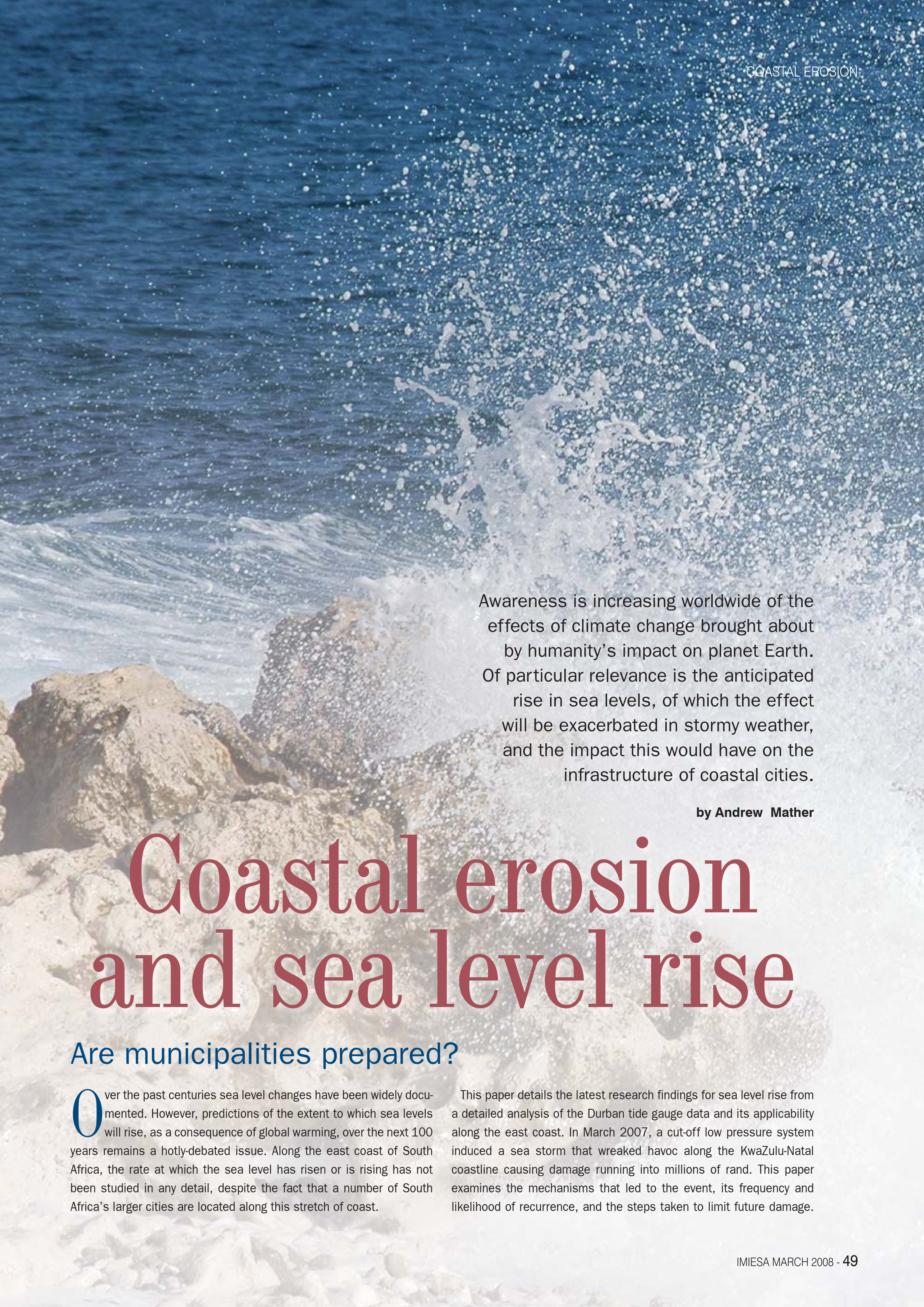


Awareness is increasing worldwide of the effects of climate change brought about by humanity's impact on planet Earth. Of particular relevance is the anticipated rise in sea levels, of which the effect will be exacerbated in stormy weather, and the impact this would have on the infrastructure of coastal cities.

by Andrew Mather

Coastal erosion and sea level rise

Are municipalities prepared?

Over the past centuries sea level changes have been widely documented. However, predictions of the extent to which sea levels will rise, as a consequence of global warming, over the next 100 years remains a hotly-debated issue. Along the east coast of South Africa, the rate at which the sea level has risen or is rising has not been studied in any detail, despite the fact that a number of South Africa's larger cities are located along this stretch of coast.

This paper details the latest research findings for sea level rise from a detailed analysis of the Durban tide gauge data and its applicability along the east coast. In March 2007, a cut-off low pressure system induced a sea storm that wreaked havoc along the KwaZulu-Natal coastline causing damage running into millions of rand. This paper examines the mechanisms that led to the event, its frequency and likelihood of recurrence, and the steps taken to limit future damage.

This paper also discusses the challenges and approaches in coastal management, which were faced by the eThekwini Municipality prior to and after the storm, the current legal framework relating to development within the coastal zone, and concludes with setting out proposed principles that will allow for rebuilt and future coastal infrastructure to be more sustainable than it is at present.

Climate change will impact directly on coastal cities, towns and subsistence communities that have built a lifestyle around the coast, which rely on the sea for income and depend on the sea to provide food for their families. The world's sandy coastline is estimated to be in the region of 170 000km (approximately 34%) with numerous urban settlements dotted along this ribbon of sand (Hardisty 1990). The United Nations (UN) has indicated that more than half of the world's population lives within 60km of a coastline and that this will rise to three quarters by the year 2020 (UN 1993). Urban settlements have expanded rapidly over the last 30 years, particularly in the developing countries (Rakodi and Treloar 1997). Recent work along the KwaZulu-Natal coast has shown that the strip of land 100m inland of the high-water mark (HWM) has been transformed from 28% urbanised in 1994 to 50% in 2006, excluding the Isimangaliso Park (formally the Greater St Lucia Wetlands Park) (Cilliers L pers.comm). This is not surprising, as we know that people are drawn to this rich and unique landscape where the land meets the sea.

> Future coastal infrastructure is to be more sustainable than it is at present

Ports and harbours have long been part of the preferred logistical transport network for nations to trade. The majority of international imports and exports are moved by sea because this method of transport is by far the cheapest compared to road, rail and air. This makes the long-term viability of ports and harbours a key element in the economic survival of many cities into the next century. Port and harbour development is hugely expensive and the developers expect to use this infrastructure for extended periods of up to a century. Durban, along with other coastal ports in SA are planning to expand their capacity (Mather, Redman and Akkiah 2006). Rising sea levels therefore are a potential threat to the viability of ports worldwide and need to be carefully planned with as much information as possible about potential sea level changes. Global foreign tourism direct spend was estimated at US$681.5-billion in 2005, with SA's direct spend accounting for R53.4-billion. A visit to the beach by foreign tourists was ranked as fifth after shopping, nightlife, socialising and visiting natural attractions. For the domestic tourism market, the beaches are the most important tourism attraction, with 73% of all domestic visitors to KwaZulu-Natal visiting the beaches (Tourism KZN 2006). Tourism is closely associated with sandy beaches, which makes up 34% of the world's coastline (Hardisty 1990). The east coast of Africa provides the ideal location for tourism facilities with its sunny climate, sandy beaches and warm Indian Ocean. Rising sea levels will lead to reduced beach widths, damage to tourism infrastructure and arguably, will be the single biggest factor in the shrinkage and/or collapse of the beach tourism industry. Beach and shoreline erosion resulting from rising sea levels will lead to the loss of valuable public and private land and property. Private landowners are often the most negatively affected as many have invested large sums of money

The Cabana Beach Resort in Umhlanga Rocks showing the close proximity of the sea, and under normal conditions

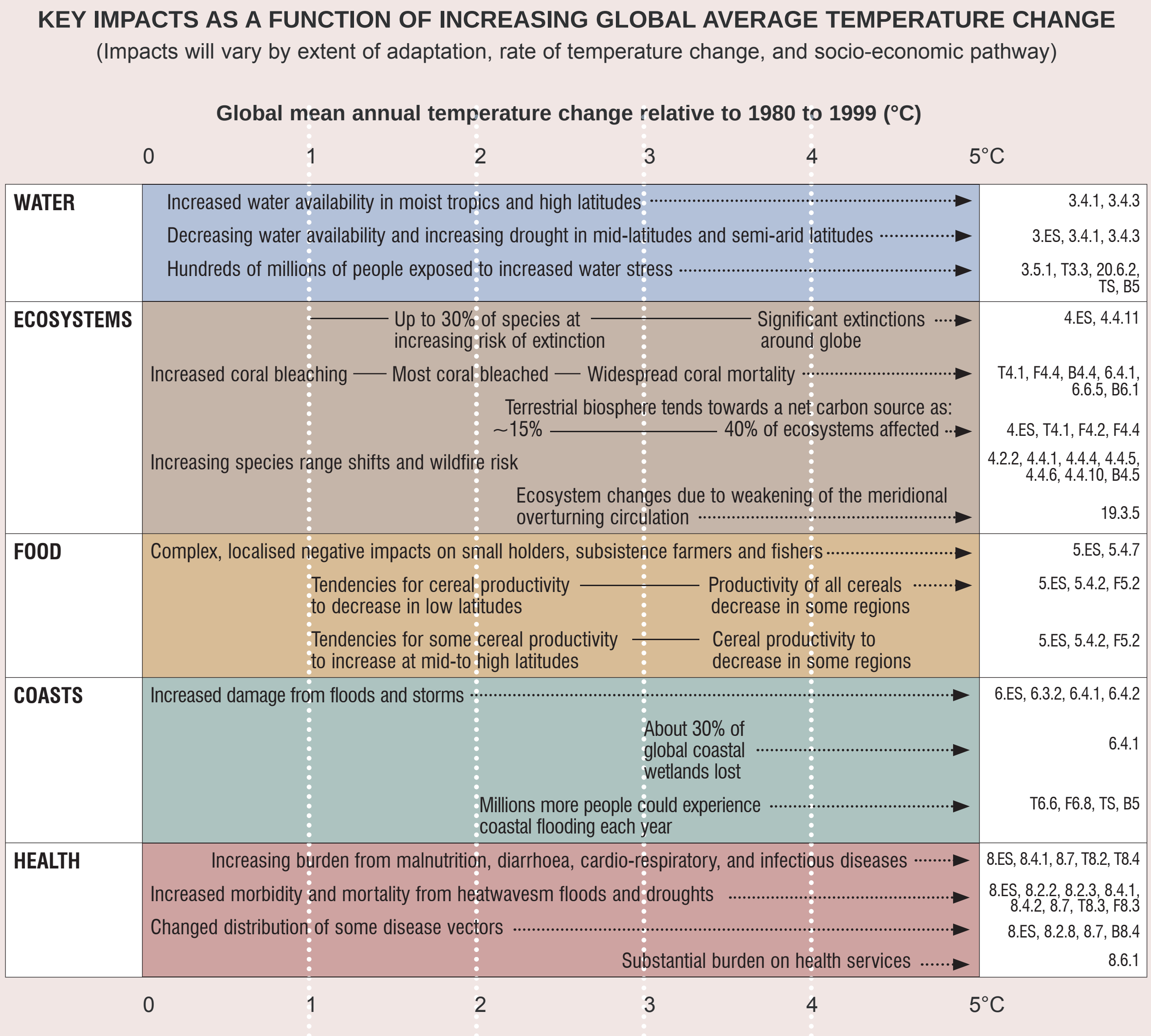
Phorograph courtesy of Zané Möhr

purchasing prime and expensive seaside properties. The options for the affected property owners to protect their properties are limited and difficult in an environment where little is known of the likely quantum and rate of shoreline regression. Where people decide to fortify the shoreline to reduce erosion damage to protect the land and property, the costs associated with this will negatively influence the economy. For local government this may mean less money to spend on developmental issues.

South African local authorities have been restructured in recent years with local government now covering the whole land surface of SA. This has created a situation where local authorities have inherited new areas and increased functions as municipal boundaries have changed. In many cases, this has stretched municipal capacity to the limit. Currently no direct authority is vested in local government for coastal management, although indirectly, many functions of local government directly affect the coast and coastal zone.

Impacts of climate change

Climate change and its likely effects on our environment have become ever-increasing points of discussion among built environment



† Significant is defined here as more than 40%
‡ Based on an average rate of sea level rise of 4.2mm/year from 2000 to 2080

Figure 1: Predicted impacts from different temperature increases (IPCC 2007). Illustrative examples of global impacts projected for climate changes (and sea level and atmospheric carbon dioxide where relevant) associated with different amounts of increase in global average surface temperature in the 21st century (T20.8). The black lines link impacts, dotted arrows indicate impacts continuing with increasing temperature. Entries are placed so that the left-hand side of the text indicates the approximate onset of a given impact. Quantitative entries for water stress and flooding represent the additional impacts of climate change relative to the conditions projected across the range of Special Report on Emissions Scenarios (SRES) scenarios. Adaptation to climate change is not included in these estimations. All entries are from published studies recorded in the chapters of the assessment. Sources are given in the right hand column of the table. Confidence levels for all statements are high.

professionals. This has constantly been in the news, and more particularly, recently when the Intergovernmental Panel on Climate Change (IPCC) released its latest report (IPCC 2007). The panel has identified several factors, which are likely to be areas that will adversely affect the coastlines of the world, as can be seen in Figure 1 opposite:

Sea level rise resulting from thermal expansion and increased storminess of the oceans are two of the key impacts in which we are likely to be exposed.

Sea level rise

One of the impacts of global warming is sea level rise, which is driven by the following factors:

- melting of the polar ice caps and glaciers
- thermal expansion of the oceans
- increased break-up of the Antarctic and Greenland ice sheets.

Global sea level was estimated to be increasing from 1993 to 2003 at a rate of 3.1, approximately 0.7mm per year (Cazenave and Neren 2004). However, the distribution of sea level rise is not going to be uniform over the surface of the oceans (Bindoff et al 2007). It is therefore important that each region identify the extent of sea level rise which is likely to occur locally. To date little work on sea level rise has taken place along the east coast of SA, however, the author has recently examined the tide gauge records in Durban. The results of this investigation yield that sea level rose at a rate of 2.7 from 1970 to 2003, approximately 0.05mm per year (Mather, unpublished data). Projected sea level rise from the work undertaken by the IPCC yields a range of projected increases from 1980 to 1999 and 2090 to 2099 to be in the range of 0.18m to 0.59m (Bindoff et al 2007). The southern oceans have exhibited a weaker rate of sea level rise than the global oceans (Park 2007). Therefore, for planning purposes a figure of 3mm per year should be factored into municipal plans from now onwards, assuming that an A1B scenario is the most probable.

Thermal expansion and increased storminess of the oceans are two of the key impacts

Increased storminess

An increasing frequency of more extreme storms and cyclones is predicted in the coming years because of the mid-latitude westerly winds strengthening since the ’60s. The IPCC considers it likely that future cyclones will be strengthened by increasing tropical sea surface temperatures resulting in more intense events with higher wind speeds and heavier rainfall (IPCC 2007). According to Theron (2007), quoting Hewitson (2006) SA is likely to experience an increase in average wind speed throughout the year caused by stronger, prevailing winds. The effect of just a 10% increase in wind speed on the coastal environment creates an order of magnitude increase of other coastal processes. This 10% increase in wind speed is predicted to result in a 26% increase in wave heights and potentially increasing long shore transport rates between 40% and 100% (Theron 2007). Actual changes will be co-determined by many other factors, including local factors, such as sediment availability and wave transformation, among others. These impacts are likely to affect the shoreline, particularly in areas weakened by previous erosion or low-lying areas relative to sea level such as the Isipingo area in Durban (eThekwini Municipality 2006).

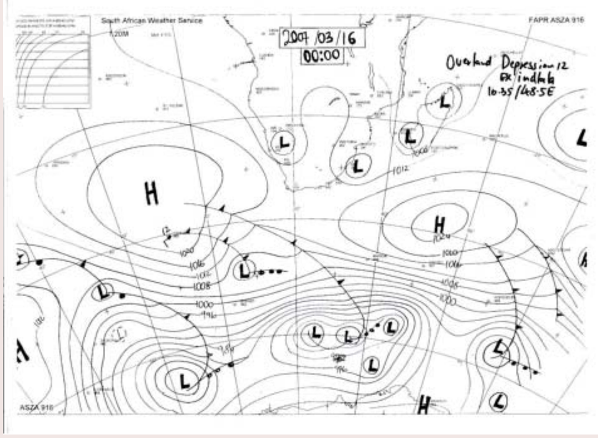


Figure 2a: Synoptic chart for 16 March 2007

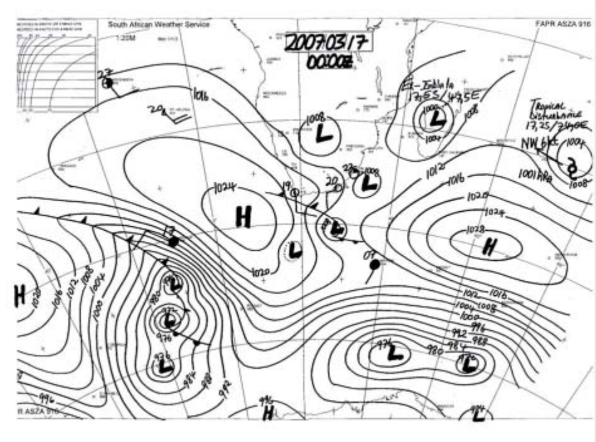


Figure 2b: Synoptic chart for 17 March 2007

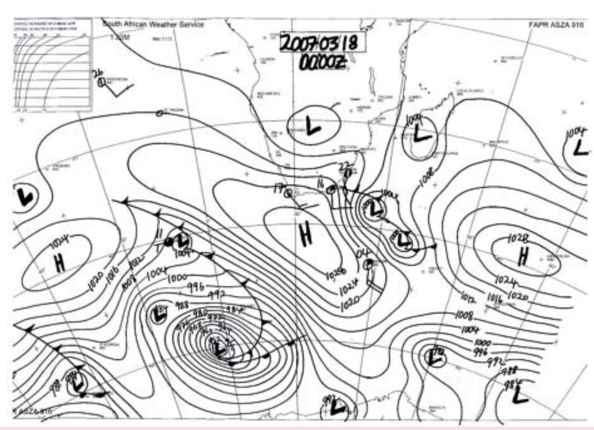


Figure 2c: Synoptic chart for 18 March 2007

The March 2007 coastal erosion event

This extreme wave event, generated by a low pressure system off the coast, occurred at a time when the maximum gravitational forces exerted by the sun and moon were at their 18.6-year peak. This combination resulted in exceptionally high waves on top of a raised sea level, causing widespread damage along the entire KwaZulu-Natal coast on 19 and 20 March 2007. The Saros equinox spring tide had been identified as early as September 2006 as a possible period of vulnerability for the Durban coastline and particularly for properties located north of Durban along Eastmoor Crescent, La Lucia (Mather 2006). However, nobody was prepared for the full impact of this event.

Sea conditions prior to the event had been unseasonable, with an unsettled sea and 2m to 3m swells running. Prior to March 2007 the prevailing sea conditions were influenced by three tropical cyclones (Dora, Favio and Gamede) located east of Durban. Of these, only cyclone Dora and Gamede were significant. Cyclone Dora, which later combined with a well developed cold front to the south, induced swells ranging from 2m to 3m and impacted Durban on 11 to 13 February 2007. Cyclone Gamede arrived several weeks later as this storm tracked westward to Madagascar on 26 February, turned southward on 28 February and eventually stalled in the south Indian Ocean from 1 to 6 March. Despite being downgraded from a cyclone to an extra tropical depression cyclone, Gamede was responsible for the first calls of concern from residents as it generated swells ranging from 2m to 4m on 1 to 5 March. This event caused local inundation and minor erosion along the Golden Mile of Durban (the beachfront strip from the harbour entrance to the Umgeni River mouth), when these swells coincided with the spring high tides on 3 to 4 March. Minor erosion damage was also recorded up and down the KwaZulu-Natal coast.

> The event caused local inundation and minor erosion along the Golden Mile of Durban

The storm of 19 to 20 March 2007

The storm started as a frontal low and passed south along the coast of SA on 16 March 2007 (Figure 2a), which intensified and rapidly developed into a cut-off low south-east of East London on 17 and 18 March (Figure 2b and c). From the dense isohyets around this low, it can clearly be seen to intensify to a peak on 19 March (Figure 2d), where it remained trapped between two high pressure cells until 20 March. The system started to weaken by midday on 19 March (Figure 2e) and was almost back to normal by 20 March (Figure 2f).

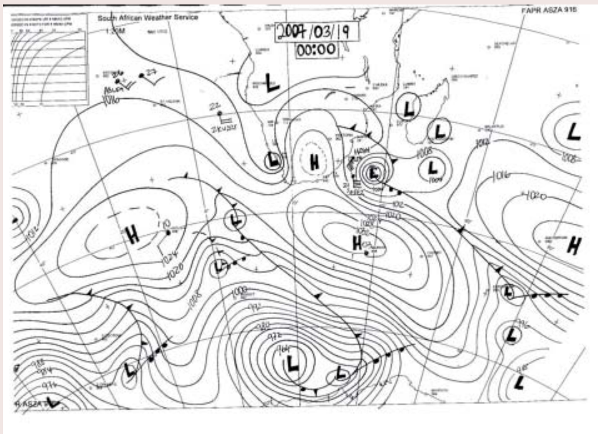


Figure 2d: Synoptic chart for 19 March 2007

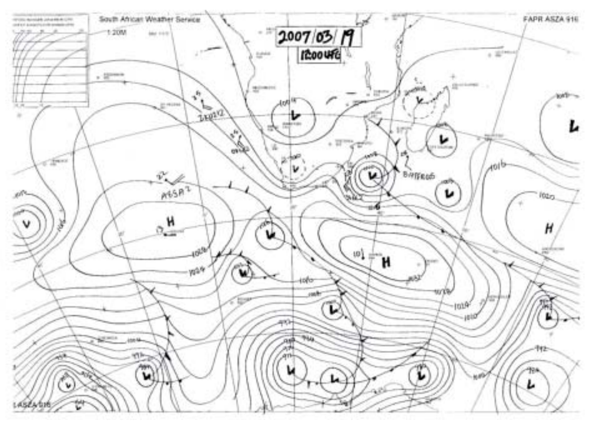


Figure 2e: Synoptic chart for 12h00 19 March 2007

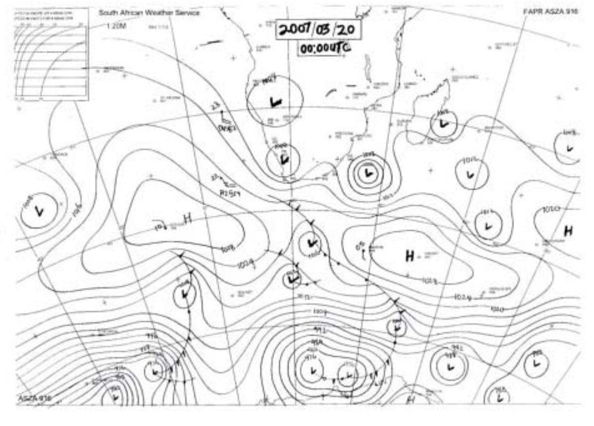


Figure 2f: Synoptic chart for 20 March 2007
Synoptic charts courtesy of the South African Weather Service

The central pressure of this low pressure cell dropped to below 996hPa. The strong pressure gradient between the low and high cells generated strong and consistent winds that were recorded between 40 knots ($21m^2$) and 45 knots (23m2) along the coast. As the system was trapped in position this allowed the wind to generate some impressive waves over a fetch length of approximately 450km that headed straight for the coastline of KwaZulu-Natal. The Acoustic Doppler Current Profiler that is normally used to record wave heights in Durban was out of commission during this event. Recorded wave heights for the event are therefore confined to the CSIR wave-rider buoy that is located off Richards Bay in 30m of water depth. This recorded a significant wave height (Hmo), defined as the average of the top third waves recorded, of 8.5m, with a period 16 seconds from the south-east to south-south-east, measured at the peak of the storm at 05:00 on 19 March (Rossouw M pers comm). The maximum wave height was recorded at 14m (Rossouw M pers comm). At the same time, the Highest Astronomical Tide (HAT) occurred which happens only once every 18.6 years. This would have elevated water levels by approximately 20cm, more than the normal spring tide levels and when synchronised with the wave event, magnified this combination for the worse. Fortunately, the wave event very quickly dissipated

Figure 3: Santorini complex showing infilling and exposed sea protection works

Phorograph courtesy of S Bundy

and by the evening of the 20 March, the swells had reduced to less then 3m.

The probability of reoccurrence

The debate regarding the return period of this event continues. Although the direction of the storm corresponded to the general wave direction, the data is not considered sufficient for an accurate statistical extreme analysis to determine the return period of this event. However, a first estimate of the return period indicates that it could be in the order of one in 35 years (Rossouw M pers comm). Furthermore, taking a simple approach of combining the different return periods of approximately one in 35 years and spring high tide levels of one in 19 years, yielding a combined probability of one in 600 years. If we look at similar previous extreme events then cyclone Imboa on 18 Feb 1984 with an Hmo of 8m to 9m would qualify. So would the low pressure system off East London on 13 June 1997 with an Hmo of 9.3m.

Figure 4: Erosion at Umkomaas

Phorograph courtesy of A Mather

This starts to indicate that this type of extreme event is more likely to occur every ten to 12 years along the east coast. Observations on site reveal a similar picture. Erosion of the beaches exposed previously constructed sea protection works in several locations. The example in Figure 3 below is that of the Santorini complex north of Ballito, which on closer examination shows previous protection works.

The lower portion of the Santorini complex was constructed in about 1990 (Bundy S. pers comm.) and therefore is not older than 17 years. It is clear that this magnitude of erosion has occurred before and fairly recently. The only conclusion we can make is that this type and scale of event is likely to be more frequent than we think, particularly in the light of climate change.

The aftermath

For many municipalities the scenes which presented themselves after the storm event were shocking and infrastructure that had weathered

Figure 5: Erosion along the base of The Bluff (Photo: A Mather)

Phorograph courtesy of A Mather

previous storms were destroyed. Senior staff kept on saying that they had never before experienced this scale of devastation. Resources were quickly reallocated to evaluate the damage and to identify emergency work, which needed to be implemented immediately. The initial focus was to identify those situations where an emergency existed that could be corrected by implementation of measures under Section 30 of the National Environment Management Act (NEMA 2006). An emergency in this instance was defined as actions to protect lives and property, and reduce risks to the environment, for example, a washed away sewer pump station is discharging effluent to the marine environment.

> The coast must be retained as a national asset, with public rights to access

The cost of repairs to municipal infrastructure along the coastline of KwaZulu-Natal was initially estimated to be in the order of R150-million. However, this figure is rising as prices are received from contractors and could reach R400-million.

Municipal readiness and response to the event

Each municipality drew up lists of damaged infrastructure and started looking at costs and potential funding. Some municipalities were prepared to rearrange their own budgets to get the damage repaired but others were not willing or able to do this and appealed to National Government to declare it a disaster area, thereby hoping to free up national funds to undertake rehabilitation work. By the middle of June 2007 no disaster declaration had occurred and as a result no money has been forthcoming from government. Most municipalities have undertaken some work constrained by their existing budgets and some have been able to undertake a majority of the work.

For example, the beaches of Ballito within the Kwadukuza Municipality are still in a state which precludes them from opening. Apart from the obvious erosion of the shoreline and loss of public infrastructure, the amount of debris washed into the sea and now situated below the water surface is a major cause for concern. Despite extensive diving in waters within the area, some of the beaches remain closed for these reasons. At the start of June 2007, seven of Ballito's 17 beaches were reopened to the public. By 20 June this increased to nine, with officials being unsure of when the other beaches would be reopened. eThekwini Municipality's beaches were opened fairly soon after the event, however, several of the Blue Flag beaches have not been able to fly the flag due to these beaches not meeting the international Blue Flag criteria in all respects.

Current and future legal framework for coastal management

Sea Shore Act of 1935

This act was specifically enacted to declare the state president to be the owner of the seashore and the sea, to provide for the granting of rights in respect of this land and to deal with alienation of this land. It is currently the oldest piece of environmental legislation in the stature books. The act is not aligned to the issues of coastal management in the 21st century, is due to be repealed soon, and therefore will not be discussed in any more detail.

White Paper on sustainable coastal management (2000)

The White Paper on sustainable coastal management was in a sense ground-breaking in that for the first time extensive public consultation on a scale not seen to date, crafted a coherent, comprehensive and forward-thinking policy framework for coastal management in SA. The principles underpinning the policy are very powerful and embody the essence of this policy. These are:

- National asset – the coast must be retained as a national asset, with public rights to access and benefit from the many opportunities provided by coastal resources.
- Economic development – coastal economic development opportunities must be optimised to meet the needs of society and to promote the well-being of coastal communities.
- Social equity – coastal management efforts must ensure that all people, including future generations, enjoy the rights of human dignity, equality and freedom.
- Ecological integrity – the diversity, health and productivity of coastal ecosystems must be maintained and rehabilitated when appropriate.
- Holism – the coastal zone must be treated as a distinctive and indivisible system, recognising the inter-relationships between coastal users and ecosystems, and between the land, sea and air.

Figure 6: Erosion in Ballito (Photo: A Mather)

Phorograph courtesy of A Mather

- Risk aversion and precaution – coastal management efforts must adopt a risk-averse and precautionary approach under conditions of uncertainty.
- Accountability and responsibility – coastal management is a shared responsibility. Everyone must be held responsible for the consequences of their actions, including financial responsibility for negative impacts.
- Duty of care – all people and organisations must act with care to avoid negative impacts on the coastal environment and resources.

The only shortfall of this policy is that the principles are very broad and open to different interpretation. The aim was to use this as a basis for new coastal management legislation, namely the Integrated Coastal Management Bill that will be discussed shortly.

Environmental impact assessment regulations

These regulations were published in 2006 and include activities that were identified in terms of the National Environment Management Act (NEMA 1998) which requires environmental approval before an activity can commence. Some of the relevant activities relating to the coastal zone are construction or earth-moving activities in the sea or within 100m of the HWM in respect of facilities for the storage of materials and the maintenance of vessels, fixed or floating jetties and slipways, tidal pools, embankments, stabilising walls, buildings and infrastructure.

The prevention of the free movement of sand, including erosion and accretion by means of planting vegetation, and by placing synthetic material on dunes and exposed sand surfaces within a distance of 100m above the HWM. The damage or removal of indigenous vegetation that is more than $10m^2$ within a distance of 100m inland of the HWM. The excavating, moving, removal, depositing or compacting of soil, sand, rock or rubble covering an area exceeding $10m^2$ in the sea or within a distance of 100m inland of the HWM. Construction of earth-moving activities in the sea or within 100m inland of the HWM, including the construction of earth-moving activities associated with the following:

- facilities associated with the arrival and departure of vessels and the handling of cargo
- piers
- inter- and sub-tidal structures for entrapment of sand
- break-water structures
- rock revetments and other stabilising structures
- coastal marinas
- coastal harbours
- structures for draining
- underwater channels.

The legislation also provides for an application of responses relating to emergencies. Typically, these are issues, such as chemical spills which require the immediate intervention of the parties concerned to reduce negative impacts to the environment. This is commonly referred to as a Section 30 application and is subject to the retrospective approval of the Department of Agriculture and Environmental Affairs (DAEA).

The integrated coastal management bill

Some six years after the finalisation of the White Paper on sustainable coastal management, the public got to see the Integrated Coastal Management Bill (DEAT 2006). The bill focuses on regulating human activity within the coastal zone, which is defined in a new way and is divided into the following areas:

- Coastal access land – land specifically set aside for the public to access the coastline and coastal public property.
- Coastal public property – common property owned by the people of SA.
- Coastal buffer zone – the area directly inland of the coastal public property, which is comprised of privately-owned land, 100m wide in the case of urban areas and 1000m wide in the case of rural areas.

It is premature to discuss this in length, save to say that the coastal buffer zone will be the new battlefield of the future and it is therefore critical that the new act and subsequent regulations make it easier for both public and private landowners to understand their obligations and rights.

Principles of sustainable coastal management and restoration

Within the current legal framework of coastal management and arising from this storm event, it became clear that the situation along our coastline was changing and that something was needed to provide the bridge between the different sets of legislation. In formulating a strategy to address the repairs of the damaged infrastructure, a set of local principles was developed by the Tidal Wave Damage Professional

Team at Kwadukuza Municipality on which the author is an advisor (Kwadukuza Municipality, unpublished data). These principles were developed to provide the level of detail not only to the municipality but to the numerous landowners who were seeking direction. These local principles interpret the principles from the White Paper on sustainable coastal management (DEAT 2000) and provide the thread from policy to implementation. These principles are:

1. Low gradient sandy coastlines are the most vulnerable to erosion

While the coastline of KwaZulu-Natal is dominated by sandy shorelines, there are sections of shorelines that can be classified as rocky. These rocky shorelines experienced some minor erosion but emerged unscathed from this erosion event. However, sandy coastlines, particularly those with low gradient coastlines, were severely affected. Because of this severe erosion, it is likely that the coastline will take many years to return to its former condition. The low gradient sandy shorelines will need to be carefully dealt with given their propensity to retreat by up to 40m in width under storm conditions.

2. Managed coastal retreat

Current international best practice in the face of sea level rise is a managed coastal retreat. Managed coastal retreat will combat the increasing risk of coastal erosion and damage because of sea level rise. The removal of structures and movement back inland providing a larger space for the fluctuation of the shoreline to occur will reduce the risk of infrastructural damage and will ultimately prevent regular repeated loss of this infrastructure, thus underpinning the concept of sustainability. Shoreline Management Plans (SMP) provides a framework in which different approaches (do nothing, hold the existing line, advance the existing line or retreat) can be considered for each section of coastline. A retreat strategy for most of the coastline is the most sustainable option. However, there are sections of coastline which have been built up and form part of the municipalities economic and tourism assets, and these will need careful evaluation of the pros and cons of not retreating.

3. Sand has been lost, so sand should be replaced

The storm has removed beach sand, and therefore, the best replacement material is beach sand, provided the size grading is of the correct order. This might sound obvious but evidence has shown that many people dumped various types of material on the eroded beach with little knowledge of the effects of these actions, while trying to protect their properties.

Two examples of inappropriate replacement materials are Berea Red sand and builder’s rubble. Berea Red sand consists of ancient marine deposits, which have accumulated inland, and along the Berea ridge in Durban approximately one to two million years before present (BP). Berea sand is coated with ferric gels such as goethite and limonite with 5% to 8% clay aggregates pasted in the interstices (Francis, pers comm) which gives this sand its distinctive colour. The median grain size (d50) of typical beach sand along the open KwaZulu-Natal coastline is 0.350mm (Mather, unpublished data). Normally, Berea Red sand is finer than the current beach sand with a d50 of 0.250mm and erodes rapidly if placed onto the beach and into the near shore zones of the high wave energy coastline of KwaZulu-Natal.

Builder's rubble is equally problematic for different reasons, apart from being unnatural in the marine environment and if eroded from its placement, becomes distributed along the beach. This change from what was a natural sandy beach to a beach covered in half bricks and pieces of concrete creates a potential liability for walkers and swimmers, and can result in the damage of launching craft. The rubble will lie dormant in the sand matrix, only to be exposed repeatedly during periods of erosion, often giving the impression of additional dumping in the beach zone.

4. Soft coastal systems need 'soft engineering' solutions

Onshore

The optimum erosion buffer is a natural dune cordon system. These should be established wherever additional protection is required. Property owners should be encouraged to re-establish and rehabilitate the dune systems between their properties and the sea. Where replication of the natural dune cordon is problematic, the use of soft-engineered, artificially vegetated dunes can be considered. Replaced sand can be stored within geo-fabric bags angled back up the erosion slope preventing further sand loss at the toe of the dunes and allowing some wave run-up over the sloping structure, thereby reducing the wave energy.

> Beach renourishment offshore involves dredging sediment offshore and distributing it along the shoreline

Offshore

Offshore protection measures can also be considered but by their very nature, are generally more expensive to undertake. An example is beach renourishment that involves dredging sediment offshore and distributing it along the shoreline. This has been widely used in the United States to address eroding beaches. A further approach is the construction of offshore structures such as artificial reefs, which act to break up wave energy before it hits the shoreline, effectively reducing the erosive power of the waves in moving sediment in the cross-shore and longshore directions. These interventions need to be carefully researched by experts, as these structures can be highly problematic and can cause unexpected local and down-drift effects. In practise, a combination of these measures should be considered.

5. Hard engineering should only be employed as a last resort

'Hard' engineering should only be employed as a last resort, as this causes local erosion and down-drift erosion. Hard engineering in this case is defined as any structure that is constructed from hard materials not likely to be commonly found in the beach zone. Examples of this are concrete sea walls, steel trench sheeting and contiguous augered pile walls. Hard vertical barriers are the worst performers in terms of reducing wave energy at the interface. The high energy wave comes into full contact with the vertical face and reflects back into oncoming waves creating turbulence, which caused a loss of sediment at the toe of the sea wall. While the structure can be designed to withstand this, the effects are that the loss of sand at the toe is not replaced as easily as a similar stretch of beach without a sea wall. This leads to a sand-starved environment locally, preventing the full recovery of the beach and its associated sand dunes because the material is usually transported offshore or down-drift and is not recovered.

> Private property owners should maintain any defence system they establish

6. Interventions are coordinated

The local authority should not undertake to provide any sea defence system for private property owners. However, the local authority has a duty of care to ensure that whatever is proposed is sustainable and that each property owner is not left to his/her own devices to construct a patchwork of different protection systems. Local authorities should encourage a coordinated or cooperative approach by affected property owners. Private property owners should remain obliged to maintain any defence system they establish. They should also be held liable for any failure, particularly where such failure may affect other properties or people.

Results

Because of the criticisms received from businesses and the public regarding a lack of urgency by the public sector in responding to this disaster, the author undertook a survey of municipal officials, provincial officials, NGOs, ratepayer bodies and consultants involved in coastal management in KwaZulu-Natal. Of the 92 questionnaires that were e-mailed out, only 28 were returned. Three additional unsolicited questionnaires were received, making up a total sample of 31 (34%). The 31 returns were distributed as follows: ten from municipalities (eight from eThekwini Municipality), three from the KZN Provincial Department and 18 from NGOs/consultants. The number of returns from the eThekwini Municipality biased the municipal group. Therefore, this may not reflect the views of all the municipalities. The results are shown in tables 1, 2 and 3.

TABLE 1: RESULTS OF QUESTIONNAIRE FROM MUNICIPALITIES

QUESTIONS	YES	NO	DON'T KNOW
Within your municipal IDP is there a specific work programme to address climate change and particularly sea level rise and coastal erosion?	50%	40%	10%
Do you think your municipality understands the likely impacts of sea-level rise and increased storm activity on your coastline?	70%	30%	
Does your municipality have dedicated resources for coastal management?	100%*		
If not, do you think it should have?			
Does your municipality have plans to address the impacts of sea level rise and coastal erosion?	60%	20%	20%
Have you heard of Shoreline Management Plans (SMPs)?	70%	30%	
If yes, is your municipality implementing SMPs?	50%	13%	37%
Have you heard of Coastal Management Plans (CMPs)?	100%		
If yes, is your municipality implementing CMPs?	80%	10%	10%
After the March 2007 coastal erosion event do you think your municipality was able to manage the reconstruction afterwards?	75%		25%
Do you think your municipality now has a better understanding of what to plan for in the future?	60%	20%	20%

** eThekwini Municipality's response*

Some key findings of the study included the following:

- A total of 88% of the NGOs and 67% of the provincial group responded that the majority of municipalities did not have a climate change programme in their respective IDP.
- When asked if municipalities understood the effects of coastal erosion and sea level rise on their coastline, 87% of the municipal group responded positively, in sharp contrast to 88% of the NGOs responding negatively.
- A total of 100% of the respondents thought that municipalities should have dedicated coastal management capacity, given the demands that the new legislation is likely to bring.
- In planning to address the impacts of coastal erosion and sea level rise, the municipal group responded positively with 60% and 22% unaware of these plans. Of the provincial group, 67% of the respondents thought that the majority of municipalities already had plans, in contrast to the NGO group in which 88% of respondents said that the majority of municipalities did not.
- SMPs are not well understood with 70% for municipal, 67% for provincial and 47% for NGOs and consultants.
- All groups, 100% for municipal and provincial, and 83% for NGOs and consultants had a better understanding of CMPs.

TABLE 2: RESULTS OF QUESTIONNAIRE FROM PROVINCIAL OFFICIALS

QUESTIONS	MAJORITY YES	MAJORITY NO	DON'T KNOW
Within municipal IDP are there specific work programmes to address climate change and particularly sea level rise and coastal erosion?	33%	67%	
Do you think municipalities understand the likely impacts of sea-level rise and increased storm activity on your coastline?	67%	33%	
Do municipalities have dedicated resources for coastal management?		100%	
If not, do you think they should have?	100%		
Do municipalities have plans to address the impacts of sea level rise and coastal erosion?	67%	33%	
Have you heard of SMPs?	67%	33%	
If yes, are municipalities implementing SMPs?		100%	
Have you heard of CMPs?	100%		
If yes, are municipalities implementing CMPs?	67%	33%	
After the March 2007 coastal erosion event do you think municipalities were able to manage the reconstruction afterwards?	33%	67%	
Do you think municipalities now have a better understanding of what to plan for in the future?	67%		33%

TABLE 3: RESULTS OF QUESTIONNAIRE FROM NGOs AND CONSULTANTS

QUESTIONS	MAJORITY YES	MAJORITY NO	DON'T KNOW
Within municipal IDP are there specific work programmes to address climate change and particularly sea level rise and coastal erosion?		88%	12%
Do you think municipalities understand the likely impacts of sea-level rise and increased storm activity on your coastline?	6%	88%	6%
Do municipalities have dedicated resources for coastal management?	24%	59%	17%
If not, do you think they should have?	100%		
Do municipalities have plans to address the impacts of sea level rise and coastal erosion?		88%	12%
Have you heard of SMPs?	47%	47%	6%
If yes, are municipalities implementing SMPs?		55%	45%
Have you heard of CMPs?	83%	17%	
If yes, are municipalities implementing CMPs?	20%	53%	17%
After the March 2007 coastal erosion event do you think municipalities were able to manage the reconstruction afterwards?	6%	76%	18%
Do you think municipalities now have a better understanding of what to plan for in the future?	59%	35%	6%

- The municipal group with 75% of the respondents feeling that they had successfully managed the disaster and reconstruction afterwards. A total of 33% of provincial officials responded that they felt that municipalities had handled the situation satisfactory, in sharp contrast to the perception of the NGOs at 6%.
- When asked if respondents felt that municipalities now had a better understanding of what to plan for in the future, the municipality group responded with 60% positive. A total of 67% of the provincial group thought that municipalities had a better understanding, while 59% of NGO respondents thought so too.

Discussion

Climate change is unquestionably happening in our region and this change places great demands on all of us. Governments are at the forefront of adaptation and mitigation strategies, and in the interest of the country will need to deliver the goods. To make a meaningful impact it is incumbent on all levels of government to play their part in the actions required to address these impacts. The public is looking to government and demanding that it initiates a programme to address the impacts of climate change and of relevance for this paper are the effects of coastal erosion and sea level rise. The coastal erosion, which occurred in March 2007, has only heightened this issue among stakeholders. The magnitude of this event was significant in that it affected many hundreds of kilometres of the KwaZulu-Natal coastline. The experts may debate the frequency of this event for some time but as Theron (2007) has highlighted, this scale of storm is most probably going to become a more regular event in the future.

The amount of sand that was lost off the visible beach is difficult to quantify. However, based on surveyed cross-sections taken before and after the event along the coastline of eThekwini Municipality (approximately 100km), almost 4 million m^3 of sand was eroded (Mather, unpublished data). Compare this with the net rate of 460 000m^3 per year for longshore sediment transport in Durban (Mather et al 2003), and one can start to appreciate the enormous power of the storm. Simplistically, this equates to about nine years of sediment supply moving off the beach into the near-shore zone where it formed an offshore bar. Fortunately, some of this sand is now returning to the beach but the sea is unlikely to return the original volume as some of this would have moved into deeper water where it will not be reworked into the beach zone by normal wave conditions. The beaches will therefore remain in this depleted state for some time until new sediment from the river systems is introduced.

The protracted change in coastal legislation from the Sea Shores Act of 1935 to a proposed Integrated Coastal Management Act, has resulted in the coastline being indirectly managed through other environmental legislation in a less than optimal way. In the absence of a new act, which was one of the key conclusions of the White Paper on sustainable coastal management, the other environmental legislation is the only means of regulating activities in the coastal zone. For example, the NEMA regulations that require activities within 100m of the HWM to undergo a scoping assessment were taken from an earlier draft of the Integrated Coastal Management Bill. In the changing legal landscape for coastal management, many municipalities are out of touch with the relevant legislation and still feel they are able to undertake certain actions and activities with no regard to the law. Difficulties in understanding the different laws and regulations applicable to the coast have resulted in a degree of confusion as to what to do to comply with the law. Many municipalities feel that they are required to undertake onerous measures to comply with these laws and regulations in the face of their mandate to deliver services to communities.

There is a need to define the principles of sustainable coastal management and restoration

After the event many private landowners repeatedly asked for assistance, but to no avail. In the face of this confusing situation, some private landowners have taken the opportunity to undertake whatever remedy they thought might be appropriate without referring to any of the authorities. Nevertheless many landowners have complied with the requirements of Section 30 but being unsure of the requirements, have sent in their applications with proposals of what they intend to do, instead of undertaking the works and then making the application. Among the private individuals, authorities and municipal groupings, the insurance companies entered. This resulted in the four groups not only being confused as what to do and how to address the erosion effects, but also actively contributed to divergent views on what should be done. The insurance companies were prepared to pay the costs of rebuilding the damaged structures. However, the private landowners were caught between the authorities and the insurers if they went ahead with repairs. There was no guarantee that the authorities would accept the repairs and therefore the landowner could be instructed to remove the intervention. If this happened, the insurance companies had made it clear to the insured that they would not pay the costs a second time.

This resulted in many landowners preparing and submitting a Section 30 NEMA application and then waiting to obtain an approval, despite the fact that this is not what the Section 30 application is designed to provide. This put the DAEA in a difficult legal predicament as to whether they approve these or not. Approval effectively sanctions the proposed measures without an assessment, effectively negating the DAEAs power to instruct the removal of these structures at a later stage. By refusing the application, they open themselves up to possible claims for damages. Fortunately, it would appear that the DAEA is able to provide a qualified response to these applications but by the middle of June 2007 the response had not been forthcoming. This situation could easily have been avoided if the Integrated Coastal Management Act had been in force, giving officials access to new tools to apply.

In an effort to address the concerns of the landowners and to give the municipality some guidance, the principles of sustainable coastal management and restoration were developed as outlined above. These principles provide a framework in which different types of interventions can be evaluated and, when first presented to the public, at which event it received a standing ovation (Bundy S pers comm). These principles are underpinned by the concepts of environmental, social and economic sustainability. These principles can be easily applied to erosion events like the March 2007 coastal erosion event. Perhaps the biggest challenge in implementing these principles is the mindset, which is, that this event is rare and will not reoccur in the near future. While none of us have a crystal ball, it is conceivable that this event is likely to reoccur in the next ten years and when it does the destruction is likely to be similar to, or even more than the previous event, if the rate of development remains unchecked.

WAVE ACTION

- Hydraulic action – this is when air in cracks on the cliff face becomes compressed by the power of the waves striking the cliff face. As this happens the air inside the crack is compressed, putting a lot of pressure on the surrounding rock. The air then expands explosively, forcing out pieces of rock. Over time, the cliff face crack breaks causing a larger crack or cave to form. The rock from the cliff face which was removed falls to the bottom of the sea bed and is used for another two wave action (Attrition and Corrasion (Abrasion)).

* Attrition – this is the when the sea grinds the rocks, and also the rock on the cliff, together, causing it to become smoother and reduced in size. As the sea rocks from side to side it moves the scree causing pieces of scree to collide with other pieces of scree thus causing them to become reduced in size and smoothed and rounded. As well as colliding with other pieces of scree the scree also collides with the cliff face base causing pieces of rock to be broken of the base of the cliff face contributing to this wave action and one more (Corrasion (Abrasion)).

- Corrasion (Abrasion) – this is when the waves break on the cliff face pounding the cliff face slowly eroding it. Along with the cliff face being eroded by the power of the sea the sea also uses the scree from other wave actions. As the sea pounds the cliff faces it also uses the scree to batter and break off pieces of rock from higher up the cliff face which can be used for this same wave action or one other (Attrition).

- Corrosion or solution – this is when the sea uses its low pH (anything below pH 7.0) to corrode away the rocks on the cliff face. Usually the only cliff faces to be greatly eroded in this manner would be limestone cliff faces as they have a high pH and would be easily eroded by a low pH. The rocking action of the sea also makes it easier for the sea to erode limestone cliff faces as the rocking action of the sea acts as the stirring motion in a chemistry experiment which helps

Source: Wikipedia.org

Historically, municipalities have sought to replace damaged infrastructure and facilities in their original positions and have convinced themselves that by strengthening the structure all will be fine. The case is not entirely hopeless, the eThekwini Municipality has, post this storm, identified facilities that will not be reconstructed in their original positions. If there is still a strong demand for the facilities, then alternative sites will be sought in less vulnerable locations. The typical facilities are inappropriately located car parks, roads, walkways and other municipal infrastructure. This change in thinking is a positive sign and must be encouraged in other municipalities.

When assessing the municipal IDPs, it became clear that apart from eThekwini Municipality, no other municipality has incorporated a climate change programme into their IDP. There are various reasons for this and these are best summed up by comments made at the Western Cape Climate Change Seminar held in Kirstenbosch in February 2006, where a representative of the Cape Town Municipality stated that the challenges for Cape Town and in fact for almost all municipalities are:

- climate change mitigation aspects have not yet been addressed
- climate change is not yet reflected in the city’s planning function
- a lack of capacity in local government
- a lack of awareness among local government officials
- financial, economic, institutional and legal barriers
- limited resources.

The key risk areas from a municipal perspective were highlighted as:

- a lack of awareness and capacity
- climate change not seen as a concern in the context of development demands
- a lack of clear understanding from the leadership (DEA and DP (2006)).

Another notable point was the perceptions between authorities and Non-Governmental Organisations (NGOs) in assessing the capacity and response of municipalities to the storm event. A sizable portion, for example, 64% of municipal and provincial authorities felt that they had handled the situation well in sharp contrast to the 6% of NGO respondents. All groups responded well to the questions regarding CMPs, but were less responsive to the questions about SMPs. This is almost certainly due to the extensive publicity of the Integrated Coastal Management Bill, which incorporates CMPs as part of the requirements of government. The desirability of having a SMP is as great as a CMP, and it is hoped that this will be incorporated into revisions of the bill and will be able to provide a framework to manage shoreline changes into the future.

The responses to municipalities having plans to address the impacts of sea level rise and coastal erosion were so overwhelming that virtually no municipalities have seriously considered this to date and it is an area that municipalities can easily address. Tools such as coastal setback lines, based on the potential erosion line using projected sea level and storm activity as a basis, are frankly just good planning. While this may become a requirement in the Integrated Coastal Management Act there really is no excuse for municipalities to start these right away. However, a recurring comment in the returned questionnaires was the question of the capacity and ability of government to address the challenges of coastal erosion and sea level rise. A sample of comments received is as follows:

"I think there is still a lack of willingness by Local Government to commit to anything that is going to cost money, this includes long-and short-term plans for managing weather patterns and coastal conditions".

"The … municipalities along the coastline do not seem to have the initiative to be proactive and in fact seem unable to deal with the problems like the recent storm events very well, even in a reactive way".

"They now are better informed after the March event, but seem to have gone back into thinking that this is a once-off event and will never happen again".

"Lack of success by municipalities in facilitating participation in terms of land owners impacted…".

The perception of the public clearly shows that municipalities are not performing at a level which inspires confidence in their abilities to address these issues. It is this challenge that needs to be addressed and it will take strong leadership by those in the field of coastal management to turn the tide. Role models are clearly needed at this stage and what we need is for some municipalities to show the way, admittedly perhaps at the risk of some failures, to improve the tools and systems for others to follow. A respondent echoed this approach:

"… our only hope for the long-term sustainability of our coastline is for … [capacitated municipalities] to lead the way, work out with the necessary expertise exactly what is needed, what is available, and then drive this at a provincial level, so that province, possibly through the Provincial Coastal Committee and Regional Coastal Committee…get this information implemented along the coastline through the various municipalities".

To address this gap in the demand for better knowledge, and have a system in place, which all stakeholders can buy into and understand, it is proposed that a mini-conference be held over two days to cover the physical aspects of the erosion event on day one followed by the legal and process issues on day two. This will allow interested parties to hear expert input first hand. The second component envisaged is the writing-up of a user manual on addressing coastal erosion in a sustainable manner, which can be distributed to all stakeholders so that in future events they will know their rights and obligations, as well as empowering the community to be in a position to help and regulate them.

Conclusion

Based on the analysis presented in this paper, municipalities are clearly not succeeding in addressing the issues of coastal erosion and sea level rise. Even within eThekwini Municipality, which is seen as one of the larger, more capacitated municipalities, there is a struggle to communicate its plans and coastal vision to its own staff, resulting in negative perceptions of the readiness of the municipality. The problems and potential impacts of coastal erosion and sea level rise appear to be just another issue, way down on municipal priority lists. With the predicted increases in sea level rise and storminess in our region, it is important that municipalities are ready to respond. This would appear to be easier said than done, as the capacity issues facing municipalities are very real. The response to the March 2007 coastal erosion event has exposed weaknesses among the coastal municipalities, particularly in KwaZulu-Natal, which will require addressing. These weaknesses are

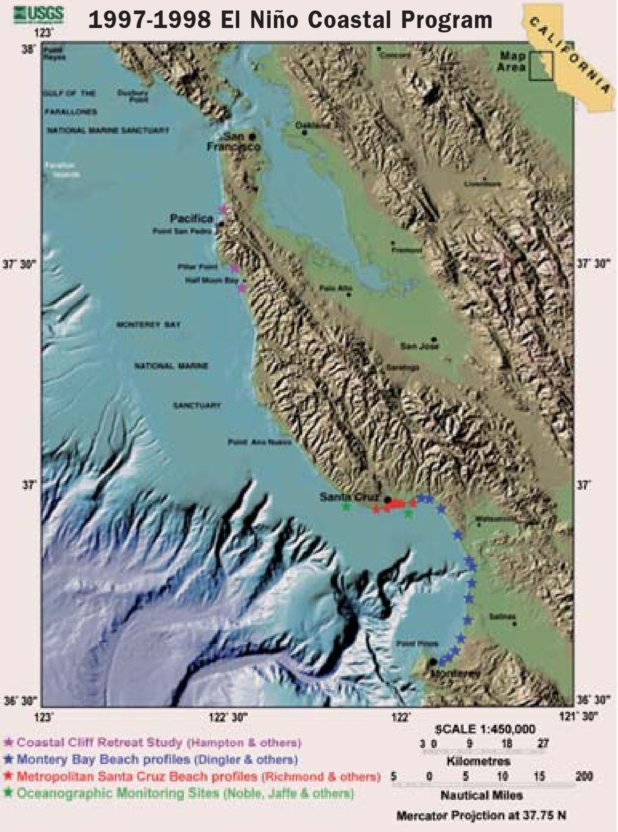
El Niño coastal erosion

During late January and early February of 1998, the California Coast was hit by a series of powerful El Niño winter storms. At least 27 counties in California were declared National Disaster Areas, with hundreds of millions of dollars in property losses. Large waves, which coincided with high tides and elevated sea levels, produced severe beach erosion.

US Geological Survey researchers and students from University of California at Santa Cruz have been conducting beach surveys and monitoring changes in coastal morphology since early October 1997. Up to 4m of vertical beach loss was measured on several Monterey Bay beaches between October and mid-February and many beaches were completely submerged during high tides. Historical structures that had been buried since 1983, such as wharf pilings, old seawalls, and trolley car trestles, became emergent on several Monterey Bay beaches.

Coastal protection structures emplaced following the 1982/83 El Niño winter were mostly successful in mitigating coastal property loss due to wave attack and inundation. Most property damage was the result of the high rainfall amounts, which caused flooding and landslides.

Source: US geological Survey



also likely to be present in other coastal municipalities around SA. To address this it is recommended that a conference be held focusing specifically on this event and that a practical manual be drawn up, based on the lessons learnt from around the country. This manual will assist coastal managers, coastal regulators and the community in improving their responses to future events of this kind.

The challenge of addressing coastal erosion and sea level rise rests firmly with government and particularly local government as the authority charged with development at the local level. Perhaps the new legislation will be the incentive to put in place better systems and management of the coastal zone. However, until then the challenge to all of us in local government is to raise awareness of these issues and provide the leadership to overcome the challenges that lie ahead.

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* Andrew Mather received the award for Best Prepared Paper at the IMESA 2007 Conference

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Southern African sea levels: corrections, influences and trends

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The tidal records of existing South African and Namibian tide gauges are examined and corrected. Regional sea level trends vary, with the West Coast rising by +1.87 mm y^{-1} (1959–2006), the southern coast by +1.48 mm y^{-1} (1957–2006) and the East Coast by +2.74 mm y^{-1} (1967–2006). The effects of barometric pressure and vertical crustal movement changes on these trends are examined. The derived relationship between sea levels and barometric pressure changes varied between 5.71 and 7.67 mm hPa^{-1}, significantly less than the theoretical inverse barometric correction. Barometric pressure has been dropping along the west coast at 1.63 hPa per decade (1987–2006), has remained fairly static along the southern coast and is rising at 0.30 hPa per decade (1970–2007) along the east coast of southern Africa. The West Coast barometrically corrected sea level trends show that most of the change can be attributed to falling barometric pressure, whereas along the East Coast, the barometric pressure increase is suppressing sea level by 0.2 mm y^{-1}. Vertical crust movements vary, with the largest recorded movements of +1.11 ± 0.25 mm y^{-1} found along the East Coast. Movement rate reduces southwards. Eustatic sea level trends vary from +3.55 mm y^{-1} along the East Coast and +1.57 mm y^{-1} along the southern coast to +0.42 mm y^{-1} along the West Coast.

Keywords: barometric pressure, sea level rise, tide levels

Introduction

Sea levels vary in time and space because of a variety of natural factors acting on the Earth's surface (Church et al. 2001, Bindoff et al. 2007), including solar and lunar tides (Pugh 2004), waves and winds (Pugh 1987), crustal movements (Baker 1993, Pirazzoli et al. 1994, Davis and Mitrovica 1996) and atmospheric conditions (Dickman 1988, Hoar and Wilson 1994, Wunsch and Stammer 1997, Proshutinsky et al. 2004), at both a localised and regional scale. The anthropogenic effects on the planet have altered this natural state of dynamic equilibrium. These influences include warming (Warrick et al. 1996, Bindoff and McDougall 2000), glacier and ice sheet melt (Dyurgerov and Meier 1997) and surface and ground water storage (Gornitz 2000).

Over the past several decades, driven by the concerns about the impacts of global warming, many researchers and organisations, such as the Intergovernmental Panel on Climate Change (IPCC), have sought to understand man's influence on global sea levels (IPCC 1990, 1996, 2001, Bindoff et al. 2007). Part of this research has been focused on the current and future rate of sea level rise (Church et al. 2001). Until the introduction of satellite altimetry in 1993 (Nerem et al. 1997), the analysis of sea level changes had been solely confined to tide gauge data, which was predominately based in the Northern Hemisphere. The use of satellite sea level data has to some extent improved the geographical coverage; however, accurate tide gauge data are still needed to calibrate the satellite altimeter results (Mitchum 1998).

Unfortunately, in the Southern Hemisphere, not many tide gauge records extend for longer than 50 years, the period deemed to be suitable for this type of analysis (Woodworth 1990, Douglas 1991). In the African context, the number of suitable tide gauge records diminishes even further, but there are plans to extend and upgrade this network along the African coastline (Woodworth et al. 2007).

This paper focuses on the tide gauges along the southern African coastline (Figure 1). Whereas, not all the records meet the 50-year length criteria, it is important that some preliminary analysis be undertaken to help in making key planning and policy decisions. Investigations on sea level changes around the South African coastline are limited. Earlier work focused on sea level changes on the West Coast (Brundrit 1984) and on the West and Cape coasts (Hughes et al. 1991). Later, Brundrit (1995) derived sea level trends from tide gauge data taken from Lüderitz in Namibia and Port Nolloth, Cape Town and Mossel Bay on the West and South coasts. Recently, Mather (2007) examined the linear and non-linear sea level trends for Durban on the East Coast.

Key to understanding these trends in sea level changes in a global context is the ability to separate out the various contributions by tides, waves and winds, which can be simply measured using tide gauge data, over as long a period as possible. However, other important factors that can influence sea level such as vertical crustal movements and barometric pressure are more difficult to quantify. These parameters are briefly outlined below.

Vertical crustal movements

Although South Africa is located on a stable cratonic base (Cooper 1995, Ramsay and Cooper 2002), the African plate is subject to motion induced by the plate and rebound movement on account of historical glacial ice sheet loading. Vertical crustal movements have been difficult to quantify in the past because they have mainly been estimated using various models, e.g. the ICE-5G model (Peltier 1994). With the advent of satellites, it has become possible to measure the land and water surface of the earth against an imaginary geoid to determine the vertical and horizontal changes in the Earth's crust. This network of monitoring points is relatively sparse over southern Africa, with only two stations in South Africa located at the coast at Simon's Town and Richards Bay (Figure 1). These geodetic stations are located next to tide recording stations. Despite data limitations, corrections for vertical land movements are applied here to the observed sea level changes in order to provide some indication of eustatic sea level rise around the southern tip of Africa.

Barometric pressure

Barometric pressure has been reported to be the second-most important climatic variable other than temperature that may be influenced anthropogenically (Gillett et al. 2003). Global barometric pressure trends yield a small positive trend of +0.02 hPa y^{-1}, with values of –0.03 hPa y^{-1} occurring in localised areas (Church et al. 2001). Northern European trends are of the order of +0.01 hPa y^{-1} (Woodworth 1987). Trends for short periods (1960–1990) can have a larger influence on sea level trends of between –0.05 mm y^{-1} (Schönwiese et al. 1994) and +0.04 mm y^{-1} (Schönwiese and Rapp 1997). Thus, it is important that the impacts of local barometric pressure variations are understood and properly taken into account in the assessment of trends using tidal records over a relatively short time

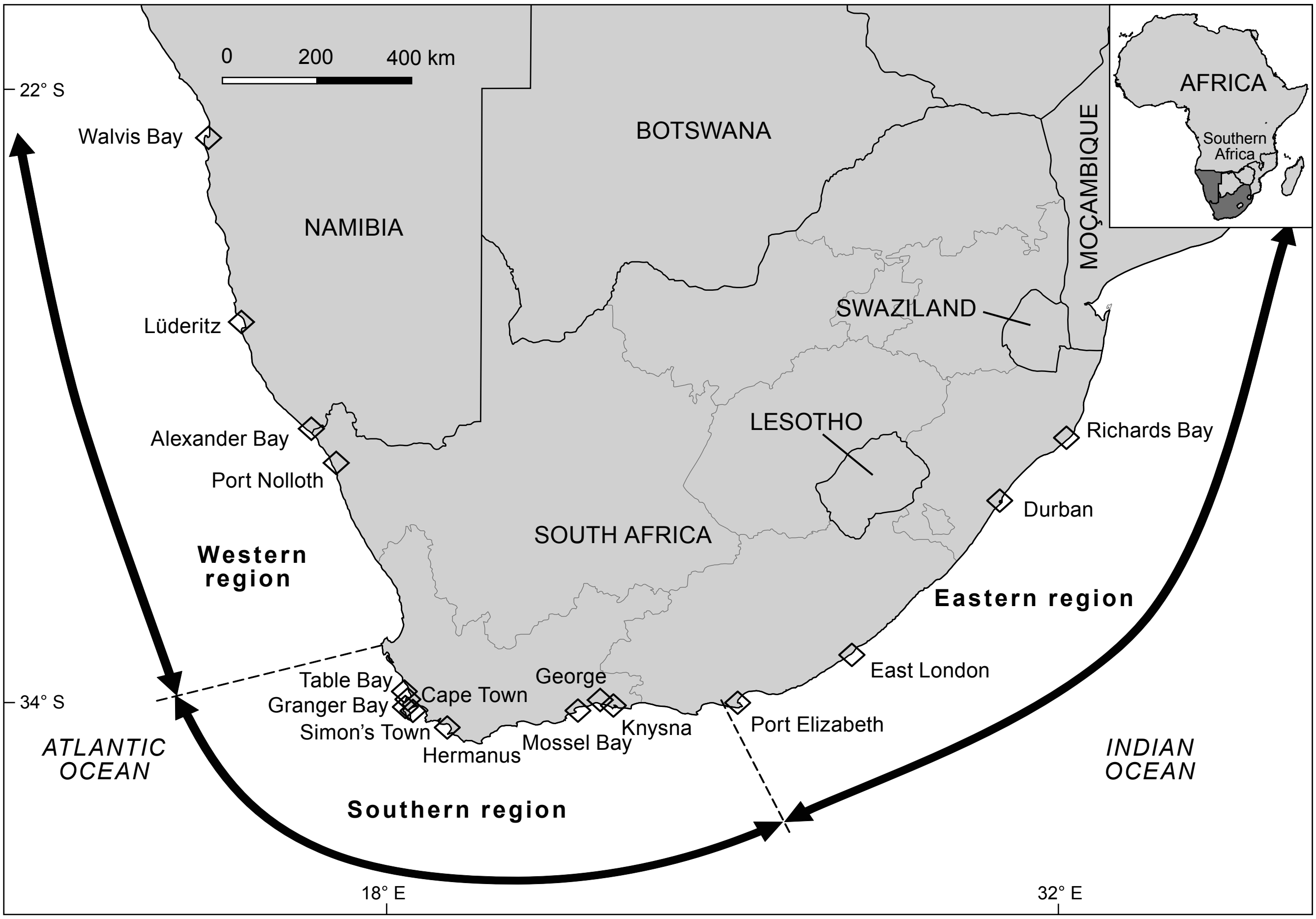

Figure 1: Map of southern Africa showing the location of the tide gauge stations and the three geographical regions referred to in the text

period. In southern Africa, where the available records of sea level are only up to 37 years long, it is critical to ensure that barometric pressure effects are taken into account in the calculation of eustatic sea level change.

The barometric pressure relationship is governed by the simple relationship that increased air pressure forces the sea surface to drop and the excess water is distributed to other regions of the sea. This relationship has been widely studied and was first postulated by Gissler (1747; cited in Roden and Rossby 1999). Doodson (1924) continued this work and coined the term 'inverted barometer response', which is now in common use (Rossiter 1962, Roden 1966, Wunsch and Stammer 1997). From the hydrostatic equation, it can be deduced that a barometric high or low pressure system should theoretically depress or elevate the sea surface. The theoretical 'local inverted barometer' (IB) correction for the sea surface can be calculated as:

$$\zeta_{IB} = -0.9948 \times (p_a - 1013.3)$$

where ζ_{IB} is the change in sea level in cm, p_a is the recorded barometric pressure in hPa, 1013.3 is the standard atmospheric pressure at sea level in hPa and –0.9948 is the IB coefficient in cm hPa^{-1} (Hoar and Wilson 1994).

The equation shows that each hPa drop in pressure leads to a 9.948 mm (often approximated to 10 mm) increase in sea level. The exact inverted barometer response is seldom found in practice (Pugh 1987) and tide gauges around the world will have different responses to this relationship, depending on many factors including the amount of storm surge influenced by wind, as well as basin characteristics, continental shelf configurations, water depth, coriolis effect, ocean upwelling, and global and local atmospheric pressure realignments. The variation of barometric pressure over the sea can have a significant influence on recorded tide levels, which at times can be of orders of magnitude greater than the annual change in sea levels (Bell et al. 2000, Singh and Aung 2005). Working on global data, Ponte (2006) found that the deduction of the IB signal can have the effect of up

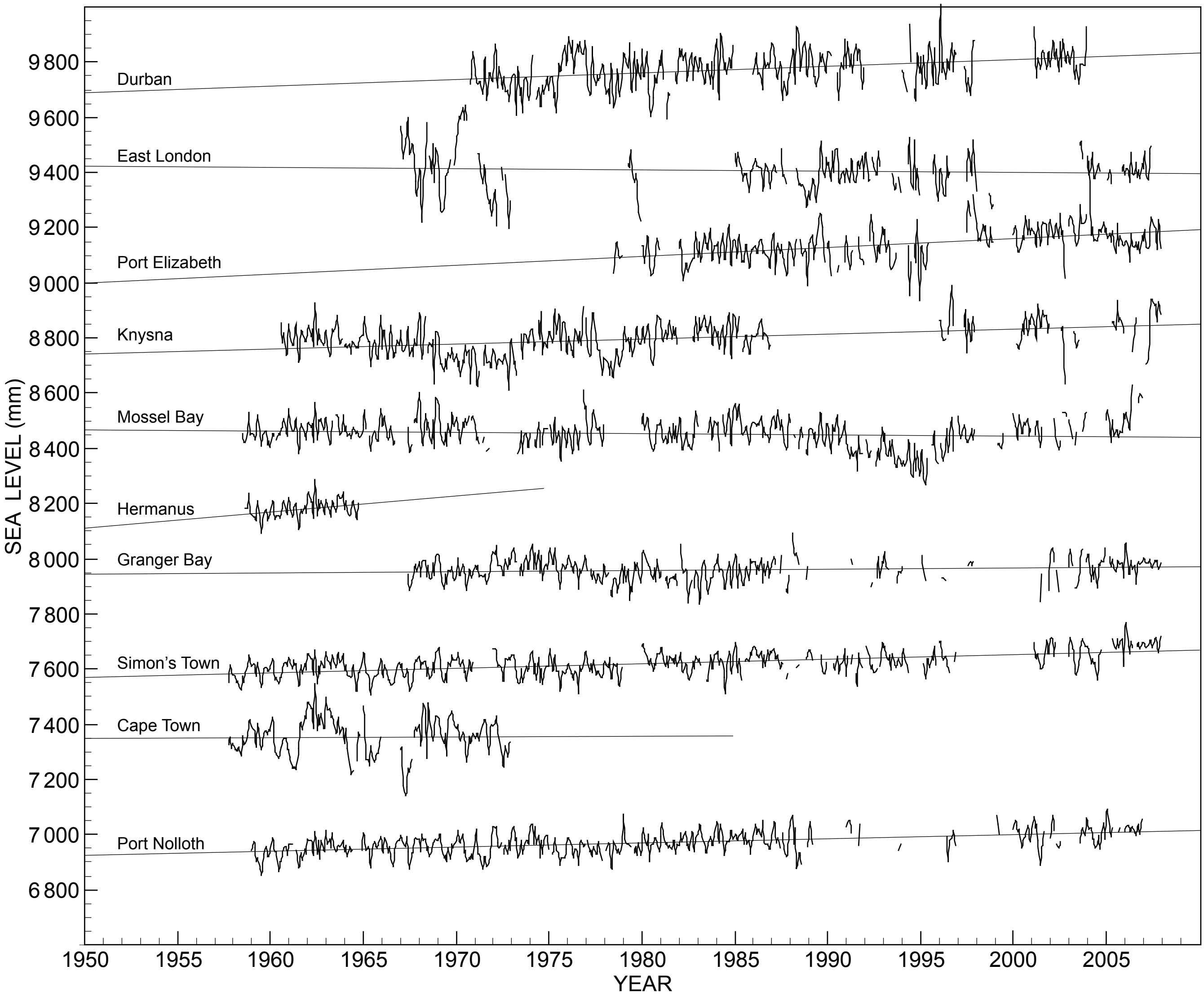

Figure 2: Tide gauge time-series for the different stations, 1959–2006

to a 40% change in the sea level trend. The understanding of this relationship is critical in isolating the weather effects from short tidal records if sea level changes are to be accurately computed.

The objectives of this paper are to determine (1) the current relative rate of sea level rise at stations around the southern African coastline, (2) the regional relative rates of sea level rise, (3) the impact of changes in barometric pressure on sea levels, (4) the influence of vertical land movements on sea levels, and (5) the regional rate of eustatic sea level rise along the coastline.

Material and methods

The analysis of the sea levels and their respective influences was based on a number of datasets. In some cases, more than one dataset was available and a choice was made between them, for the reasons given below. The monthly and annual revised local reference (RLR) tidal dataset for all South African and Namibian tide gauge stations was sourced from the Permanent Service for Mean Sea Level (PSMSL) at www.pol.ac.uk/psmsl. The tide data for Durban were derived from Mather (2007, 2008), which required rectifying some errors (detailed below). The sea level data used in this study are shown in Figure 2.

Sea level pressure data (HadSLP2) were sourced from the Hadley Centre for Climate Change, UK, and monthly barometric pressure data were obtained from the South African Weather Service. The HadSLP2 data are in 5° × 5° grids for the period 1955–2004. Examination of the area of interest in this study revealed that in half of the grids required for the analysis, only one land station was located in the grid. Because the tide gauge and weather station pairs to be examined (Alexander Bay and Port Nolloth) were not further than 80 km apart, the actual weather station data rather than the HadSLP2 data were used (Figure 3).

Vertical crustal movement data were available as model outputs at all the tide station sites from both the ICE-5G (VM2) and (VM4) models and were obtained from the PSMSL website. Vertical crustal movement from GPS stations coupled with tide gauge stations were supplied by the Hartebeesthoek Radio Astronomy Observatory, South Africa (HartRAO).

A simple linear regression analysis was used to determine annual sea level trends from the monthly and annual tide gauge data. For each location, a proxy IB coefficient was determined from the correlation of recorded monthly sea levels and barometric pressure. A linear regression analysis was undertaken on a scatterplot to determine the slope of the line and hence the proxy IB coefficient applicable to monthly records of sea level. From these results, two methods were used to determine the effect of barometric pressure changes on the sea level trends. Method 1 involved the direct arithmetic deduction of the barometric trends from the sea level trends at each of the locations. Method 2 involved correcting the monthly sea level for

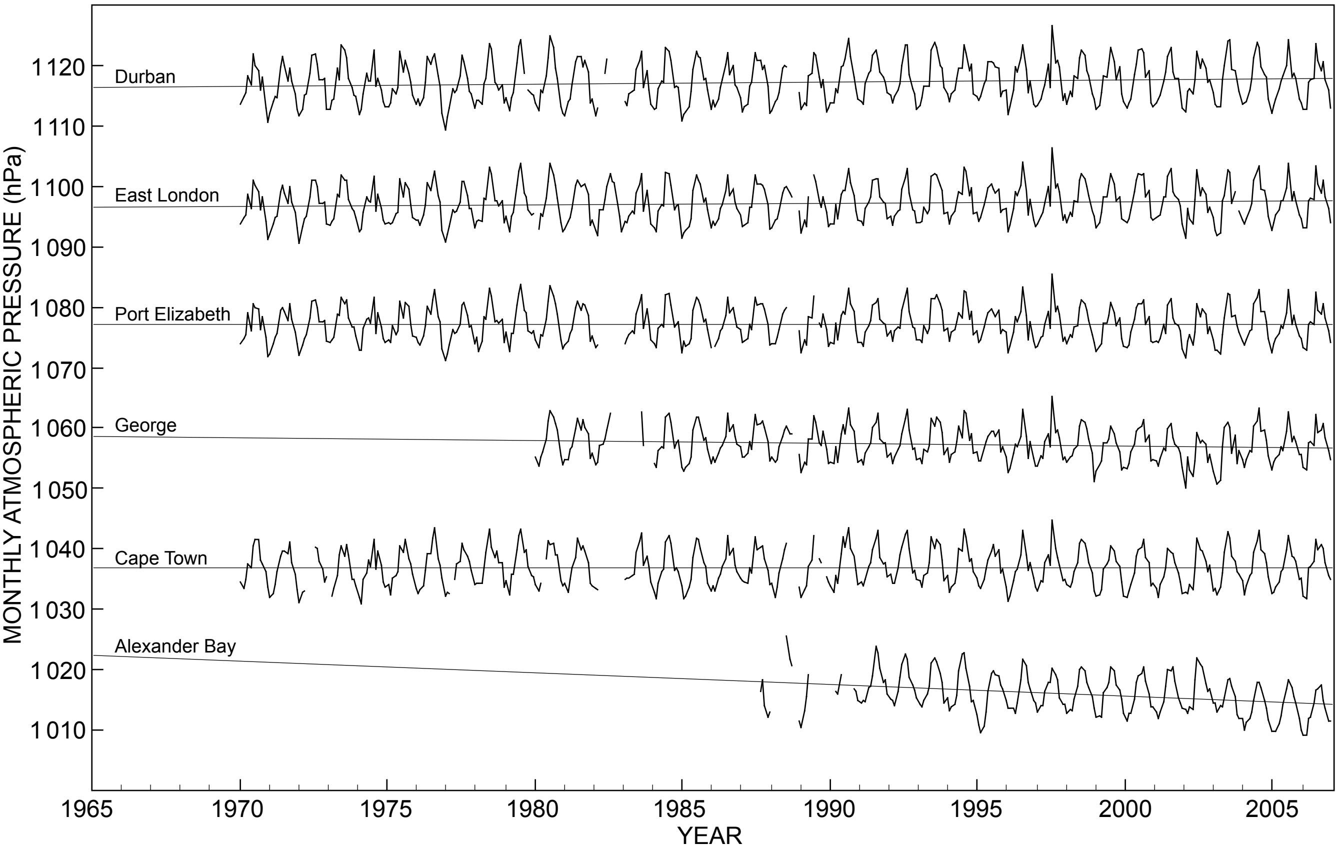

Figure 3: Monthly barometric pressure recordings for the different stations, 1970–2007

every monthly recording at each of the locations, and thus a trend of the barometrically corrected sea levels could be calculated for each station. Both methods utilised the derived proxy IB coefficient for each station (e.g. Durban's proxy IB coefficient used was –6.04 mm hPa^{-1}). This process was repeated for annual tide gauge data, but owing to the small series of annual data, the analysis was confined to Method 1 only.

Results and discussion

The main problem with the South African tide gauge records is confined mainly to the period between 1998 and 2002 when the data for recorded tide levels were confused with the mean level (ML) at each site. In the derivation of the chart datum (CD) to land levelling datum (LLD) conversion, an error was inadvertently introduced. This error was first identified during the analysis of the Durban sea level records (Garland and Mather 2007) and has subsequently been found in other South African tide gauge records. The magnitude of the error varies between sites (Table 1). This over-correction resulted in artificially raising sea levels for the period 1998–2002 (Garland and Mather 2007). To obtain the correct LLD sea levels for the tide gauge locations, it was necessary to correct all records. This was achieved using Table 2, which is based on the South African Navy's conversion table (SAN 2008). Due to these problems, we used the PSMSL revised local reference (RLR) data, excluding Durban, where additional data-correction processes have been applied. It should be noted that data for the period 1998–2002 have been largely removed from the RLR data by the PSMSL, possibly for the abovementioned reasons.

Sea levels from the various southern African locations using the PSMSL RLR data (excluding Durban) exhibited a scatter between rising and falling sea level (Figure 2). At each tide gauge location, an analysis of relative sea level trends was undertaken (Table 3). All stations showed a rising sea level, except for Mossel Bay where there was a change of –0.40 ± 0.19 mm y^{-1}. Low results from Walvis Bay (+0.38 ± 0.33 mm y^{-1}), Granger Bay (+0.08 ± 0.20 mm y^{-1}) and East London (+0.17 ± 0.05 mm y^{-1}) appear to be inconsistent with trends from adjacent locations and may suggest possible further data problems with these stations.

To improve reliability, records from periods longer than 30 years with at least 60% data coverage were selected and used to determine the regional relative sea level trend (Table 4). Similarly, trends of barometric pressure were determined for the sites (Table 5). These stations were

Table 1: Chart datum to land levelling datum corrections for South African tide gauge sites for the period 1998–2002

Port	Correction to be applied to chart datum tide levels (m)
Port Nolloth	+0.12
Saldanha	–0.15
Cape Town	–0.11
Simon's Town	–0.16
Hermanus	–0.19
Mossel Bay	–0.23
Knysna	–0.26
Port Elizabeth	–0.19
East London	–0.29
Durban	–0.20
Richards Bay	–0.19

Table 2: Height of chart datum relative to land levelling datum in South Africa. Corrected data conversions shown in bold

Port	Up to 31 Dec. 1978	1 Jan. 1979– 31 Dec.1997	1 Jan. 1998– 31 Dec.2002	1 Jan. 2003 onwards
Port Nolloth	–0.718*	–0.900	**–0.955**	–0.925
Saldanha	–0.582	–0.900	**–1.125**	–0.865
Cape Town	–0.829	–0.900	**–1.085**	–0.825
Simon's Town	–0.651	–0.900	**–1.163**	–0.843
Hermanus	–0.619	–0.900	**–1.168**	–0.788
Mossel Bay	–0.761	–0.900	**–1.393**	–0.933
Knysna	–0.625	–0.900	**–1.308**	–0.788
Port Elizabeth	–0.838	–0.900	**–1.216**	–0.836
East London	–0.762	–0.900	**–1.296**	–0.716
Durban	–0.838	–0.900	**–1.313**	–0.913
Richards Bay	–0.900	–0.900	**–1.395**	–1.015

* In use until 1 January 1994

Table 3: South African and Namibian uncorrected sea level trends. All stations are from the PSMSL data holdings except Durban (Mather 2007)

Tide station	Period of record	Years of record	Completeness of record (%)	Observed annual sea level trend using monthly data (mm y^{-1})	Observed annual sea level trend using annual data (mm y^{-1})
Walvis Bay	1958–1998	41	58	+0.38 ± 0.33	+0.67 ± 1.06
Lüderitz	1958–1998	41	78	+2.73 ± 0.81	+2.40 ± 1.64
Port Nolloth	1959–2007	49	75	+1.25 ± 0.23	+1.11 ± 0.41
Table Bay	1957–1972	16		Insufficient data	
Simon's Town	1957–2007	51	78	+1.58 ± 0.22	+1.14 ± 0.51
Granger Bay	1967–2007	41	77	+0.08 ± 0.20	+0.44 ± 0.53
Hermanus	1958–1964	7		Insufficient data	
Mossel Bay	1958–2007	50	77	–0.40 ± 0.19	–0.66 ± 0.56
Knynsa	1960–2007	48	64	+1.27 ± 0.50	+1.95 ± 1.62
Port Elizabeth	1978–2007	30	76	+2.97 ± 1.38	+2.89 ± 2.05
East London	1967–2007	41	50	+0.17 ± 0.05	–2.03 ± 1.86
Durban	1970–2003	34	79	+2.70 ± 0.05	+2.40 ± 0.29
Richards Bay	1990–2000	11		Insufficient data	

Table 4: Regional relative sea level trends. Equal weighting was given to each location in the calculation of regional sea level trends in each region

Region	Port	Observed annual sea level trend using monthly data (mm y^{-1})	Observed annual sea level trend using annual data (mm y^{-1})	Regional relative sea level trend based on the average of annual and monthly trends (mm y^{-1})
Western	Lüderitz	+2.73 ± 0.81	+2.40 ± 1.64	+1.87
	Port Nolloth	+1.25 ± 0.23	+1.11 ± 0.41	
Southern	Simon's Town	+1.58 ± 0.22	+1.14 ± 0.51	+0.68 or +1.48 (excluding Granger Bay and Mossel Bay)
	Granger Bay	+0.08 ± 0.22	+0.44 ± 0.53	
	Mossel Bay	–0.40 ± 0.19	–0.66 ± 0.56	
	Knynsa	+1.27 ± 0.50	+1.95 ± 1.62	
Eastern	Port Elizabeth	+2.97 ± 1.38	+2.89 ± 2.05	+2.74
	Durban	+2.70 ± 0.05*	+2.40 ± 0.29	

* Mather (2007)

Table 5: South African barometric level trends

Station	Period of record	Years of record	Completeness of record (%)	Observed monthly linear pressure trend (hPa month^{-1})	Observed annual linear pressure trend (hPa y^{-1})
Alexander Bay	1987–2006	20	89	–0.0160 ± 0.0034	–0.1630 ± 0.0521
Cape Town	1970–2006	37	95	–0.000395 ± 0.001200	+0.0073 ± 0.1220
George	1980–2006	27	95	–0.00384 ± 0.00175	–0.0566 ± 0.0157
Port Elizabeth	1978–2006	29	95	–0.00103 ± 0.00160	–0.0114 ± 0.0123
East London	1970–2006	37	98	+0.00221 ± 0.00110	+0.0281 ± 0.0074
Durban	1970–2006	37	97	+0.00277 ± 0.00162	+0.0304 ± 0.0071

analysed further to determine the extent of barometric pressure influence on sea level. These sea level trends were then barometrically corrected to provide an indication of the underlying rate of sea level change along the South African coastline. It should be noted that barometric stations are usually located at airports and can be situated several kilometres from the coastline. Ideally, the stations need to be adjacent to each other. However, because monthly or annual averages at the sites were used, the small variation between tide gauge and barometric station is assumed to be negligible or relatively constant between the sites.

To determine the proxy IB coefficients, monthly sea level recordings were correlated with monthly barometric pressure recordings (Figure 4). With the exception of Alexander Bay, the proxy IB coefficients compared well with the globally distributed IB coefficients derived by Hoar and Wilson (1994). The proxy IB coefficient for Alexander Bay of +3.60 mm hPa^{-1} implies that when barometric pressure increases sea level also increases. Although this trend is contrary to the established theory, it has been reported elsewhere (e.g. in the South Atlantic, Woodworth et al. 1995; in the Red Sea, El-Din et al. 2007) and may reflect specific local conditions. The derived proxy IB coefficient for Durban, which is at the same latitude as Alexander Bay, was used as an alternative. Hoar and Wilson (1994) showed that the IB coefficient is latitude-dependent, and that for southern Africa (28°–35° S) the expected values are between –5.3 mm hPa^{-1} and –6.9 mm hPa^{-1}. Using the derived barometric relationship, the sea level trends were corrected for barometric influences for the selected datasets and are shown in Tables 6 and 7.

In reviewing the vertical crustal movements from the Peltier ICE-5G model and the HartRAU GPS data, it was clear that the former model was relatively close to the actual recorded movements at Simon's Town, but it appeared to underestimate the movement farther east at Richards Bay (Table 8). In order to provide a specific vertical crustal movement value at each tide station, the vertical movement was distributed linearly along the East Coast between the two stations. Because no data are available for the West Coast, those for Simon's Town were used. This was done on the basis that, because the African plate is tilting upward in a south-west to north-east direction, the West Coast gauges would be approximately perpendicular to Simon's Town. The difference between the HartRAU data value estimated for Simon's Town and the Peltier model results for Port Nolloth and Saldanha was not significant, being only 0.09 mm y^{-1}.

The eustatic sea level trends were determined using the relative sea level trends corrected for barometric influences using Methods 1 and 2 (as detailed earlier). Vertical land movements were then taken into account and the resultant local and regional eustatic trends were determined (Tables 9 and 10).

At a regional level, sea levels are rising around the southern African coastline. For comparative purposes, the coastline was divided into the western, southern and eastern regions (Figure 1). The dissimilar physical factors between these regions could explain the differences found in sea level change.

Western region

This region contains one of four major coastal upwelling centres worldwide. The region is unique in that it is dominated by the cold upwelling waters of the Benguela system, which is trapped by warm waters to the north and

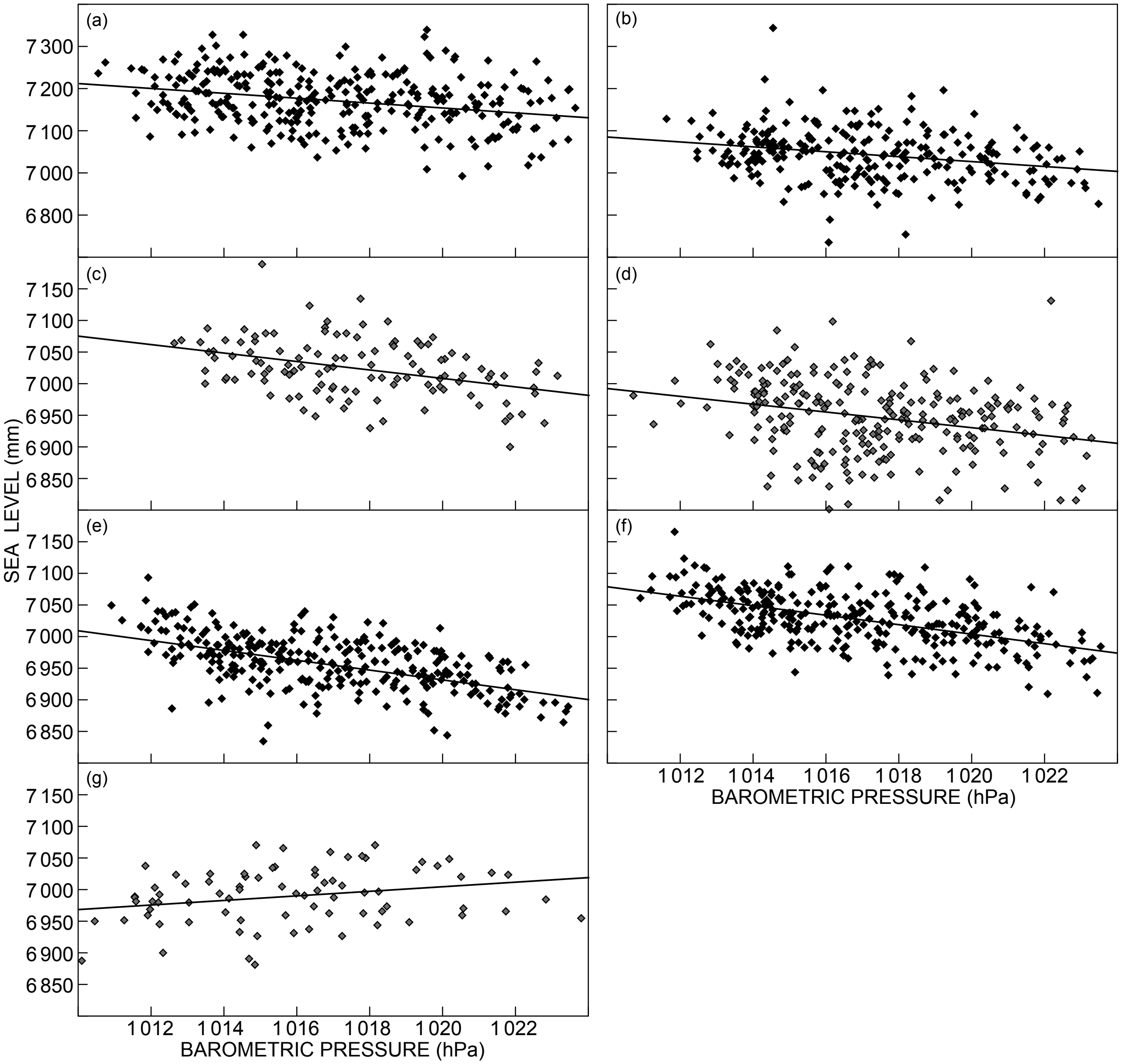

Figure 4: Relationship between sea level and barometric pressure, i.e. proxy IB coefficients for (a) Durban, (b) Port Elizabeth/Port Elizabeth, (c) George/Knysna, (d) George/Mossel Bay, (e) Cape Town/Granger Bay, (f) Cape Town/Simon's Town and (g) Alexander Bay/Port Nolloth

south (Shannon and O'Toole 2003). The western region is represented by three stations, Port Nolloth, Lüderitz and Walvis Bay. Unfortunately, the PSMSL does not have data for the past decade for these stations which reduces the period of analysis. As mentioned earlier, the sea level trend for Walvis Bay (+0.38 ± 0.33 mm y^{-1}) was excluded from the analysis because of concerns regarding the reliability of the data. The Port Nolloth and Lüderitz tide stations yielded a regional relative sea level trend of +1.87 mm y^{-1}. The barometric correction was not applied to Lüderitz owing to a lack of air pressure records at that station. However, the correction was applied to Port Nolloth, which yielded a sea level trend of between +0.76 mm y^{-1} and +0.13 mm y^{-1}. When vertical crustal movements were introduced, the eustatic sea level trend at Port Nolloth rose between +1.05 mm y^{-1} and +0.56 mm y^{-1}, with an average of +0.80 mm y^{-1}.

These trends appear to concur with the IPCC assessment of global sea level change when the contributions from ice melt and thermal expansion are considered. Global ice and glacier contributions have been estimated at +0.69 mm y^{-1} (glaciers and ice cap +0.5 ± 0.18 mm y^{-1}, Greenland ice sheet +0.05 ± 0.12 mm y^{-1} and Antarctic ice sheet +0.14 ± 0.41 mm y^{-1}) over a comparable period (to this study) of 1961–2003 (Bindoff et al. 2007). Thermal expansion of seawater has been found to be mainly confined to the upper layers of the ocean. Levitus et al. (2005) found that

Table 6: Barometrically corrected annual sea level trends using monthly data

Region	Station (tide gauge station/ weather station)	Observed annual sea level trend using monthly data (mm y^{-1})	Proxy IB coefficient (hPa y^{-1})	Method 1: summation of trends			Method 2: monthly barometrical corrected data
				Linear barometric trend (hPa y^{-1})	Resulting linear sea level trend (mm y^{-1})	Barometric-corrected linear sea level trend (mm y^{-1})	Barometric-corrected linear sea level trend (mm y^{-1})
Western	Port Nolloth/ Alexander Bay	+1.25 ± 0.23	–6.04 ± 6.59*	–0.163	–0.984	+0.27	+0.76 ± 1.11
Southern	Simon's Town/ Cape Town	+1.58 ± 0.22	–7.51 ± 5.12	+0.007	+0.053	+1.63	+1.89 ± 0.34
	Granger Bay/ Cape Town	+0.08 ± 0.22	–7.67 ± 7.20	+0.007	+0.053	+0.03	+0.39 ± 0.20
	Mossel Bay/ George	–0.40 ± 0.19	–6.19 ± 8.21	–0.004	–0.020	–0.38	+0.22 ± 0.46
	Knysna/George	+1.27 ± 0.50	–6.73 ± 9.72	–0.006	–0.038	+1.23	+1.60 ± 0.76
Eastern	Port Elizabeth/ Port Elizabeth	+2.97 ± 1.38	–5.73 ± 8.04	–0.011	–0.063	+2.91	+3.38 ± 1.48
	Durban/Durban	+2.70 ± 0.05	–6.04 ± 6.59	+0.030	+0.180	+2.88	+2.63 ± 0.96

* Durban IB-value used

Table 7: Barometrically corrected annual sea level trends using annual data

Region	Station (tide gauge station/ weather station)	Recorded linear sea level trend using annual data (mm y^{-1})	Proxy IB coefficient (hPa y^{-1})	Method 1: summation of trends		
				Linear barometric trend (hPa y^{-1})	Resulting linear sea level trend (mm y^{-1})	Barometric-corrected linear sea level trend (mm y^{-1})
Western	Port Nolloth/ Alexander Bay	+1.11 ± 0.41	–6.04 ± 6.59*	–0.163	–0.984	+0.13
Southern	Simon's Town/ Cape Town	+1.14 ± 0.51	–7.51 ± 5.12	+0.007	+0.053	+1.19
	Granger Bay/ Cape Town	+0.44 ± 0.53	–7.67 ± 7.20	+0.007	+0.053	+0.49
	Mossel Bay/ George	–0.66 ± 0.56	–6.19 ± 8.21	–0.004	–0.020	–0.64
	Knysna/George	+1.95 ± 1.62	–6.73 ± 9.72	–0.006	–0.038	+1.91
Eastern	Port Elizabeth/ Port Elizabeth	+2.89 ± 2.05	–5.73 ± 8.04	–0.011	–0.063	+2.83
	Durban/Durban	+2.40 ± 0.29	–6.04 ± 6.59	+0.030	+0.180	+2.58

* Durban IB-value used

Table 8: Vertical crustal movements along the southern African coastline

Station	ICE-5G VM2 model results (Peltier 2004) (mm y^{-1})	ICE-5G VM4 model results (Peltier 2004) (mm y^{-1})	HartRAU vertical crust movements for 2000–2007 (mm y^{-1})
Port Nolloth	+0.33	+0.21	+0.29*
Saldanha	+0.30	+0.20	+0.29*
Cape Town	+0.29	+0.19	+0.29*
Simon's Town	+0.27	+0.18	+0.29 ± 0.18
Hermanus	+0.29	+0.20	+0.36$^{\$}$
Mossel Bay	+0.35	+0.25	+0.49$^{\$}$
Knysna	+0.34	+0.23	+0.54$^{\$}$
Port Elizabeth	+0.25	+0.15	+0.66$^{\$}$
East London	+0.23	+0.13	+0.78$^{\$}$
Durban	+0.21	+0.12	+1.03$^{\$}$
Richards Bay	+0.16	+0.08	+1.11 ± 0.25

* Same value as Simon's Town used
$^{\$}$ Linear interpolation between Simon's Town and Richards Bay

most (69%) of the ocean warming has occurred in the upper 700 m over the period 1955–1998, a finding that was confirmed by Bindoff et al. (2007) for a slightly longer period of 1955–2003. Domingues et al. (2008) reported that 91% of the warming has occurred in the top 300 m. Reporting on the Benguela Current Large Marine Ecosystem, Shannon and O'Toole (2003) found a progressive warming of the surface waters of 0.7 °C from 1920 to 2003 in the Benguela region. This figure would induce a thermal expansion component of 0.51 mm y^{-1} (using a depth of 700 m of seawater and thermal expansion coefficient $\beta = 88 \times 10^{-6}$ m^3 K^{-1}) over a longer period than this analysis. The global thermal expansion component over the period 1961–2003 was estimated to be 0.42 ± 0.12 mm y^{-1} (Bindoff et al. 2007).

The combined contributions of global glacial and ice melt (+0.69 mm y^{-1}) and global thermal expansion (+0.42 mm y^{-1}) of +1.11 mm y^{-1} is similar to the rate of +0.80 mm y^{-1} derived in our study, and is in the lower end of the range of

Table 9: Eustatic annual sea level trends using monthly data

Region	Station (tide gauge station/ weather station)	Recorded linear sea level trend relative to land (Table 3) (mm y^{-1})	Barometric-corrected linear sea level trend (Method 1 from Table 6) (mm y^{-1})	Barometric corrected linear sea level trend (Method 2 from Table 6) (mm y^{-1})	Vertical crustal movements from Table 8 (mm y^{-1})	Sea level corrected for vertical crustal movement and barometric changes (Method 1) (mm y^{-1})	Sea level corrected for vertical crustal movement and barometric changes (Method 2) (mm y^{-1})	Regional eustatic sea level change (mm y^{-1})
Western	Port Nolloth/ Alexander Bay	+1.25 ± 0.23	+0.27	+0.76 ± 1.11	+0.29 ± 0.18	+0.56	+1.05	+0.80
Southern	Simon's Town/ Cape Town	+1.58 ± 0.22	+1.63	+1.89 ± 0.34	+0.29 ± 0.18	+1.92	+2.18	+1.23 or +2.00 (excluding Granger Bay and Mossel Bay)
	Granger Bay/ Cape Town	+0.08 ± 0.22	+0.03	+0.39 ± 0.20	+0.29 ± 0.18	+0.32	+0.68	
	Mossel Bay/ George	–0.40 ± 0.19	–0.38	+0.22 ± 0.46	+0.49	+0.11	+0.71	
	Knysna/ George	+1.27 ± 0.50	+1.23	+1.60 ± 0.76	+0.54	+1.77	+2.14	
Eastern	Port Elizabeth/ Port Elizabeth	+2.97 ± 1.38	+2.91	+3.38 ± 1.48	+0.66	+3.57	+4.04	+3.75
	Durban/ Durban	+2.70 ± 0.05	+2.88	+2.63 ± 0.96	+1.03	+3.73	+3.66	

Table 10: Eustatic sea level trends using annual sea level data

Region	Station (tide gauge station/ weather station)	Recorded annual sea level trend (Table 3) (mm y^{-1})	Barometric-corrected linear sea level trend (Method 1 from Table 7) (mm y^{-1})	Vertical crustal movements from Table 8 (mm y^{-1})	Sea level corrected for vertical crustal movement and barometric changes (Method 1) (mm y^{-1})	Regional eustatic sea level change (mm y^{-1})
Western	Port Nolloth/ Alexander Bay	+1.11 ± 0.41	+0.13	+0.29 ± 0.18	+0.42	+0.42
Southern	Simon's Town/ Cape Town	+1.14 ± 0.51	+1.19	+0.29 ± 0.18	+1.48	+1.14 or +1.97 (excluding Granger Bay and Mossel Bay)
	Granger Bay/ Cape Town	+0.44 ± 0.53	+0.49	+0.29 ± 0.18	+0.78	
	Mossel Bay/ George	–0.66 ± 0.56	–0.64	+0.49	–0.15	
	Knysna/ George	+1.95 ± 1.62	+1.91	+0.54	+2.45	
Eastern	Port Elizabeth/ Port Elizabeth	+2.89 ± 2.05	+2.83	+0.66	+3.49	+3.55
	Durban/ Durban	+2.40 ± 0.29	+2.58	+1.03	+3.61	

0.8–1.6 mm y^{-1} provided by Ishii et al. (2006). The eustatic sea level result of +0.42 mm y^{-1} using annual data appears to be low, which may have been influenced by the limited annual sea level data. Also, the large negative barometric trend recorded at Alexander Bay appears questionable. Unfortunately, this is the only sea pressure gauge in the area so it is difficult to confirm this result. The HadSLP2 data trends given in Gillett et al. (2005) also reflect a negative trend for this grid location. This negative trend, however, at Alexander Bay should be viewed with caution.

Southern region

This region forms the south-eastern extreme of the Benguela system and upwelling has been observed seasonally as far east as Port Elizabeth (Shannon and O'Toole 2003). The region is subject to variability in water temperature because of the mixing of the Benguela and Agulhas currents. Based on the work of Levitus et al. (2005), Bindoff et al. (2007) noted a significant warming off Cape Town and cooling off Mossel Bay/Knysna over the period 1955–2003. It is postulated that these two warm and cool seawater nodes are non-stationary and, depending on the relative strength of the Benguela and Agulhas currents, these nodes flux in an east/west and onshore/offshore direction, adding to the variability of the region.

There are four suitable gauge sites along the coastline of the southern region (Figure 1), which provides better coverage in the calculation of regional sea level changes than in the western region. Three of the tide gauges recorded rising sea levels, whereas the one at Mossel Bay recorded a change of –0.40 ± 0.19 mm y^{-1}. This difference appears to be at odds with surrounding stations and previous measurements for Mossel Bay (i.e. +1.01 mm y^{-1}) for the period 1960–1988 (Brundrit et al. 1989). The tide records of Mossel Bay and Knysna, situated approximately 105 km apart, were examined in more detail (Figure 5). The two gauges should record similar sea levels because of their close proximity, but there may be small differences due to dissimilarities between the sites. For example, Knysna may be affected by the dynamics at the mouth of the lagoon due to the Knysna Heads. The records at Mossel Bay show a drop in sea levels of approximately 100 mm for the period 1991–1995. If this period is removed from the records, then Mossel Bay shows little sea level change. The tide gauge records at Knysna is similarly affected, but at different times. Knysna has two drops in sea level of similar magnitude for the periods 1969–1972 and 1978–1979, and a rise of approximately 80 mm for the period 1996–2008. Removal of these periods from the record reduces the dataset to such an extent that trend estimates are not reliable. These variations are not temporally synchronised at both tide gauges so they are not the result of large-scale oceanic processes. These drops in sea level could be a result of data or gauge errors, which will require further investigation to improve the quality of the data.

The stations of Simon's Town and Knysna yielded a regional barometrically corrected sea level change of +1.48 mm y^{-1}. When vertical crustal movements were factored in, the regional eustatic sea level trends were +1.97 mm y^{-1} and +2.00 mm y^{-1} respectively. The eustatic sea level change was higher in the warmer southern region than in the cooler western region.

Eastern region

This region is affected by the warm Agulhas Current which moves southwards along the coastline. The warm water is mainly near the surface, which has been exposed to rising air temperatures in the equatorial zone. There are four tide gauge stations along this coastline. Because data from Richards Bay were only over an 11-year period and those from East London had just 50% coverage, they were excluded from the analysis. The average regional sea level change rate of +3.03 mm y^{-1} estimated for this region was the highest found along the South African coastline. Correcting for local influences of barometric pressure at Port Elizabeth and Durban results in both stations recording a marginally higher rate of sea level change than the uncorrected sea level trends. Those at Port Elizabeth ranged from +2.83 mm y^{-1} to +3.38 mm y^{-1} and at Durban from +2.58 mm y^{-1} to +2.88 mm y^{-1}. At both stations, increasing barometric trends

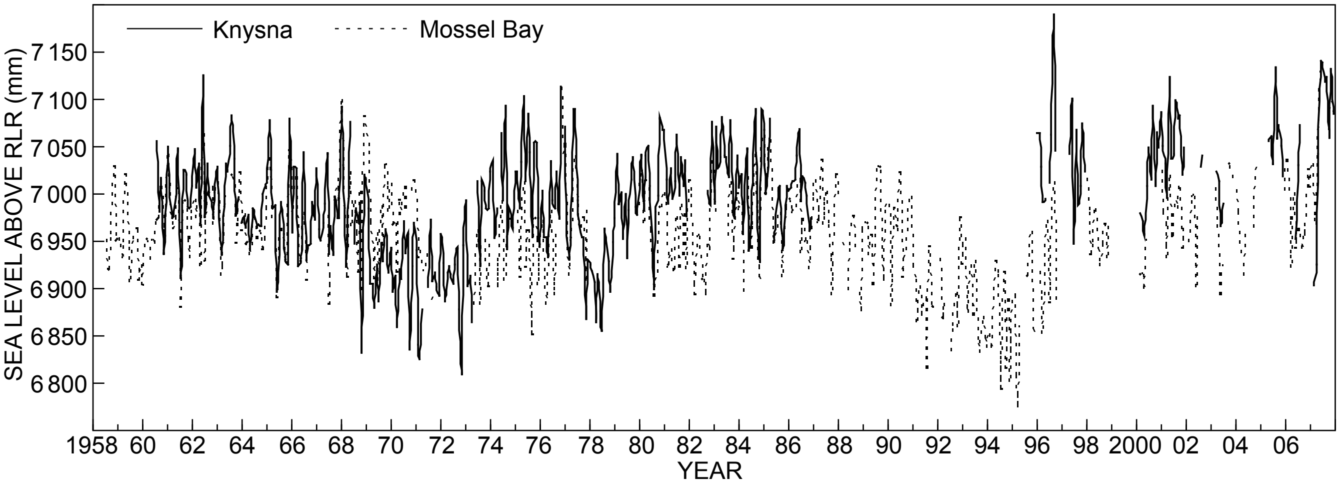

Figure 5: Tide records for Knysna and Mossel Bay, 1958–2008

suppress sea level changes to varying degrees, specifically in Durban, by as much as +0.18 mm y^{-1}. When these sea level trends were adjusted for vertical crustal movements, the regional eustatic sea level trends ranged between +3.55 mm y^{-1} and +3.75 mm y^{-1}. These figures are greater than the global average of +3.0 mm y^{-1} (Bindoff et al. 2007), which is to be expected for a region that is driven by warm water feeding in from the equator.

Conclusion

This is the first study to investigate all tide gauge sites along the southern African coastline and to assess the problems associated with the tidal records. It also considers for the first time the effects of barometric pressure and vertical crustal movements on sea level trends along the coastline. Several problems with the SAN tide dataset have been identified, which need to be rectified using corrections derived from this study. Over the past 50 years, sea level change around the southern African coastline has not been constant, thus it would be incorrect to apply a globally calculated sea level rise value uniformly to that coastline. The regional sea level trends determined here can be applied with more confidence to the various sections of our coastline for integrated coastal zone planning, including adaptation to sea level rise as well as coastal infrastructure planning. The variations in sea level change around the coast show distinctive differences in response, depending on their location. These changes are principally driven by a combination of physical characteristics at each location, most notably by the influences and interactions of the Agulhas and Benguela currents, and in turn by water temperature, barometric air pressure changes and vertical crustal movements. Whether these results reflect long-term trends or are part of a shorter cycle will be better understood when more data are accumulated in the future.

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PREDICTING EXTREME WAVE RUN-UP ON NATURAL BEACHES FOR COASTAL PLANNING AND MANAGEMENT

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A simple empirical model is proposed for predicting extreme wave run-up on natural beaches during severe wave events (deep water wave heights $H_0 \gtrsim 8\,\mathrm{m}$ or return periods of about 50 years). The new model departs from traditional approaches that use the slope of the beach face β_f and the Iribarren number ξ_0 as parameters for predicting run-up and instead uses the distance offshore x_h to water depth h to estimate a near-shore profile slope as $S = h/x_h$, where the depth of closure is the proposed choice for h. Extreme run-up R_x is then expressed in terms of S as $R_x/H_0 = CS^{2/3}$. Observations from recent severe storm events in South Africa are used to estimate the dimensionless coefficient $C \simeq 7.5$. The data are also compared with those of Holman [1986] and the results verify his regression equations and confirm they are valid for significant wave heights extending to 8.5 m for beach-face slopes around 0.1. The run-up predictions of Holman [1986], Nielsen and Hanslow [1991] and Stockdon *et al.* [2006] are compared to those of the proposed new model. The results suggest that the new model reduces the uncertainties in predicting wave run-up on natural beaches compared with previous models, and thus enables improved estimates of extreme wave run-up and the upper limit of beach change for coastal planning and management.

Keywords: Wave run-up; beaches; storms.

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1. Introduction

The prediction of extreme wave run-up on natural beaches is of particular interest to coastal engineers, coastal managers and land use planners. Extreme wave run-up levels are important in many planning processes but especially for estimating appropriate development setback lines [Holland and Holman, 1993] and the upper limit of beach change [Roberts *et al.*, 2010]. Wave run-up has been defined as the "time-varying location of the shoreline water level about still-water level" [Holman and Sallenger, 1985]. Extreme wave run-up may therefore be defined as the maximum level, relative to the still water level (SWL), reached by a wave or by a series of waves as they break and run-up the natural beach profile. It is often visible as a line of debris left after a wave event and can also be marked by a small scarp at the back of the beach left by the eroding waves.

The magnitude of wave run-up depends on a number of factors. For example, the maximum run-up observed at a particular location will depend on the duration of the observations because longer durations mean higher probabilities of sampling more extreme events. Wave run-up is expected to depend on wave parameters e.g. deep water significant wave height (H_0), period (T_0) and steepness may all have some influence. Run-up can also depend on the shape of the storm peak tide [Nielsen, 2009]. In this paper we focus on the extreme run-up of large storm waves defined as waves with H_0 exceeding 8 m and return periods (or average recurrence intervals) of about 50 years.

In developed areas extreme wave run-up is used to estimate the risk to existing and proposed infrastructure within the coastal zone. Early work on wave run-up was confined to laboratory experiments using regular waves on impermeable slopes [Iribarren and Nogales 1949; Miche, 1951; Saville, 1956; Savage, 1958; Hunt, 1959; Battjes, 1974a, 1974b] and extended by more recent work [Mase, 1989; Hedges and Mase, 2004]. Under these conditions wave run-up is entirely predictable. Irregular waves on permeable slopes are less predictable and generate a range of wave run-ups over time as shown in Fig. 1. The wave run-up $R(t)$ for a given range of wave conditions varies around an average value R_{av}, commonly referred to as the swash level [Holland and Holman, 1993], and between maximum and minimum values ($R_{\max}$ and $R_{\min}$) that depend on the duration of the record (as noted above). Statistical measures based on exceedance probabilities are widely used to characterize extreme wave run-up e.g. values of R that are exceeded say 2% of the time (denoted R_2 herein) are commonly used. However, for practical applications in coastal planning or risk assessment, it is useful to know the wave run-up associated with storm events having a specified average recurrence interval or return period [e.g. Callaghan *et al.*, 2009]. Those values are not in general simply related to exceedance statistics such as R_2. Since our main concern in this paper is risk assessment due to wave attack, we focus on extreme run-up due to storm waves with average recurrence intervals of about 50 years as a typical design life for coastal structures. These values will be

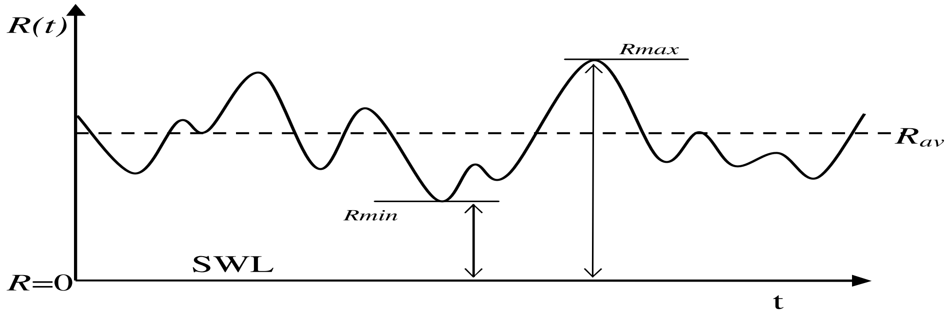


Fig. 1. Definition sketch of random wave run-up over time.

compared with previously published results for R_2 which are often used for coastal management and planning purposes.

Despite the development of empirical models to determine wave run-up on slopes, relatively little work has focused on extreme run-up on natural beaches. Previous research concerning wave run-up on natural beaches has used two approaches. The first approach is where run-up due to a range of wave conditions is observed at a single location. For example Holman [1986] used observations from the US Army research facility at Duck, USA. The data was for a range of wave heights from 0.4 m to 4.0 m, but included only a narrow band of beach slopes near 0.1.

A second approach is where data is sampled from several geographical locations for generally short periods. An example of this approach has been the work of Nielsen and Hanslow [1991] who collected data from six beaches in New South Wales, Australia. The data coverage was for deep water root mean squared wave heights $H_{0\,\mathrm{rms}}$ ranging from 0.53 m to 3.76 m (H_0 ranging between 0.75 m and 5.32 m), significant wave periods from 6.4 s to 11.5 s, and beach foreshore slopes from 0.026 to 0.189.

There is a third possible approach where data from a single extreme storm event is collected from a large number of beaches of varying beach slope. In this case the range of wave heights is limited, but the beach parameters can vary considerably. This approach relies on the (rare) occurrence of extreme storm events that leave clearly visible "telltale" signs of their effects on the beach which can subsequently be measured. This method was used for the present study. We could not find any published research that has previously adopted this approach to investigate wave run-up.

The variability of wave run-up has challenged researchers attempting to resolve the respective interactions which determine the extent of wave run-up e.g. infra gravity waves, swash action and incident wave energy. The relative strength of these components varies in the onshore direction: decreasing incident wave energy is progressively balanced by infra gravity wave energy between the inner and outer surf zones [Aagaard and Greenwood, 1995]. Infra gravity waves comprise bound long waves, leaky waves and edge waves [Bowen, 1972; Huntley and Kim, 1984] and bore and swash interactions [Emery and Gale, 1951; Carlsen, 1984; Mase, 1995]. In addition physical factors such as the beach topography will result in some variability of wave run-up. Secondary features of the storm event will also influence the magnitude of wave run-up, for example, eye-wall eddies of the cyclone wind field [Nielsen, 2009]. The complex interaction of these factors in time and space produces considerable variability in wave run-up observations.

Observations by Mase [1989] have ascribed R to a combination of (1) the incident wave height (2) low frequency infra-gravity waves or "surf beat" [Munk, 1949; Tucker, 1950] and (3) wave groups (as opposed to a single wave) resulting in a larger R. Aagaard and Greenwood [1995] have shown that infra-gravity waves dominate the surf zone and R is dominated by infra-gravity waves when $\xi_0 < 1.5$, as is the case here. The infra-gravity waves periodically raise the water levels allowing the incident waves to run further up the beach slope [Wright, 1980]. Previous work by Goda [1975], Guza and Thornton [1985] and Howd *et al.* [1991] have estimated that infra-gravity wave amplitudes vary between 20% and 60% of the incident wave height.

Our observations of extreme wave run-up are presented in Sec. 2 which is followed by a discussion of existing wave run-up models in Sec. 3. The wave run-up observations are compared to values of R_2 predicted by existing wave run-up models in Sec. 4. A proposed new model is introduced and evaluated in Secs. 5 and 6. Discussion and conclusions are presented in Sec. 7.

2. Observations

The coastline around South Africa can be described as having an energetic wave climate and is typically steep (due to absence of a wide flat coastal terrace) with water depths reaching 15 m within 750 m of the shoreline. Wave events, particularly in the southern coastline of South Africa, are influenced by coastal lows and cutoff low pressure systems generated by weather systems in the Southern Oceans. Along the east coast of South Africa, these influences, as well as tropical cyclones that originate from the north-east of Madagascar, influence the wave climate [Taljaard, 1985]. During these events, the deep water significant wave heights occasionally reach 8 m to 10 m (periods between 11 s and 17 s) off Durban and 10 m to 12 m (periods between 14 s and 20 s) off Cape Town [Ematek, 1991]. Two such extreme wave events that occurred recently were analyzed for this study.

The first event occurred during 19–21 March 2007 when a stationary cutoff low pressure system induced a sea storm which impacted approximately 400 km of the South African coastline in the province of KwaZulu-Natal (KZN) between Richards Bay in the north to approximately 200 km south of Durban (refer Fig. 2). Extreme waves persisted for several days and during the peak, significant wave heights $H_0 \simeq 8.5$ m were recorded in water depth of 30 m by the Richards Bay wave rider buoy [Mather, 2008]. The waves inflicted severe damage (valued at about US$100 million) to infrastructure and private homes [Mather, 2008].

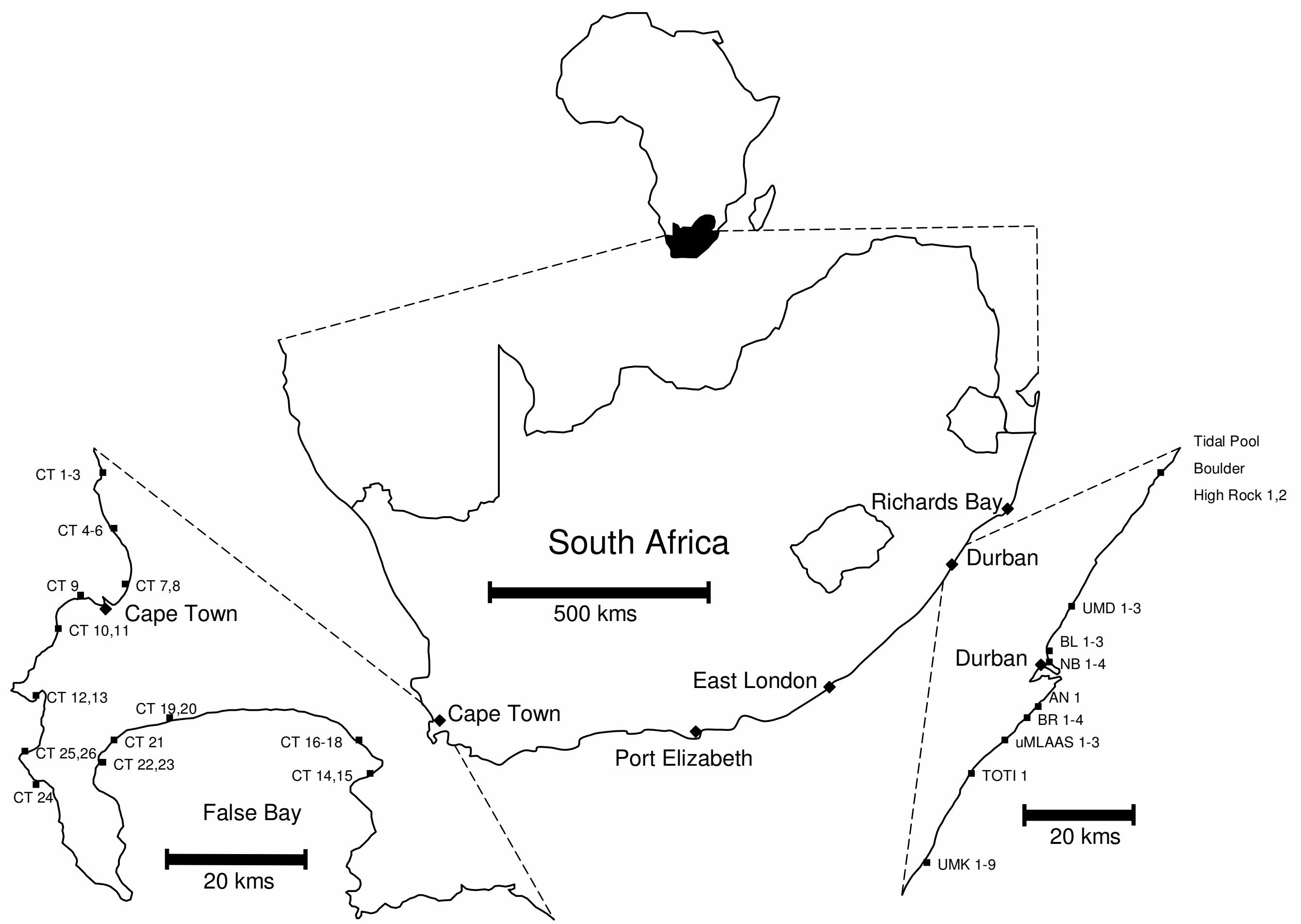


Fig. 2. The South African coastline showing the location of the present wave run-up measurements.

Shortly after the storm had subsided a land surveyor collected data on the maximum wave run-up heights. The surveyor used the telltale debris line along the beach that marked the locations where debris had been washed up on the beach. In some instances, a small scarp had been eroded on the upper beach and this was also recorded. These measurements were collected at twelve beaches along the KZN coastline (refer Fig. 2 and Table 1). Beach slopes at these locations ranged from 0.020 to 0.129 and the Iribarren number ξ_0 varied between 0.145 and 0.918 i.e. dissipative to intermediate beaches.

Table 1. Extreme wave run-up data for the March 2007 storm in the Durban region (see Fig. 2).

Locator Reference (see Fig. 2)	Run-up (m above SWL)	Beach slope $\tan \beta_f$	Iribarren No. ξ_0
UMD 1	5.106	0.129	0.918
UMD 2	4.910	0.129	0.918
UMD 3	5.558	0.129	0.918
BL 1	3.090	0.020	0.145
BL 2	2.609	0.020	0.145
BL 3	2.202	0.084	0.594
NB 1	2.269	0.058	0.594
NB 2	2.213	0.058	0.413
NB 3	2.573	0.058	0.413
NB 4	2.921	0.058	0.413
NB 5	2.785	0.058	0.413
AN 1	5.615	0.100	0.413
BR 1	4.271	0.115	0.711
BR 2	5.399	0.115	0.817
BR 3	5.948	0.115	0.817
BR 4	6.539	0.115	0.817
UML 1	5.070	0.040	0.286
UML 2	5.041	0.040	0.286
UML 3	4.727	0.040	0.286
TOTI 1	4.669	0.054	0.384
UMK 1	4.133	0.086	0.610
UMK 2	1.870	0.086	0.610
UMK 3	2.742	0.086	0.610
UMK 4	2.893	0.086	0.610
UMK 5	4.579	0.054	0.383
UMK 6	4.012	0.054	0.383
UMK 7	5.852	0.054	0.383
UMK 8	5.551	0.054	0.383
UMK 9	5.907	0.054	0.383
TIDAL POOL	5.923	NA	NA
BOULDER	6.193	NA	NA
HIGH ROCK 1	9.093	NA	NA
HIGH ROCK 2	9.203	NA	NA

The return period (or average recurrence interval) of this storm has been estimated by Phelp *et al.* [2009] to be between 35 and 85 years depending on the threshold used for their peak-over-threshold (POT) analysis (see e.g. Goda, 2010). Assuming an actual return period of say 50 years, and that the event causes run-up values with the same probability of occurrence, it follows that observed wave run-up heights during the event would be equalled or exceeded on average only once in any 50-year sample of continuous observations at the same location.

Visual observations after the storm revealed that the waves had propelled large rocks, concrete blocks and road works up the dune slopes as far as 10 m above Mean Sea Level (MSL) [Mather, 2008]. The storm scoured out large volumes of sand off the visible beach and dumped this sand in a bar 400 m offshore [Ramsay, 2008]. Shoreline retreat of 30 m was recorded in many locations [Smith *et al.*, 2010]. Observation made from the air during the event showed a correlation between surf zone width and the underwater bathymetry. In areas where the bathymetry was shallow, a wide (± 500 m) surf zone was evident. In areas with steeper bathymetry, the surf zone was correspondingly narrower (± 200 m) which suggests that the wave run-up is dependent on the bathymetric profile.

A second extreme event with significant wave heights $H_0 \simeq 10.7$ m occurred in the Cape province during the period 31 August to 4 September 2008. A frontal weather system developed approximately 600 km south-west of Cape Town. A secondary low pressure zone then grew as an example of explosive cyclogenesis [Hunter, 2008]. The secondary low migrated in a north-easterly direction causing damage along approximately 1200 km of the South African coastline between Cape Town and Port Elizabeth (Fig. 2). Significant damage to harbours, fishing craft, coastal infrastructure and transportation systems occurred due to the event. After the storm, wave run-up heights were measured at seventeen beaches around the Cape Town coastline using similar telltale signs as for the KZN storm event (refer Fig. 2 and Table 2).

A sample of photographs taken during the above-mentioned storm events are shown in Fig. 3 and illustrate some of the damage experienced.

3. Previous Work on Irregular Wave Run-Up

The processes involved as waves propagate from deep water inshore to a beach are complex. However, it is well known that as waves approach a shoreline their shape and height change. This can cause a change in wave direction depending on the incident wave angle to the coastline. Svendsen *et al.* [1978] and Short [1999] have identified four hydrodynamic sections along a sloping beach: (1) a pre-breaking or shoaling section where waves steepness increases until the wave breaks, (2) an outer surf zone where the highest waves in the distribution break, (3) the inner surf zone section where waves transform into surges or bores, and (4) a wave run-up section which is of particular interest in this paper. The local maximum of the radiation

Table 2. Extreme wave run-up measurements from a storm (Aug/Sept 2008) in the Cape Town region (see Fig. 2). The coast type "small bay" refers to embayments with about 3 km between headlands, while "large bay" refers to embayments with about 40 km between headlands (see Fig. 2).

Locator Reference (see Fig. 2)	Run-up (m above SWL)	Coast Type
CT 1	2.104	OPEN COAST
CT 2	3.464	OPEN COAST
CT 3	2.494	OPEN COAST
CT 4	2.864	OPEN COAST
CT 5	2.224	OPEN COAST
CT 6	2.064	OPEN COAST
CT 7	4.804	OPEN COAST
CT 8	4.534	OPEN COAST
CT 9	3.144	OPEN COAST
CT 10	7.864	OPEN COAST
CT 11	3.114	SMALL BAY
CT 12	2.054	SMALL BAY
CT 13	2.154	SMALL BAY
CT 14	4.734	SMALL BAY
CT 15	0.964	SMALL BAY
CT 16	1.294	LARGE BAY
CT 17	1.294	LARGE BAY
CT 18	2.324	LARGE BAY
CT 19	3.464	LARGE BAY
CT 20	2.304	LARGE BAY
CT 21	2.174	LARGE BAY
CT 22	1.504	LARGE BAY
CT 23	NO DATA	LARGE BAY
CT 24	2.374	OPEN COAST
CT 25	3.364	OPEN COAST
CT 26	2.534	OPEN COAST

stress at the breaking location generates a drop in water level at the start of the surf zone (wave "set-down") and a rise in water levels (wave "set-up") approaching the shoreline [Longuet-Higgins and Stewart, 1963; Bowen *et al.*, 1968; Nielsen, 1988]. The surf zone accounts for most of the wave energy dissipation [Stockdon, 2006]. When the waves reach the beach some of the remaining energy is converted to potential energy in the form of wave run-up on the slope of the beach [Hunt, 1959] and some is reflected back out to sea. The wave run-up provides some of the energy needed to rework the beach slope, erode the toe of any dunes [Ruggiero *et al.*, 2004; Sallenger, 2000] and attack any manmade structures in its path.

(a)

(b)

(c)

(d)

(e)

Fig. 3. Storm wave damage in KwaZulu-Natal at (a) Balito Bay (BL) (b) Umkomaas (UMK), and in the Cape Province at (c) Strand (CT16) (d) Kalk Bay (CT21), and (e) Port Elizabeth. Refer Fig. 2 and Tables 1 and 2 for location details. (Photos by S. Bundy, A. Mather, A. Theron, R. Klein, M. Hoppe.)

Holman and Sallenger [1985] analyzed 154 wave run-up time series and found that

$$\frac{R}{H_0} \propto \xi_0 \,, \tag{1}$$

where

$$\xi_0 = \frac{\tan \beta_f}{\sqrt{H_0/L_0}} \,, \tag{2}$$

where β_f is the beach slope, confirming the earlier work of Hunt [1959] and Battjies [1974]. Holman [1986], using data gathered from Duck, USA, where deep water wave heights H_0 ranged between 0.4 m and 4.0 m and wave periods T_0 between 6 s and 16 s, was able to deduce a relationship for R_2, the run-up exceeded for 2% of the time, as

$$R_2 = 0.45H_0 + 1.21 \,, \tag{3}$$

where H_0 is the significant wave height (m) in 20 m water depth. Holman also gave an alternative regression equation in terms of ξ_0 as

$$\frac{R_2}{H_0} = 0.83\xi_0 + 0.20 \,. \tag{4}$$

Douglass [1992] re-analyzed the Holman [1986] field measurements and argued that beach slope was not an important parameter in predicting wave run-up on natural beaches. Douglass suggested the relationship

$$\frac{R_2}{H_0} = \frac{0.12}{\sqrt{H_0/L_0}} \,, \tag{5}$$

where L_0 is the deep water wave length associated with wave period T_0.

Nielsen and Hanslow [1991] undertook field studies on beaches with irregular waves where deep water root mean squared wave heights $H_{0\,\mathrm{rms}}$ ranging from 0.53 m to 3.76 m (H_0 between 0.75 m and 5.32 m), wave periods between 6.4 s to 11.5 s, beach slopes between 0.026 and 0.189, and beach sand grain size d_{50} between 0.2 mm and 0.8 mm. Their results yielded an equation for the 2% exceedance wave run-up as

$$R_2 = 1.98\, L_{zwm} \,, \tag{6}$$

where

$$L_{zwm} = 0.60\sqrt{H_{0\,\mathrm{rms}}\, L_0}\tan \beta_f \quad \text{for } \tan \beta_f > 0.1 \,, \tag{7}$$

$$L_{zwm} = 0.05\sqrt{H_{0\,\mathrm{rms}}\, L_0} \quad \text{for } \tan \beta_f \leq 0.1 \,. \tag{8}$$

Stockdon *et al.* [2006] examined data from beaches in the USA and the Netherlands and derived their formula for the 2% exceedance wave run-up as

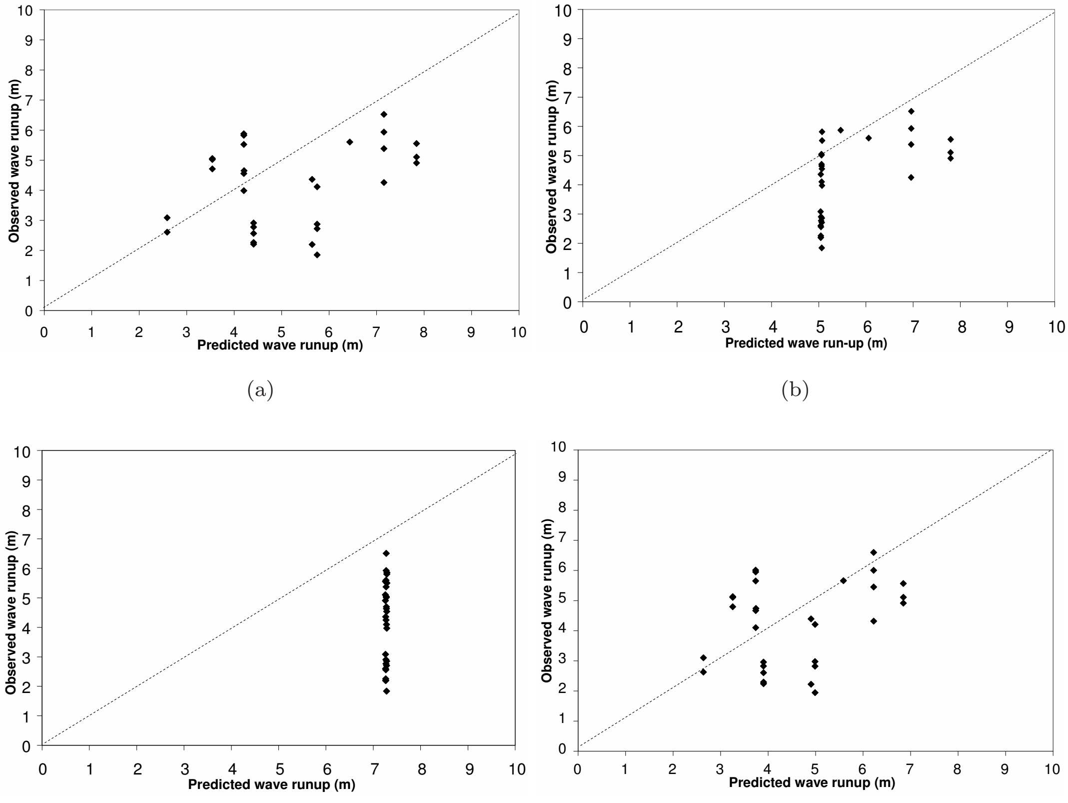
$$R_2 = 1.1\left[0.35\beta_f \sqrt{H_0 L_0} + 0.5\sqrt{H_0 L_0 (0.563{\beta_f}^2 + 0.004)}\,\right], \tag{9}$$

where $0.1 < \xi_0 < 2.2$, $L_0 = \mathrm{g}{T_0}^2/2\pi$.

Predictive models of wave run-up have traditionally focused on the beach foreshore slope β_f as the key determinant of R in studies using regular waves [Miche, 1951; Hunt, 1959; Battjes, 1974b; Mase, 1989; Hedges and Mase, 2004] and irregular waves [Holman and Sallenger, 1985; Sallenger and Holman, 1986; Guza and Thornton, 1989; Nielsen and Hanslow, 1991; Sallenger, 2000; Ruggiero, Holman and Beach, 2004; Stockdon *et al.*, 2006]. An exception is the model proposed by Douglass (1992) who argued that extreme run-up is independent of the beach-face slope β_f.

4. Performance of Existing Run-Up Models

The extreme wave run-up observations described in Sec. 2 provide an opportunity to test the wave run-up models discussed in Sec. 3. Using the data collected from the KZN March 2007 storm event, comparisons between observed wave run-up and predicted R_2 wave run-up were undertaken using the models of Holman [1986], Nielsen and Hanslow [1991], Douglass [1992] and Stockdon *et al.* [2006]. The results are shown in Fig. 4.



(a)

(b)

(c)

(d)

Fig. 4. Observed against predicted wave run-up for the March 2007 storm (a) Holman [1986], (b) Nielsen and Hanslow [1991], (c) Douglass [1992], (d) Stockdon *et al.* [2006].

The models of Holman [1986, Fig. 4(a)], and Nielsen and Hanslow [1991, Fig. 4(b)] mostly over-estimate the observed extreme wave run-up from the storm event, a trend that has been previously reported in other contexts [CEM, 2006]. The predictions of the Nielsen and Hanslow [1991] model (Fig. 4(b)) has no dependance on beach slope for $\tan \beta_f \leq 0.1$ (see Eq. (8)), which is evident in the results shown in the plot. The Douglass [1992] model (Eq. (5)) over-estimates the observed wave run-up in all instances (Fig. 4(c)). It yields a maximum calculated value of 7.26 m compared to an observed value of 6.54 m (see Fig. 4(c)) but the predictions over-estimate the observed run-up by up to a factor of 3.5. The Douglass model does not use any physical beach parameters and is understandably constrained by this fact. Eq. (9) from Stockdon *et al.* [2006] also over-estimates the observed wave run-up (Fig. 4(d)) but its predictions show slightly less scatter that the other models.

Holman's equation provides a relationship between R_2 and H_0 (Eq. (3)) for average beach slopes of about 0.1 and with wave heights limited to about 4 m. The data available from the present study for large wave heights provided an opportunity to verify the relationship between R and H_0 for an extended range of wave heights. The original Holman data (his Fig. 4(a) on page 534) was replotted against the wave run-up values obtained in the KZN event for beach face slopes between 0.10 and 0.13 (Fig. 5). All the extreme wave run-up data are located within an envelope

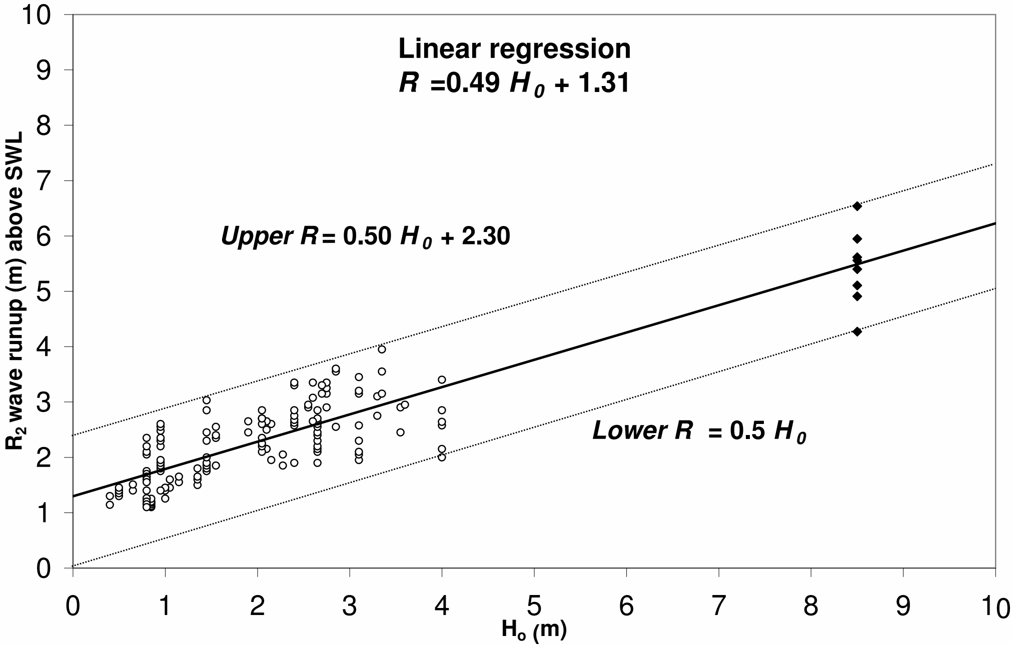


Fig. 5. Re-analysis of Holman [1986] (shown as circles) with wave run-up data from the March 2007 storm (shown as solid diamonds). All data is for beach slopes between 0.1 and 0.13.

bounded by upper and lower limits given by

$$\text{Upper-bound} \quad R_{\max} = 0.5H_0 + 2.30\,, \tag{10}$$

$$\text{Lower-bound} \quad R_{\min} = 0.5H_0\,. \tag{11}$$

The linear regression line including the new data gives (see Fig. 5)

$$R = 0.49H_0 + 1.31 \tag{12}$$

for $\tan\beta_f \approx 0.1$ and $H_0 > 1.5\,\text{m}$, which is very similar to that originally obtained by Holman [1986] and given earlier in this paper as Eq. (3). Note that for small H_0 a linear relationship may be expected to break down.

5. A Proposed New Wave Run-Up Model

Our approach differs from previous research in this field as it focuses on parameters other than beach-face slope to define the amount of wave run-up. The basis of the model rests with the interconnected relationships between various natural beach attributes. Previous research on wave run-up has found it to be proportional to beach foreshore slope β_f e.g. Hunt [1959], Holman [1986], Mase [1989], Nielsen and Hanslow [1991], Sallenger [2000], Hedges and Mase [2004], and Stockdon *et al.* [2006]. The beach foreshore slope β_f has in turn been found to be proportional to beach sand grain size d_{50} by Bascom [1951], Emery and Gale [1951], McClean and Kirk [1969], King [1972], Komar [1976], Sunamura [1984], Antony [1998].

Bruun [1954], following on the initial work of Fenneman [1902], hypothesized that the smoothed bed profile can be represented by a power law in the form

$$h = Ax^p\,, \tag{13}$$

where h is the depth below mean sea level at a distance x offshore, and A is an empirically determined coefficient. This was developed further by Dean [1977, 1987, 1990, 1991] who provided a rationale for Eq. (13) and published the well-known equilibrium profile equation

$$h = Ax^{2/3}\,. \tag{14}$$

The parameter A in Eq. (14) governs the overall steepness of the profile. Further work found that A varied with sediment fall velocity [Work and Dean, 1991; Kreibel *et al.*, 1991] and with sediment grain size d_{50} [Rouse, 1937; Moore, 1982; Swart, 1974; Boon and Green, 1988; Dean, 1987].

The above-mentioned work suggests that there is a relationship between the offshore profile shape given by Eq. (14) and the beach foreshore slope β_f. In other words, the whole beach profile from the high water mark to the closure depth is interrelated and shaped by the wave climate and sediment size available at each location. Therefore, we postulated that it is possible to correlate wave run-up R

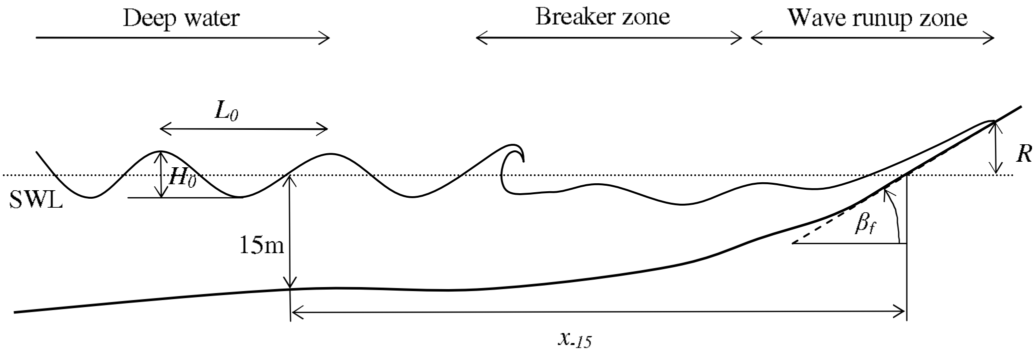


Fig. 6. Sketch defining the parameters for the proposed new wave run-up model.

with the shape of the offshore profile or more specifically to a specified point on the sea bed at a distance x_h and depth h seaward of the surf zone (see Fig. 6), whence

$$\frac{R_x}{H_0} \sim \left(\frac{x_h}{h}\right)^p. \tag{15}$$

To test the new model, extreme wave run-up heights along the open KZN coastline were plotted against the slope of the nearshore bathymetry. For this analysis, it was necessary to choose a depth contour and in this case a depth of 15 m was selected for three reasons. Firstly, the closure depth as defined by Bruun [1954] is between 10 m and 18 m along this coastline [Theron, 1994; Mather, 2008] with 15 m a representative average value. On physical grounds the closure depth seems an appropriate choice for characterizing the average nearshore bathymetry since it delineates the morphologically active profile from the less active deeper water profile. Secondly, the 15 m depth contour is typically available on regional navigation charts [South African Navy, 2007]. Thirdly, this is approximately the depth where regional maximum wave heights of 8 m to 10 m start behaving as shallow water waves (i.e. $h/L_0 \leq 0.05$ with $L_0 \approx 300$ m).

The recorded wave run-up levels are plotted against the distance offshore to the 15-m depth contour in Fig. 7. All the open coastline data from Tables 1 and 2 are shown in the plot. From Fig. 7, a relationship between observed extreme wave run-up R_x and the horizontal distance from the beach (SWL) to the selected depth contour can be expressed in the form

$$\frac{R_x}{H_0} = CS^{2/3}, \tag{16}$$

where $S = (h/x_h)$ is a representative nearshore slope ($h \simeq 15$ m in our case), H_0 is the deep water significant wave height, and C is a dimensionless coefficient. The data in Fig. 7 suggests that Eq. (16) with $3 \leq C \leq 10$ gives upper and lower bounds for R_x for all the open coastline measurements. Median values are described approximately by $C \simeq 7.5$.

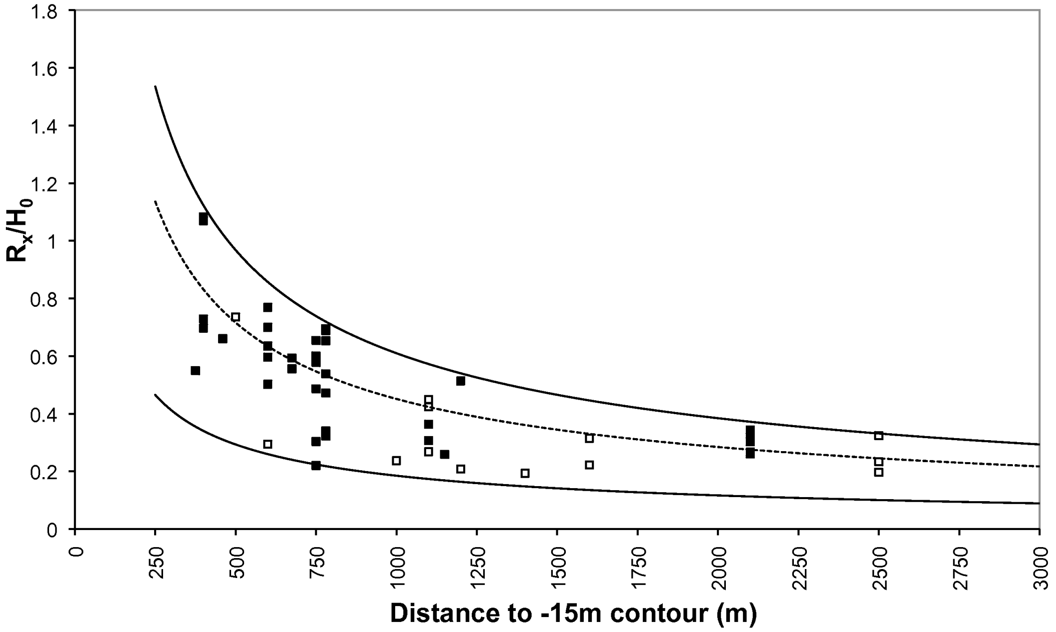


Fig. 7. Open coastline run-up data for the KZN (solid symbols) and Cape (open symbols) storm events, plotted versus the distance offshore to the 15 m depth contour. The upper bound line is Eq. (16) with $C = 10$ and lower bound line has $C = 3$. The dotted line approximately represents median values with $C = 7.5$.

Table 3. Root mean square error statistics comparing various model predictions of extreme wave run-up.

Model	Sample Size	RMS Error
Holman (1986)	29	2.28
Nielsen and Hanslow (1991)	21	2.28
Stockdon *et al.* (2006)	29	2.01
Mather *et al.* (this paper)	29	1.55

The run-up observations are shown re-plotted in Fig. 8 for comparison with the previous model predictions shown in Fig. 4. There remains considerable scatter in the data but a small improvement over the previous models is evident. Note that data from the Cape storm event are not included in Fig. 4 since measurements of beach-face slopes β_f were not recorded in that case. Error statistics are summarized in Table 3 where it is evident that the two models which predict the least dispersion are those of Stockdon *et al.* [2006] and that proposed in this paper.

As a further test of the proposed new model, it was used to predict an extreme wave run-up line along the KZN coastline for the March 2007 storm conditions ($H_0 \simeq 8.5\,\text{m}$). Comparison between the model predictions and an observed wave run-up line was undertaken. The latter was determined visually from aerial photography

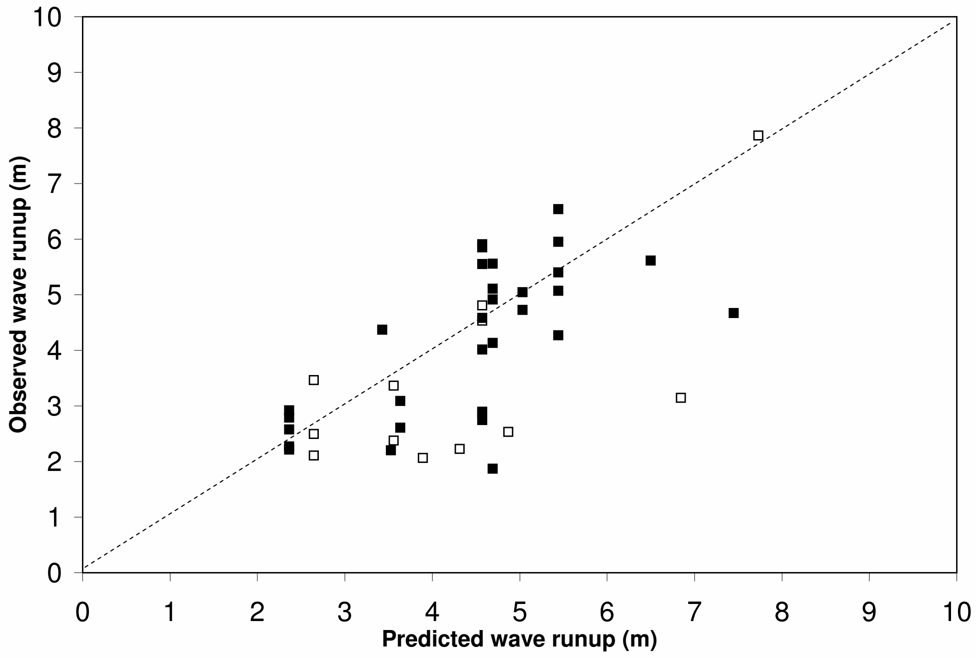


Fig. 8. Open coastline run-up data for the KZN (solid symbols) and Cape (open symbols) storm events, compared with the predictions of Eq. (16) with $C = 7.5$.

taken shortly after the storm. The most obvious feature was the small beach scarp or wave-cut platform left on the back beach. This wave-cut line was mapped using GIS and compared with the model prediction in several locations. Approximately 1000 values (a 5% sample) of the differences between the observed and predicted horizontal wave run-up positions were thus obtained. The result of this analysis is shown as a histogram in Fig. 9, and indicates that 52% of the predicted wave run-up positions are within a horizontal distance of about 1 m from the observed positions. The model on average over-predicts by a horizontal distance of 1.6 m.

6. Extension to Different Coastline Types

The new run-up model was initially developed and tested for the long straight open KZN coastline. For this model to be useful, it was necessary to verify its applicability at alternative locations and for different types of coastlines. In order to test this, the Cape and KZN data were combined by normalizing R_x by H_0 and plotting all the data together as shown in Fig. 7. A similar pattern emerges in that wave runup is confined between an upper bound where $C = 10$ and a lower bound where $C = 3$. The combined data confirm the original KZN formulae of $R_x/H_0 = C\ S^{2/3}$ where $C \simeq 7.5$. Further separation of the data into open coastlines, large embayments and small embayments are shown in Fig. 10. The family of applicable C values

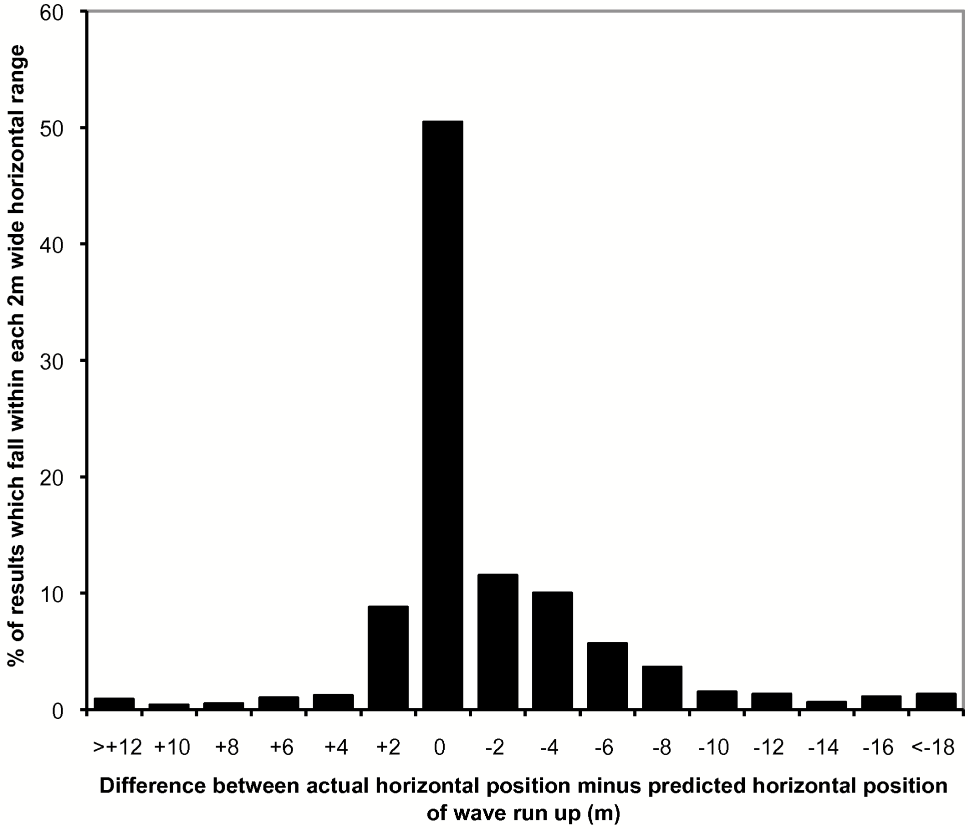
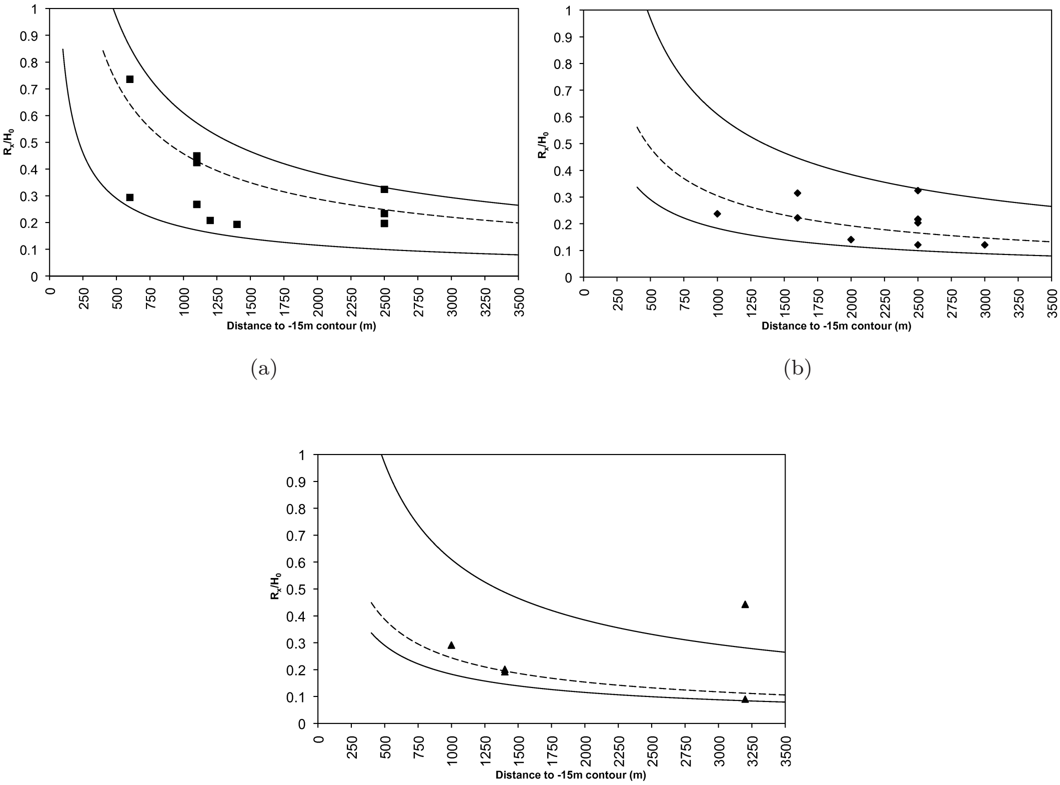


Fig. 9. Histogram of the differences between the actual horizontal wave run-up position versus the positions predicted using the proposed new run-up model.

Table 4. Model coefficients (refer Eq. (16)) for predicting extreme wave run-up on different coastline types. Coefficients are shown for upper/lower bounds and median values as depicted in Fig. 10. The coast type "small bay" refers to embayments with about 3 km between headlands, while "large bay" refers to embayments with about 40 km between headlands (see Fig. 2).

Coastline Type	Upper Bound	Median	Lower Bound
Open coast	$C = 10$	$C = 7.5$	$C = 3.0$
Large embayment	$C = 10$	$C = 5.0$	$C = 3.0$
Small embayment	$C = 10$	$C = 4.0$	$C = 3.0$

is summarized in Table 4. In Fig. 10(c), there is a single outlier point, and closer examination revealed that the measurement was made adjacent to a man-made structure which focussed the incoming wave energy causing a local anomaly.



(a)

(b)

(c)

Fig. 10. Run-up data from the Cape coast (refer Table 2) re-plotted as a function of the distance to the 15 m depth contour, but grouped as (a) open coastlines, (b) large embayments (~ 40 km between headlands), and (c) small embayments (~ 3 km between headlands). The upper and lower bound curves in each plot are Eq. (16) with $C = 10$ and $C = 3$ respectively. Curves for median values are shown using $C = 7.5$, 5, 4 for each case (refer Table 4).

7. Discussion and Conclusions

Predicting wave run-up is difficult given the complexities of processes such as energy dissipation through the surf zone. This has lead to the development of empirical models. The seminal work undertaken by Holman [1986] and Nielsen and Hanslow [1991] has been widely used to predict extreme wave run-up. More recent work by Stockdon *et al.* [2006] on setup, swash and run-up has further advanced our understanding of these processes. However, the empirical models produce a wide scatter of results when applied to real situations (Fig. 4). This scatter may be the result of small differences in beach slope, underwater features such as rocky outcrops, and the fact that not every section of the beach was exposed to the same incoming wave energy. The random, distributed nature of the incoming wave energy could cause spatial variations even in the same study area. For practical applications in coastal management and planning, it is important that uncertainties are minimized to provide improved confidence in the predicted results.

In this paper, we have approached the problem from a different perspective. Using established relationships between beach variables, the extreme wave run-up associated with storm conditions with a particular return period has been related to the near-shore profile as parametrized by the distance offshore to a chosen depth contour. We have shown that the proposed model slightly over-predicts run-up position (an average of 1.6 m horizontal distance inland) but this over-prediction may well be related to the use of the beach scarp as an indicator of maximum run-up location. This scarp slope may have moved further inland with a longer storm duration. Under the circumstances, the small bias in the model predictions is considered negligible and the proposed model provides a good indication of wave run-up position on natural beaches.

In contrast, existing models are predominately based on the final portion of the beach profile i.e. the beach face slope β_f. The performance of these models has been compared to our new model (Figs. 4 and 8). All models exhibit scatter in their predictions, which is not surprising given the complexities of the processes they are trying to explain. The error statistics in Table 3 indicate that the two models which predict extreme run-up with the least dispersion are those of Stockdon *et al.* [2006] and that proposed in this paper.

Previous run-up models require significantly more information than the new model e.g. the model of Stockdon *et al.* [2006] requires information about the beach face slope β_f which would need to be gathered in the field. The new model also departs from the models of Holman [1986], Nielsen and Hanslow [1991] and Stockdon *et al.* [2006] by not including any dependance on ξ_0. Initially this appears to be surprising as ξ_0 has been incorporated into most run-up formulae to date. However, recent large scale laboratory tests by Roberts, Wang and Kraus [2010] have shown that the exclusion of ξ_0 provides better predictions. Roberts *et al.* [2010] were able to show that wave run-up is dependent only on the breaking wave height i.e. $R_{tw} = H_{bs}$ where R_{tw} is the vertical excursion of total wave runup and H_{bs} is the significant breaking wave height. Their comparisons with the models of Holman [1986] and Stockdon *et al.* [2006] indicated that their simple model was superior. The next best predictor for wave run-up was the model of Guza and Thornton [1982]. Guza and Thornton's model also does not use ξ_0. Roberts *et al.* [2010] also discussed the Nielsen and Hanslow [1991] model, and they confirm that ξ_0 does not appear to be a factor in wave run-up on gentle beaches with a slope of less than 0.1.

The prediction of extreme wave run-up is an important component in coastal management. Our research has shown that while there are several wave run-up models available, they give a wide range of predicted wave run-ups when applied to storm waves impinging on natural beaches. One aim of this research was to develop a simple yet practical extreme wave run-up predictive tool which can be used for natural sandy beaches by coastal planners or managers. There are financial and technical resource limitations for organizations along the African coastline. It is only in extremely rare cases that detailed information, such as wave height, period and beach-face slope, is available to predict wave run-up in accordance with most existing models. The present study should assist these under-resourced organizations to better plan for extreme events and provide a guide for assessing hazards associated with extreme wave run-up.

A problem in practical applications of run-up models based on beach face slope is that the latter is likely to change during storm events. Even an H_0 of 2 m is sufficient to alter the beach face profile [Holman *et al.*, 1978]. It is therefore less reliable to base predictions of extreme wave run-up on the pre-storm beach-face slopes, although this has become a common approach to predicting wave run-up. The bathymetric profile during storms, particularly at depths beyond the closure depth (or about twice the wave height) is more stable and easier to measure, and does not undergo as much change during a storm. This makes it a superior indicator of the profile shape than the beach-face slope for use as a parameter in predicting extreme wave run-up heights.

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Article

A Perspective on Sea Level Rise and Coastal Storm Surge from Southern and Eastern Africa: A Case Study Near Durban, South Africa

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Abstract: Recent coastal storms in southern Africa have highlighted the need for more proactive management of the coastline. Within the southern and eastern African region the availability of coastal information is poor. The greatest gap in information is the likely effects of a combination of severe sea storms and future sea level rise (SLR) on the shoreline. This lack of information creates a barrier to informed decision making. This research outlines a practical localized approach to this problem, which can be applied as a first order assessment within the region. In so doing it provides a cost effective and simple decision support tool for the built environment and disaster professionals in development and disaster assessments. In a South African context the newly promulgated Integrated Coastal Management Act requires that all proposed coastal developments take into consideration future SLR, however such information currently does not exist, despite it being vital for informed planning in the coastal zone. This practical approach has been applied to the coastline of Durban, South Africa as a case study. The outputs are presented in a Geographic Information System (GIS) based freeware viewer tool enabling ease of access to both professionals and laypersons. This demonstrates that a simple approach can provide valuable information about the current and future risk of flooding and coastal erosion under climate change to buildings, infrastructure as well as natural features along the coast.

Keywords: climate change; coastal erosion; flooding; hazards; sea-level rise

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1. Introduction

In recent years, much work has been done on global climate change and the likely impacts that may arise from this change [1–6]. However, relatively little research on climate change has been undertaken for the African continent and in the southern and eastern African region to date, with the exception of South Africa. Climate change impacts are likely to affect many different aspects of the world's environment. However, this paper focuses on coastal flooding hazards, both now and under future sea-level rise (SLR) along the southern and eastern African shoreline.

In South Africa, amid increased awareness and concern of climate change and SLR, several government agencies have commissioned research in these areas. Studies of SLR in Durban [7] and SLR in Namibia and South Africa [8] and regional impacts of climate change in the Western Cape [9] have recently been completed. Three of South Africa's major coastal cities, Durban [10–14], Cape Town [15] and Port Elizabeth have embarked on studies to understand and address these impacts. Research institutions are now also contributing [16–18]. Within Africa, outside of South Africa there has been even less research work done although Mozambique has initiated discussions and projects on SLR [19,20].

While this new impetus is encouraging, the capacity of governments, regions, cities and communities in Africa to proactively manage, mitigate and adapt to the impacts of climate change has been a concern in international circles [21]. This concern arises due to the high mitigation and adaptive costs that are likely to be required. The region is financially poor by world standards and very little funding is likely to be available for widespread interventions, which makes the challenge of dealing with climate change and SLR even more difficult. In reality, there is limited scope for mitigation of climate change and therefore efforts must be concentrated on adaptation. In order to adapt for the future, it is important to understand the nature and significance of possible threats. Without any understanding of the possible risks, any adaptation interventions run the risk of being mis-directed.

2. Problem Statement

The southeastern coastline of southern Africa, comprising South Africa, Mozambique, Tanzania and Kenya, is regularly affected by cyclonic and other significant weather events that have the ability to unleash large wave events along the coast. The impacts of climate change and SLR are likely to exacerbate the existing problems of coastal flooding and erosion [14]. Much of this coastline comprises sandy beaches backed by flat low coastal plains that are already vulnerable to flooding and erosion in extreme wave events. Progressive SLR will worsen the situation but it is the episodic wave events, occurring with little advanced warning that results in significant flooding and erosion.

In order to plan for these hazards some baseline data is needed. The reality is that countries in this region do not have spare funds to generate this data and so it is unlikely that in the foreseeable future data that would meet first world standards will be collected. However, historical data on cyclone events are available [22]. There are tide gauges in the region but with inadequate spatial coverage and of those stations that have tide data they are for relatively short durations that prevent high confidence sea-level change trends from being deduced [23]. There is very limited coastal erosion and shoreline change data along this coast as pointed out earlier and that is unlikely to change given human resource capacity, skills and funding limitations.

Under these circumstances it is essential that a simple, practical approach to identifying the coastal flooding hazard zone be applied. The method must be easy to use and conservative enough to help coastal managers identify the flooding and erosion hazard zones. The objective of this paper is to demonstrate this by identifying the regional hazards and then applying a simple model that informs the extent of the coastal flooding hazard zone in the region between Mombasa and Cape Town, a distance of over 6000 km in length. Mombasa and Cape Town were selected as the ends of the region as both sites have functional tide gauges. Tide information is a vital input into determining the impact of wave events since storms occurring at low tide cause less damage than storms occurring at high tide. In order to demonstrate the approach it was decided to work with a manageable length of coastline. As the authors are based in Durban and the first author is employed by the eThekwini municipality, it was logical to choose the eThekwini municipal coastline, approximately 100 km in extent, as the case study (Figure 1).

Figure 1. Regional map with place names referred to in the text. The case study is located in Durban (Source: Adapted from NASA [24]).

3. Coastal Flooding, Erosion and Wave Hazards in the Region

3.1. Weather Systems

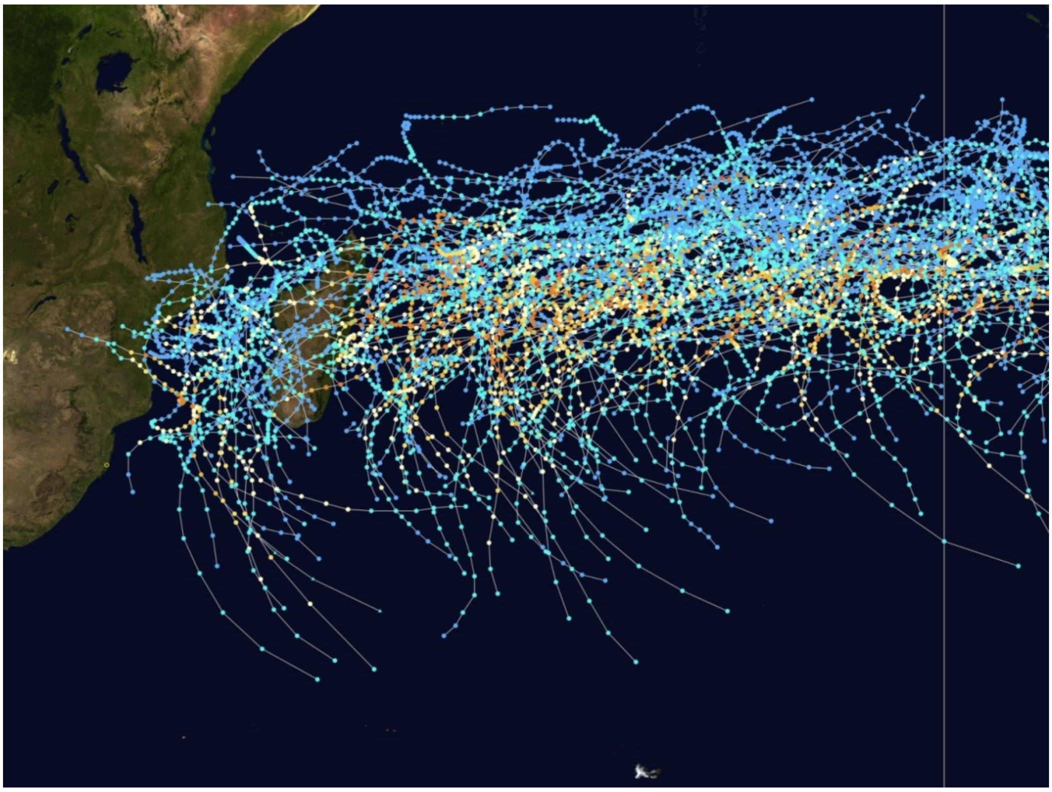
The southern African coastline is intermittently impacted by extreme swells associated with tropical cyclones (which are also referred to as hurricanes in the North Atlantic and typhoons in the eastern

Pacific Oceans) and cut-off low-pressure systems [25].

In the eastern Indian Ocean, cyclones generally form to the east of Madagascar. Most of the time they move in a west-south-westerly direction towards the African continent. Some make their way across Madagascar into the Mozambique Channel, while others move southward. The majority of tropical cyclones track in a south-easterly direction, away from the mainland, and back towards the Indian Ocean. It is these cyclones which turn south-easterly and sometimes remain semi-stationary south of Madagascar that are the ones that cause the biggest swells in the region.

Occasionally tropical cyclones do make landfall and can devastate the coastal zone in its path (Figure 2).

Figure 2. Tracks of all tropical cyclones in the Southwest Indian Ocean from 1980 to 2005. 90° E longitude is marked (vertical blue line) as this is the eastern boundary of the basin. The points show the locations of the storms at six-hourly intervals (Source: Wikimedia Commons [26]).



One such event, Tropical Cyclone Domoina, occurred in January 1984 and made landfall near Maputo, Mozambique causing extensive wind and rainfall damage. Tropical cyclones typically occur in the summer months but are most frequent in January, February and March, which is also when the tides lead up to the equinox (March/April) as shown in Table 1 [25].

Table 1. Monthly frequency of the 934 tropical cyclones since 1848 in the Southwest Indian Ocean [25].

Month	September	October	November	December	January	February	March	April	May
%	1	2	3	13	30	26	17	6	2

In contrast, cutoff lows are generated in the Southern Oceans when an anti-cyclonic depression occurs as a result of strong upper ridge advancing southeastwards and separating a cold upper air pool. They are characterized by a convex shaped surface high-pressure system along the southern Cape coast [27]. The formation of cut-off lows over land are not uncommon, however, these rarely result in high seas.

An intense cyclonic mid-latitude system is often referred to as an extra-tropical or mid-latitude cyclone, and is normally associated with a cold front that follows a strong ridge of the Atlantic high-pressure system. Cold fronts are often preceded by coastal lows, which are typically responsible for the southwesterly winds along the east coast of Southern Africa. Well-formed cold fronts can generate significant swell. The passage of this type of system results in gale force winds and high seas [27]. When these weather systems coincide with spring high tides they set the scene for exceptional flooding and erosion.

3.2. The March 2007 Storm in KwaZulu-Natal, South Africa

3.2.1. Conditions Preceding the Storm

Sea conditions had been unusual in the months leading up to this event as the region had been affected by three cyclonic events, Dora, Favio and Gumede. Cyclone Dora, which combined with a well developed cold front to the south of the country, resulted in 2–3 m swells and impacted the KwaZulu-Natal coastline from 11 to 13 February 2007. Cyclone Favio, which generated 185 km/h winds within 37 km of the center and significant wave heights above 14 m [28], moved from the south of Madagascar, through the Mozambique Channel, making landfall in Mozambique The cyclone generated high seas in Mozambique and heavy rainfall in south-eastern Zimbabwe and southern Malawi. However, it did not produce large wave heights along the KwaZulu-Natal coastline [29]. Cyclone Gamede closely followed and although downgraded from a tropical cyclone to an extra tropical depression, remained relatively stationary between the 2 and 5 March and created localized flooding along the KwaZulu-Natal coastline. However, Cyclone Gamede also depleted the beaches of their buffer of sand as the waves moved sand from the beaches into deeper water.

3.2.2. Conditions During the Storm

The weather system responsible for the March sea storm started as a frontal low, which passed south along the coast of South Africa on 16 March 2007. The frontal low intensified and rapidly developed into a cut-off low south-east of East London on 17 and 18 March. It intensified to a peak on the 19 March, where it remained trapped between two high-pressure cells until 20 March. The cut-off low started to weaken by midday on the 19 March and conditions had almost returned to normal by 20 March [30]. The central pressure of this cell dropped to below 986 hPa at its peak. The strong pressure gradient generated strong and consistent winds. Wind speeds started picking up on the 17 March, recorded hourly wind speed rose to 10.9 m/s (peak 10 min speed of 18.5 m/s at 24H00), on the 18 March, the recorded hourly wind speed peaked at 11.9 m/s (peak 10 min speed 22.1 m/s (43 knots) at 14H10) and over the course of the 19 March subsided [31].

As the system was trapped in position this allowed the wind to generate some impressive waves straight at the coastline of KwaZulu-Natal for approximately 48 hours. Wave heights at Richards Bay, approximately 180 km north of Durban reached a significant wave height (H_{m0}) of 8.5 m, with a peak single wave height of 14 m. The event was felt along a stretch of coastline from Maputo (25°58'S, 32°34'E), Mozambique [32] to Port Elizabeth (33°58'S, 25°38'E). Fortunately, the wave event very quickly dissipated and by the evening of 20 March, the swells had reduced to less than 3 m [30].

3.2.3. Tide, Storm Surge and Wave Run Up Levels

The Highest Astronomical Tide of the Year (HATOY) at 2.284 m above MSL (2 cm less then the Highest Astronomical Tide (HAT) of the 18.6 year cycle) was predicted to occur on the 19 March 2007 at 04H32 South African Standard Time (SAST). This event had already been forecast as having the potential to create widespread erosion should it coincide with a large wave event. The South African Navy tide gauge in Durban recorded a peak storm surge of 70 cm (3 min average). Wave run-up levels recorded along the beaches ranged between +4 m and +10.5 m above MSL [33]. Highest levels were recorded in open coastal locations where the bathymetry dropped off sharply.

3.2.4. The Impact of the Storm

The storm resulted in widespread damage to private and public infrastructure and homes along ±400 km of coastline at an estimated cost of about US$100 million [30]. Several homes were completely lost or damaged beyond economic repair and damaged sewer reticulation poured raw sewage into the sea for several months after the event prompting a bathing ban along many of the popular swimming beaches.

3.3. The Likelihood and Magnitude of Future Storm Events and Sea Level Rise by 2100

The threat of similar events in the future has been accepted [34] and therefore the attention has turned to developing a planning framework around these events. The goal is to reduce the flooding and erosion hazard associated with these events. With a coastline that has significant coastal development already in place, the task is made more difficult by the social and economic considerations associated with such decisions [35]. Kay and Alder [36] defined a hazard as "an event or process with potential harm to people, property and the environment". Their definition takes the concept of a risk, in other words the likelihood of occurrence of a defined event with no human or environmental consequences as a risk. Conversely, where there is the likelihood of occurrence of a defined event with human or environmental consequences this becomes a hazard. It is becoming clearer that this hazard will continue to be ever-present and may increase with ongoing climate change in the region [17].

3.4. Past and Future Storm Activity

The March 2007 event, while significant, was by no means unusual. Events of similar magnitude have occurred in the recent past. On the 13 June 1997 a cut-off low system off the coast of East London, South Africa created similar conditions to this storm. Significant wave heights of 9.3 m were only marginally higher but the effects were of similar erosion and property loss. Cyclone Imboa occurred in mid February 1984 off the coast of Maputo, Mozambique and created high winds and large waves with a significant wave height between 8 and 9 m. During 1970, a wave event caused erosion and damage along the Durban coastline. In late May 1966, a sea storm with a significant wave height of approximately 8.5 m stripped the sand off the beaches along the coastline south of Durban, South Africa revealing a Quaternary fossil bed [37].

As has been previously pointed out, wave events along this coast are driven by the wind generated from cyclonic and cutoff low events. To generate the most erosive waves two factors must coincide. Firstly, high sustained winds blowing onshore and secondly, a suitably long fetch (the distance over which the wind can blow and in so doing, creating waves). Using the physical layout of the regional coastline as a starting point, potential maximum wave height using either fetch limited or duration limited wind speeds can be estimated using the Coastal Engineering Manual developed by the US Army Corps of Engineers [38]. On that basis the potential maximum wave height along the South African, Mozambique, Tanzanian and Kenyan coastlines have been calculated and are shown in Table 2.

Table 2. Potential maximum wave heights in the region calculated using the US Corps of Engineers Coastal Engineering Manual [38].

Coastal segment		**Duration limited**	**Fetch limited**	**Maximum regional wave height (m) (lesser of duration or fetch limited)**
From	**To**	**Maximum wave height generated by wind duration(m)**	**Maximum wave height generated by fetch length (m)**	
Cape Town South Africa	Mossel Bay South Africa	10	10	**10**
Mossel Bay South Africa	Lake Poelela Mozambique	9	9	**9**
Lake Poelela Mozambique	Ruvuma Bay Mozambique	9	8	**8**
Ruvuma Bay Mozambique	Mombasa Kenya	10	10	**10**

The wind speeds and fetch lengths in the Mozambique Channel are restricted by the proximity of Madagascar to the Mozambique coastline, effectively capping the maximum wave heights to 8 m (see Table 2). When these results are compared to other data, the results are similar. The Voluntary Observing Ships (VOS) observed wave height data from 1960–1999 that indicates only 0.1% of the total 17,168 records exceeding 9.0 m at the southern tip of Madagascar [39]. Reduced wave heights in the Mozambique Channel have been reported by Theron [17].

3.5. Sea Level Changes by 2100

Various authors have used a variety of different factors and methods to predict future sea level change. The use of global climate change models [6], a temperature/SLR relationship [40], ice melt yield [41] and quadratic equation projections from tide records [42,43] are a few of the methods employed. Predicted rates and magnitude of future global SLR are still hotly debated but there is agreement that these will rise. Several countries have adopted SLR scenarios based on the work of the IPCC [6] and others, notably post 2007. For example, Germany has taken 1 m of SLR as the upper bound of potential SLR by 2100 [44]. The Dutch, with their extreme vulnerability to the impacts of

SLR, have adopted a maximum SLR, excluding settlement, of 1.1 m by 2100 [45] and California has adopted a maximum of 1.4 m by 2100 [46].

Recent sea-level analysis in the region has shown that there is variation in the rate of sea-level change in the region [7,8,47]. Virtually all tide gauges show a rise with the exception of Zanzibar at −3.6 mm/yr) [47]. For this particular case study, the observed SLR trend in Durban is +2.7 ± 0.05 mm per year [7] and for the eastern region of South Africa is estimated as +2.74 mm per year [8].

In order to model the effects of any SLR several scenarios were chosen [48]. These scenarios have been determined as follows:

- Scenario 1: 300 mm based on current linear SLR
- Scenario 2: 600 mm based on doubling of the current SLR rate
- Scenario 3: 1,000 mm based on an accelerated ice melt scenario.

The last scenario was included since recent literature has suggested accelerated ice melt [49].

3.6. High Water Mark and Wave Run Up

An important factor in determining the hazard zone is the extent of wave run-up along the shoreline. Traditionally the coastline has a legally defined measure of wave run up, the High Water Mark (HWM). Generally these HWM's are a combination of a high tide level and storm wave run up. In most instances they are delineated following actual events, *i.e.*, a land surveyor co-ordinates the position of the debris line and this is declared the HWM. These HWM's are not helpful in identifying the hazard zone, as they generally do not account for extreme waves in the order of 8 to 10 m.

As waves approach a shoreline their shape and height changes and wave energy is lost to friction on the ocean floor. This can also causes a change in wave direction depending on the incident wave angle to the coastline. As the waves make their way inshore, the wave height increases until the wave breaks before reforming as a smaller wave that proceeds inshore. The surf zone (the area where the waves break) accounts for the majority of the loss of wave energy [50]. The wave then reaches the beach and the remaining wave energy is converted to potential energy in the form of run-up on the sloping face of the beach [51]. The run-up of the waves provide the energy needed to rework the beach slope, erode the dunes [52–55] and endanger any human-made structures in its path.

Planning for coastal impacts requires an understanding of the likelihood and extent of water/wave action and sea-level rise along the coast while considering its geological context as Jackson *et al.* (2005, 2009) [54,55] have pointed out. Intuitively one understands that the closer a structure is located to the sea the higher the risk of likely damage. The magnitude of wave run-up across and up the beach slope is therefore critical in understanding the extent of the potential coastal hazard zone for large wave events. However, the identification of this zone varies along the coastline depending on numerous factors relating to the beach, beach material, wave regime, wave direction and underwater bathymetry. Rising sea levels have the effect of lifting the Still Water Level (SWL) along the coastline and allowing more wave energy to move closer inshore and in so doing eroding the sandy coastline. If a sandy coastline is backed by human settlements then this process may present problems for these facilities.

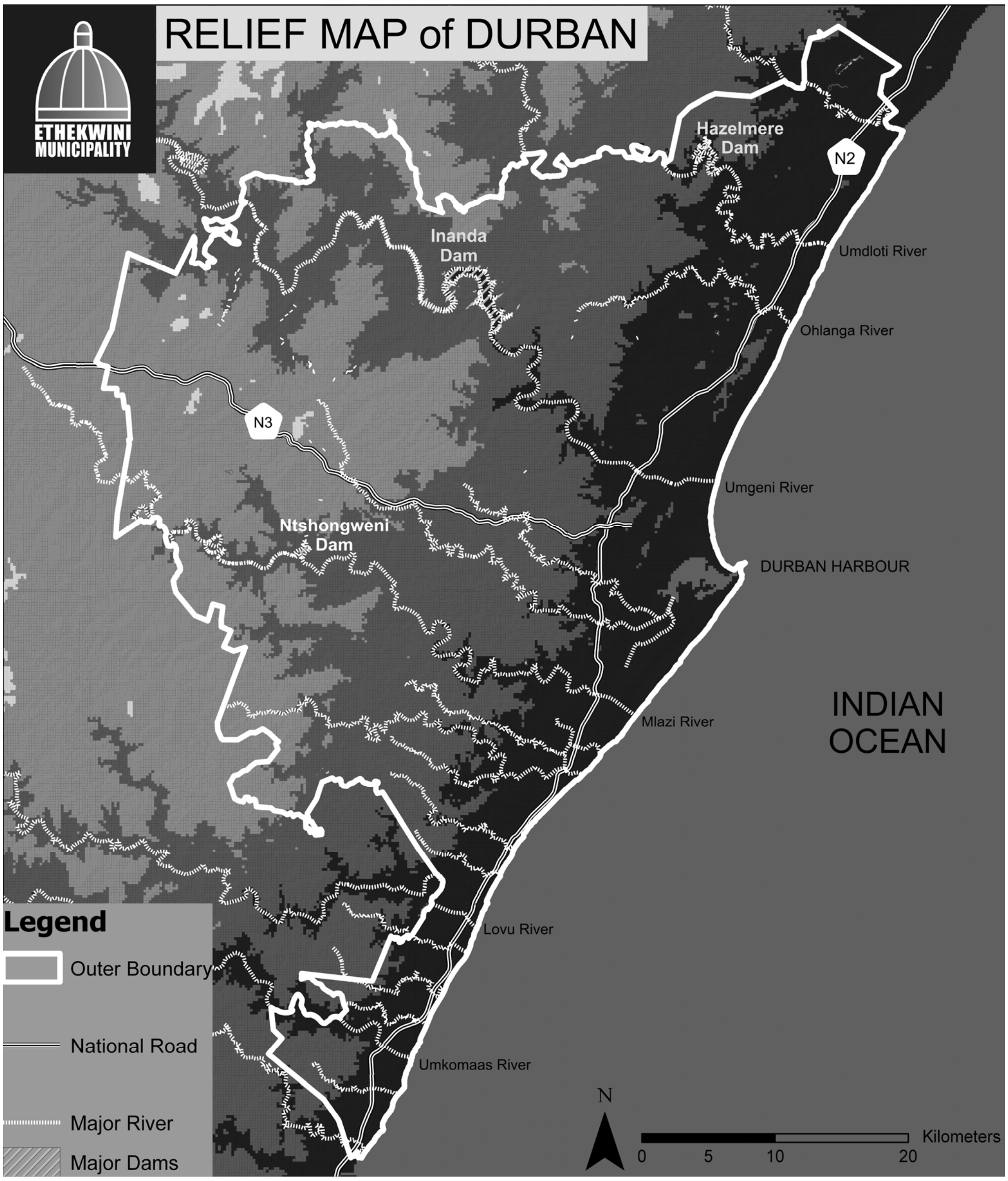
Waves heights are generally recorded in an offshore location, *i.e.* in depths of water exceeding 30 m. The offshore wave heights will be different to the inshore conditions particularly if the bathymetry is complex and/or the shoreline is not an open straight coastline. In the case of an open straight coastline the model of Mather *et al.* (2010) [33] is applicable. More complex coastlines will require models that include wave refraction, (such as Waves Nearshore or SWAN model) to provide inshore wave heights.

Wave run up levels can be calculated using a number of international wave run up models [56–59] however, as Mather *et al.* [33] have pointed out, the best of these international models do not predict the observed wave run-up very well along this coastline and therefore a new local model was developed for the case study area. This model will be used as the basis of the predicted wave run-up heights in this paper.

4. High Water Mark and Coastal Flood Hazard Delineation Model: A Case Study of the Durban Coastline

The case study that will be used to demonstrate the approach will be the entire municipal coastline of the eThekwini municipality as shown in Figure 3.

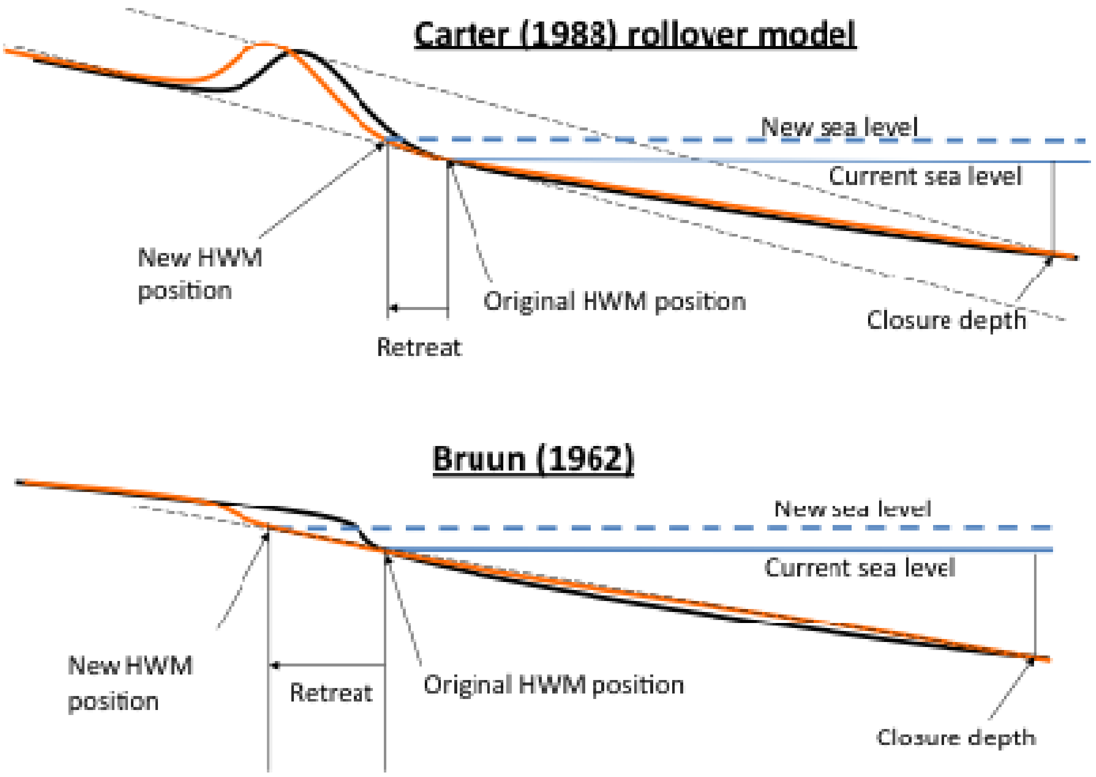
Figure 3. Map showing the eThekwini municipal coastline.



4.1. The Model

The model consists of two separate parts. The first part is to calculate the amount of wave run-up along the shoreline based on the offshore wave, bathymetry and the state of the tide. The second part is the determination of the extent of retreat of the coastline under differing SLR scenarios. In the preliminary assessment to decide which model to use, two models were considered; namely the Carter Roll-over model [60] and the Bruun Rule [61], as shown in Figure 4.

Figure 4. Cross-shore sections showing the application of the Carter [60] and Bruun [61] models. Original shoreline in solid black and sea level rise (SLR) modified shoreline in orange.



The Carter and Bruun models are simple profile transition models where continuity of sediment in the cross-shore direction is preserved. The difference between the models is the landward control point used. Carter uses the intact dune system as part of the active profile while Bruun uses the waterline. Both models define a slope of retreat as the sloping dotted line from the land control point to the closure depth. The Carter model takes into account the landward dune system as part of the sediment budget available to mitigate erosion in the cross-shore direction. The Bruun rule has been criticized by some [62–65] and supported by others [66–72], and therefore applicability should be tested prior to its application. Historically the Bruun rule has been applied in South Africa without testing its appropriateness as a suitable shoreline regression model [73,74]. In a parallel study to this one, the applicability of the Bruun rule in the case study region was tested. Using a series of 14 paleoshorelines from +4 m to −170 m above sea level, the Bruun rule was able to predict the observed retreat distance between successive paleoshorelines to within 10% of the retreat [75]. This result is acceptable given the simplicity of the Bruun rule and has provided some confidence in the application of the Bruun rule in this region. The shoreline retreat for the tested sample locations showed that at locations that had an intact primary dune, the predicted shoreline retreat using Carter's model was less than the retreat using the Bruun rule. However, at sites where the primary dune had been removed or did not exist, the results from both models were similar. Within the case study area, urban development has removed most of the primary dunes and therefore it was decided to apply the Bruun rule exclusively while recognizing that in areas where the primary dune still remained intact the retreat would be slightly overstated. This approach is conservative, however, it was deemed acceptable given the limitations of both models. For a full discussion of the Bruun's rule, readers are referred to [76,77].

4.2. The Input Data

Topography was obtained from high-resolution aerial survey. The aerial photo scale was defined as 1 in 4,600. This equates to a flying height of 800 m above the ground. The ground control consisted extensive existing municipal ground control points. In areas where the coverage was sparse, municipal land surveyors placed additional ground control points. The captured aerial images were developed and the diapositives scanned at a resolution of 12 microns to produce an accurate set of digital images for the photogrammetric process. The images were then triangulated and the center point of each image assigned a Global Positioning System coordinate. These center points act as auxiliary aerial control points. Using a flying height of 800 m the X and Y positions (planar points) were captured to an accuracy better than ±10 cm Root Mean Squared error and the Z positions had similar accuracy.

The wave run-up model requires information on the offshore wave height H_{mo}, tidal level at the time of the storm, and distance to the −15 m bathymetric contour (closure depth at this location). Data for the model were obtained for wave heights [39], tide levels and the −15 m bathymetric contour from Admiralty charts [78]. The accuracy of the bathymetry on the Admiralty charts is estimated to be within 0.5 m of the published bathymetric contour values. The model can be run with any combination of these variables and for varying conditions *i.e.* a wave height of 10 m at HAT. For the case study, a set of variables were chosen that reflect the conditions in the case study region. Model runs assumed the state of the tide as at Mean High Water Spring (MHWS) tide at 2.01 m CD, combined with a 1:10 year storm wave height ($H_{mo} = 7.1$ m) and SLR of 300 mm, 600 mm and 1,000 mm.

4.3. GIS Procedures and Data Presentation

Each stereo aerial image pair was used to generate an irregular triangular network (TIN) or Digital Terrain Model (DTM) that was exported into a Computer Aided Design (CAD) environment as a mesh of triangles. Supplementing this data were the −15 m (below sea level) depth contour line and the +0 m contour line. From these data a series of section lines perpendicular to the −15 m depth contour line were generated and extended until they intersected the +0 m contour line. These section lines were generated at approximately 5 m intervals along the 100 km of coastline. Using custom software, which runs inside the CAD environment, the wave run-up model was applied using the information for each section line. This produced a point height which was placed along the transect line where it intersected with the terrain thus gradually building up a string of points which were then joined to form a reference line.

The amount of beach retreat was then calculated using Bruun's model [61]. The case study coastline was sectioned at 5 m intervals. The wave run-up model provided the elevation level of maximum wave run-up at each point. The regressed HWM position was then determined from the DTM. This retreated maximum wave run-up prediction was then used to determine the slip failure of any dune structure that existed inland of this. The slip failure angles were determined from previous data [79]. This slip failure zone was plotted on the sections and the top of the failure zone was determined. Once each cross-section had been analyzed a line joining the entire respective model results was created and shown as a line on the aerial imagery.

4.4. Costs

The costs associated with undertaking this work have been kept to a minimum by using only a basic amount of information. The most expensive element was the special low-level aerial survey undertaken especially for this project at ZAR 300,000 (US$ 37,500). This cost included the aerial photography, rectification, geo-referencing and Digital Elevation Model. The modeling and freeware viewer came to ZAR 30,000 (US$ 3,750) and internal staff costs came to approximately R25,000 (US$ 3,125). The overall cost came to ZAR 355,000 (US$ 44,375) or about ZAR 3,500 (US$ 450) per kilometer.

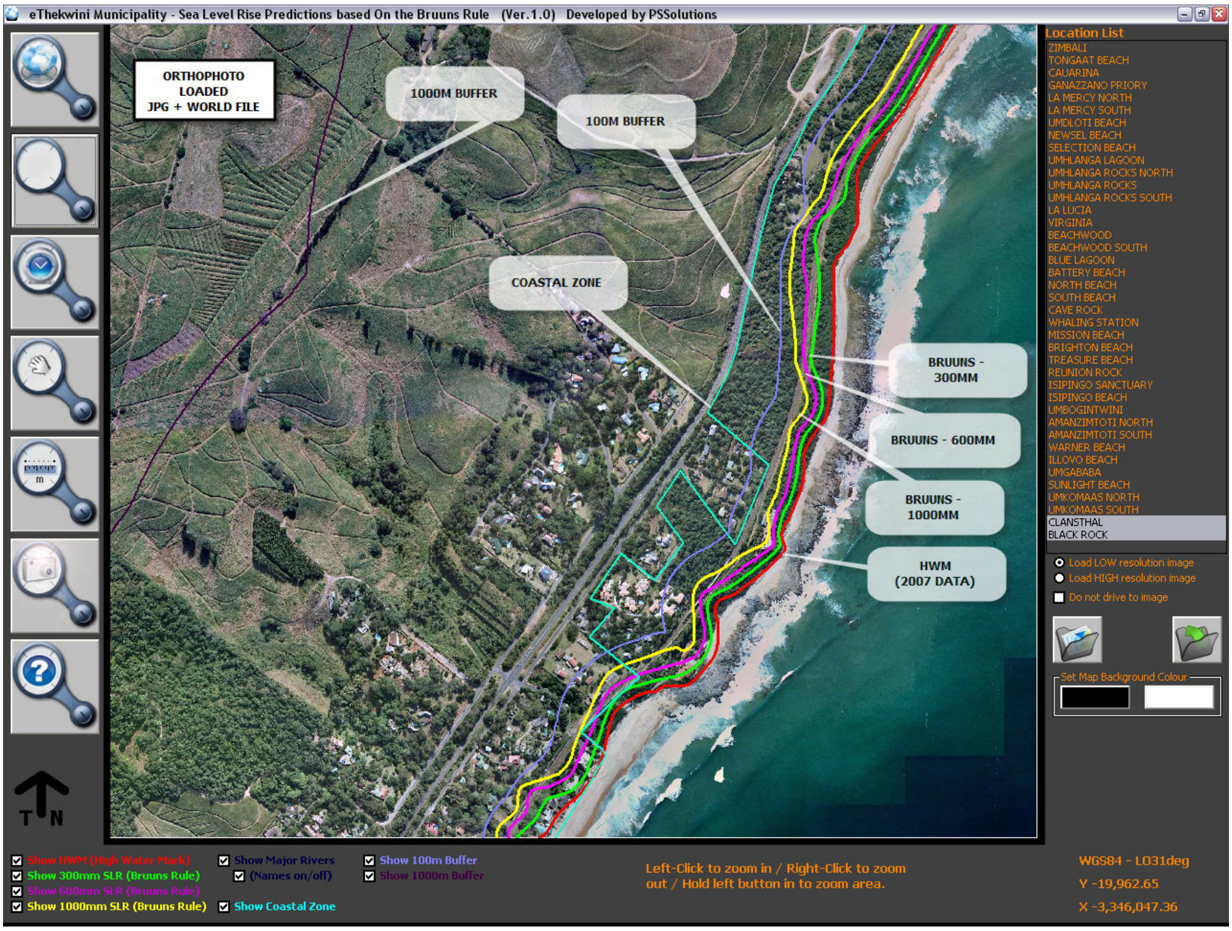
4.5. Presentation of the Model Results

Often the results of GIS based models are only accessible to a limited group of GIS operators who have commercial software packages and the technical skills to work with the applications. To avoid this, the final output was created using a combination of Visual Basic and Action Script/Flash technology that can be compiled in such a way that no external or third party software is needed to run the application. Action Script/Flash is a multimedia platform that can manipulate vector and raster images and can be displayed on various computer systems and devices without the need for proprietary software. This freeware application can be distributed on DVD to any interested party to install on their personal computers. The decision to distribute the data using DVD allowed public access to the results of the study without the need for proprietary software, therefore eliminating the costs and skills associated with commercial GIS platforms. The costs of compiling and distributing the disc were below ZAR 25 (US$ 3) which allowed enabled the municipality to distribute large numbers at very little cost. Those skilled in the use of commercial GIS packages can export the GIS shapefiles directly into those packages if they desire. The ability of the public to view the data meant that they were better informed and were able to interact in a more meaningful way. A screen shot of the SLR viewer is shown in Figure 5.

5. Results

All four scenarios were plotted against the aerial photography backdrop yielding the positions of the current HWM (red) and future HWM with SLR of 300 mm (green), 600 mm (purple) and 1,000 mm (yellow). A sample of the visual output is shown in Figure 6.

Figure 5. Screen view of the standalone SLR viewer [48].



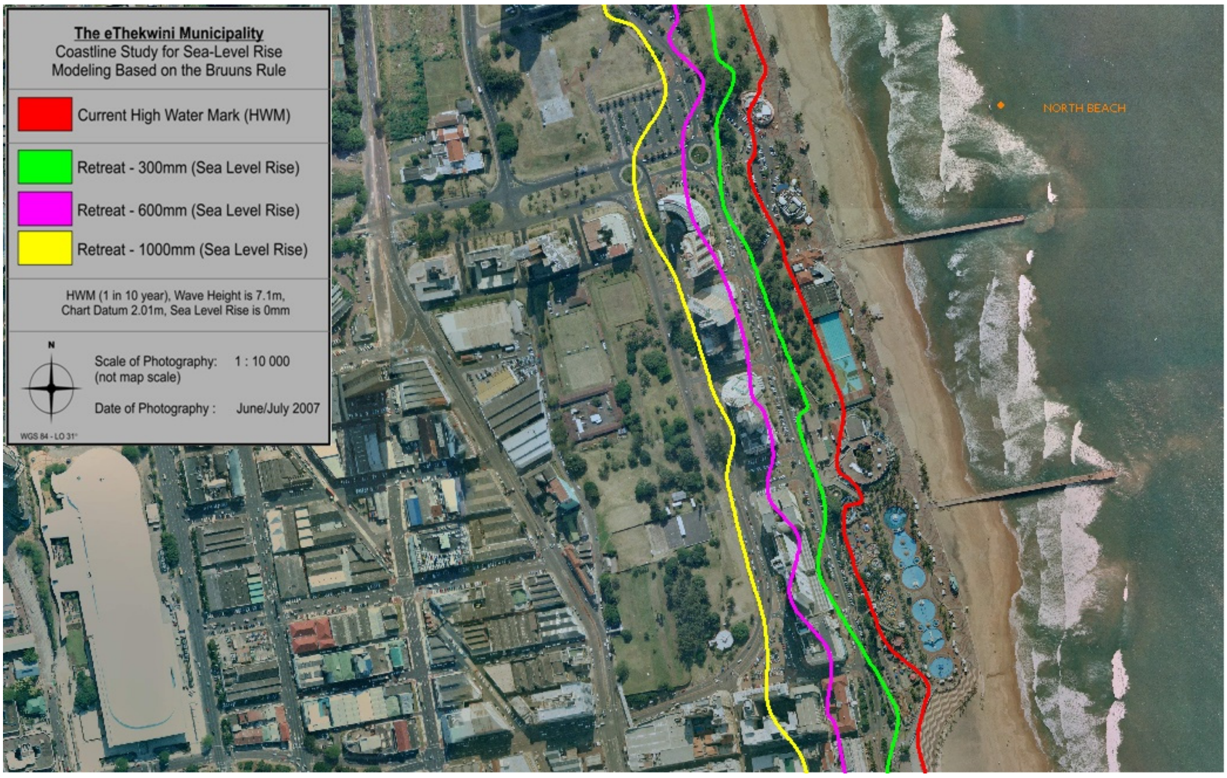
● Load LOW resolution image
○ Load HIGH resolution image
☐ Do not drive to image

☑ Show HWM (High Water Mark)
☑ Show 300mm SLR (Bruuns Rule)
☑ Show 600mm SLR (Bruuns Rule)
☑ Show 1000mm SLR (Bruuns Rule)
☑ Show Major Rivers
☑ (Names on/off)
☑ Show Coastal Zone
☑ Show 100m Buffer
☑ Show 1000m Buffer

Left-Click to zoom in / Right-Click to zoom out / Hold left button in to zoom area.

WGS84 - LO31deg
Y -19,962.65
X -3,346,047.36

Figure 6. Present and future High Water Mark (HWM) along the Durban central beachfront [48].



6. Discussions on the Management Implications

The implications for SLR along the sandy southern African shoreline will have far reaching effects extending beyond just inundation and coastal erosion. In this paper the focus is on the primary impacts as they relate to the typical types of shoreline present. A management response to SLR will need to be developed from this assessment based on each locality where infrastructural responses/interventions may be considered. A detailed investigation at each site is beyond the scope of this paper, however, some generic evaluation is possible using the study area. In order to provide some meaningful management responses, typical coastal types have been identified and the extent of possible impacts will be discussed in more detail below.

6.1. Rocky Shores

Rocky shorelines are represented along the southern African coastline particularly in the Western and Eastern Cape regions of South Africa. By their very nature these shorelines are relatively stable and are not subject to erosion to the extent that sandy shorelines are. The main impacts of rising sea levels will be the increase in wave run-up levels resulting in loss of vegetation at these locations.

6.2. Undeveloped Natural Sandy Shorelines

This type of shoreline exists in limited areas in South Africa but is more widespread in Mozambique, Tanzania and Kenya. Like rocky shores, this shoreline type is least likely to present a hazard to humans simply because they are undeveloped. Small increases in sea level result in significant regression of the high water mark. Typically these areas were inundated in the previous high stands of sea level around 6,000 years ago [80]. This type of coastline is common in Mozambique with a wide continental shelf where large portions of the flat, low elevation coastal plains are river deltas. There is sufficient land for the sea to retreat naturally with little impact on man.

From an adaptation point of view these areas need to be allowed to naturally respond to rising sea levels and perhaps the only management interventions should be to actively prevent new settlement in the potential flooding and erosion zone. A development set back line should be formulated with various SLR scenarios so that the authorities can manage development as well as prevent additional development in high-risk areas. The development set back lines must sufficiently distance from the existing shoreline to cover the risk zone. From previous experience in the region, often these developments set back lines are underestimated and are of insufficient width to perform their function. This will lead to problems with developments that are too close to the coast in the future [18]. However if these development set back lines are properly determined they have the ability to reduce risk sufficiently that the economic activities undertaken for the developments are fully realized before they are lost or need to be relocated.

6.3. Beachfronts and Coastal Development

Beachfronts are significant local and regional economic generators and are often constructed with significant back of beach amenities and infrastructure. The extent of these facilities has evolved over several decades and cannot simply be moved overnight. It is along this coastal type where the largest impacts will be experienced. Many beachfronts already have some form of sea defense in place to protect infrastructure and it is often this infrastructure that is the first to be damaged by heavy seas. Unfortunately, as is the case for many urban beachfronts, the opportunity to retreat or reconfigure the development is no longer practically possible. An adaptation response must be tailored to suit each location and its respective circumstances. For example, without any adaptation interventions the beachfront at Durban, South Africa will result in the loss of significant development and infrastructure ranging from parts of the ZAR750 million Ushaka Marine World (the fifth largest aquarium in the world when it was completed in 2003) to roads, coastal structures and tourism amenities.

In the short term it is possible to maintain the shoreline by providing additional sand from dredge sites offshore to replace and offset the increased erosion and beach reduction caused by SLR. The economic costs of this option will determine when this intervention is no longer viable. In the medium term, the decision to defend will need to be taken, since retreat will probably not be possible. The nature of the coastline will then change permanently with sea walls replacing the once sandy beaches along ‘Durban’s golden mile’. Other less developed beachfronts may not be so fortunate and may find that the renourishment option is too expensive and will need to move directly to a defend position. On a positive side, the development in these less developed beachfronts will be less intense and it may be possible to retreat some distance inland, effectively putting off the inevitable defend option.

6.4. Estuaries and Mangroves

Estuaries, often with associated mangrove stands, are highly productive systems [81] and form part of coastal ecosystems that are amongst the most threatened ecosystems in the world [82]. Their functioning is controlled by two main drivers (1) fresh water river flows and (2) the marine process of sedimentation and accretion. Some estuaries remain permanently open to the sea, some open and close depending on which factor is dominating and some remain permanently closed relying on seepage to the sea. These systems may be delicately balanced so any changes can significant impact their normal functioning e.g. frequent mouth breaching reduces the productivity while insufficient breaching results in the accumulation of pollutants leading to low oxygen levels and fish kills.

Against this background estuaries will be impacted by SLR in two ways. Firstly, as the sand bar across the estuary mouth migrates inland this has the potential to fill the estuary basin with marine sediments. This in turn will limit the available water volume and reduce the efficacy of the estuary to provide a fish nursery for marine species. Secondly, raised water levels will allow more wave energy into the mouths of estuaries and will start to negatively affect the mangrove stands that have formed within some systems, disrupting the nutrients which many organisms rely on to survive. This has a knock on effect through the food chain. Along this coastline mangroves do not survive when exposed to direct wave action and so when this occurs the mangroves will start to die off.

6.5. Harbors

The main Southern African harbors are located along the east shoreline of Africa *i.e.*, Cape Town, Port Elizabeth, Coega, East London, Durban (the largest container port in Africa and 3rd in the southern hemisphere) serving as a major import/export hub for the Southern African region, Richards bay (largest coal export terminal in the southern hemisphere exporting approximately 100 million tons per annum), Maputo, Beira, Nacala, Dar Es Salaam and Mombasa. This string of ports provides for the flow of goods into and out of Southern and Central Africa. It is expected that a small rise in sea levels could be handled within the design capacity of the current harbors. However, should SLR be 1 m, this will start to lead to problems. The extra water depth will result in an increase in wave energy both outside and inside the harbor. Impacts outside the harbor are like to be wave overtopping of the entrance breakwaters with loss of some of the structure leading to increased maintenance costs and additional capital costs to redesign the harbor entrance works.

Within harbors, the extra water depth will result in less freeboard along the quayside resulting in more frequent wave wash/overspray onto the working area with increased down-time and loss of productivity. With the increased wave energy, ships moored alongside the quays will not be as stable as required for the offloading of cargo. This will result is longer off-loading times, longer ship turn-around times, inefficiency at the berth-side and extra costs. Management interventions could be the fortifying of the entrance breakwater structure to reduce the increased wave energy and changes to reduce the additional wave energy penetration that affects moored ship stability at berth. In the extreme scenario of several meters' of SLR this will inundate the harbors preventing them from operating and transporting goods.

6.6. Large Prehistoric Dune Systems

There are several large primary dune systems, which dominate sections of the South African and Mozambique coast. The most well known of these are the red dunes of the Berea Red formation, which exists along the coast from south of Durban to beyond Maputo, Mozambique. These ancient dunes, formed around 1.2 million years ago, are aeolian deposits of fine quartz grains coated with clay containing ferric oxide giving the sand its distinctive red color. These dunes have been eroded back since the last sea level low-stand approximately 18,000 years ago [80]. As these are unconsolidated sand dunes or bluffs they are unstable. Up until the present time these unstable slopes have been identified, demarcated and development precluded from the slip area. With rising sea levels the slip failure zone will migrate inland.

Just 300 mm of SLR is sufficient to endanger existing developments. Figure 7 shows the main sewerage treatment works that services the Central Business District of Durban and a SLR of 300 mm will affect the main sewer pipeline around the tip of the Bluff. Adaptation measures could be to protect the pipeline or works through the construction of sea walls or alternatively to relocate this infrastructure on the inland side of the dune with a pipeline through the dune and to the sea outfall. Figure 8 shows the same dune formation but further south where the existing coastal forest is at risk of slipping into the sea under the scenario of 1,000 mm of SLR. Under these circumstance there is little one can do given the fact that urban development prevents the natural system from retreating inland.

Figure 7. Sea level rise scenarios for the Central sewerage treatment works in Durban [48].

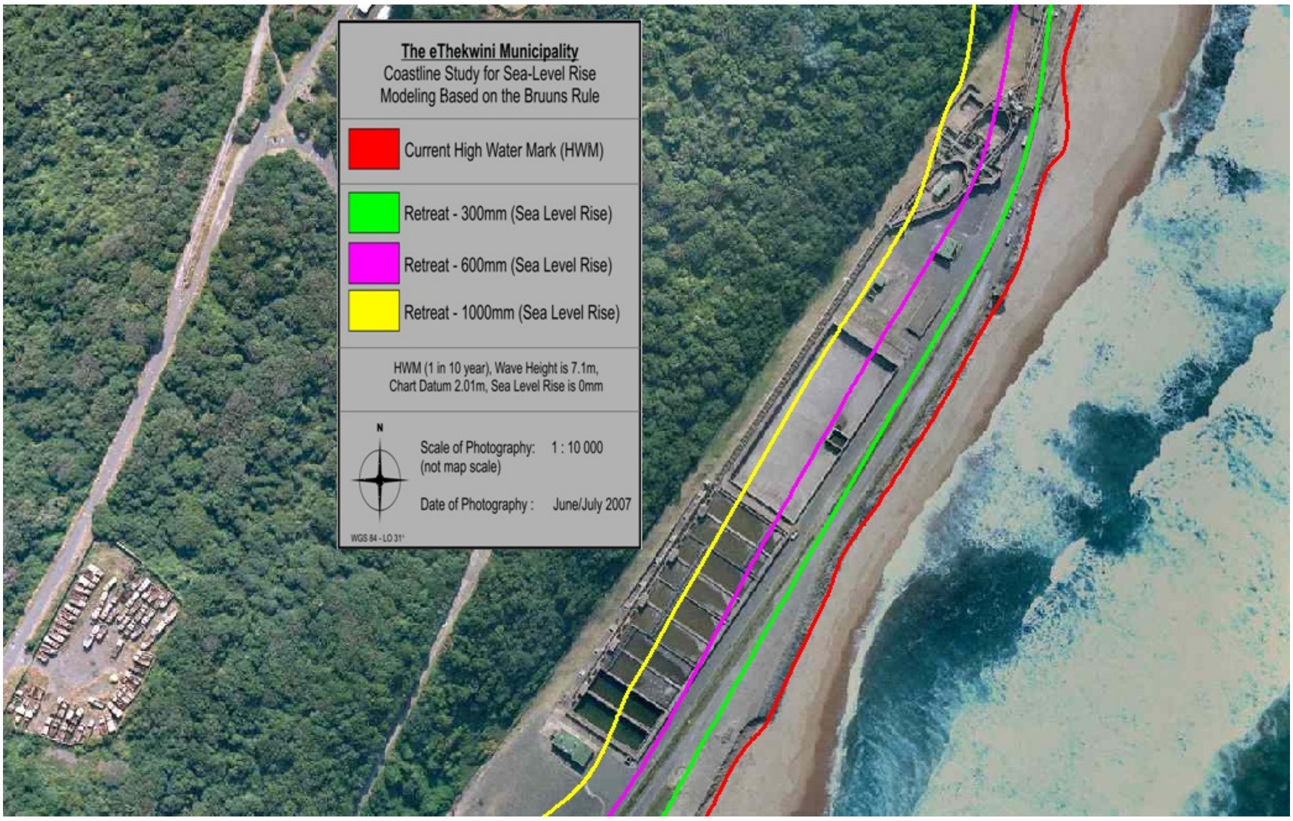


Figure 8. Slope failure of dunes with 1000 mm of sea level rise and loss of coastal forest [48].

6.7. Armored or Fortified Coastlines

Shorelines that have previously been fortified using sea wall of other defense systems will not be immune from attack. Increases in water depth as a result of SLR will allow increased wave energy to penetrate closer inshore. This increased wave energy could exceed the original designers design condition, if so the structure will be subjected to more wave energy then it is capable of withholding, resulting in partial or full failure of the structure. Adaptation to increased SLR would be to check the design parameters of existing critical infrastructure where failure could result in severe financial, social and environmental costs. New infrastructure adaptation is easier as these additional wave forces can be designed into the structure at the initial stage.

In all the developed cases discussed above, the need to provide some recreational activities close to the sea has to be tempered with the risks associated with this approach. In these circumstances managed retreat would be the preferred international best practice action in this case [83] but as that is ruled out the need arises for a multi-layered approach to the problem of coastal flooding and erosion. The rate of SLR has been predicted to increase over time and so in the next decades there exists a "window of opportunity" to provide some infrastructure close to the hazard zone when sea levels are still close to current levels.

This raises the question as to what should/could be allowed in this zone that does not place undue financial hardship on the owners of the infrastructure when SLR starts to impact them. By balancing the risk of failure against the value of the infrastructure it is possible to review what is suitable in the various risk zones or not. This is outlined in Table 3.

Table 3. Recommended amount of sea level rise to be incorporated into the design of new infrastructure [84].

Value of infrastructure in South African Rands (ZAR)	Life of infrastructure	Impacts of failure of the infrastructure	Planned amount of sea level rise
Low **(up to ZAR 2 million)** *i.e.*, Recreational facilities, car parks, board walks, temp beach facilities	**Short term** Less than 20 years	**Low** Minor inconvenience, alternative facilities in close proximity, short rebuild times	**0.3 m**
Medium **(ZAR 2 million to 20 million)** Tidal pools, piers, recreational facilities, sewerage pump stations.	**Short to Medium Term** Between 20 and 50 years	**Medium** Local impacts, loss of infrastructure and property	**0.6 m**
High **(ZAR 20 million to 200 million)** Beachfronts, small craft harbors, Residential homes, sewerage treatment works.	**Medium to Long Term** Between 50 and 100 years	**High** Regional impacts, loss of significant infrastructure and property	**1.0 m**
Very High **(greater then ZAR 200 million)** Ports, desalination plants, nuclear power stations	**Long term** In excess of 100 years	**Very High** Major disruption to the regional and national economy, failure of key national infrastructure	**2.0 m**

The approach in Table 3 takes a balanced view of risks and has been recommended for use in South Africa.

7. Conclusions

The results of this paper show that the zone of high risk above the HWM within the coastal zone can be relatively easily described and mapped. This provides the basic information that decision makers require when planning any new and existing activity within the coastal zone. The results show that each portion of the coastline will be affected differently by SLR. These results can be shared with a much broader grouping of society than had this information been only available in a conventional GIS application. Key management issues arising from this work have been identified for each coastal type and it has been relatively easy to describe these changes generically for each coast type.

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