THE ECOLOGICAL IMPLICATIONS OF SEA-LEVEL RISE AND STORMS FOR SANDY BEACHES IN KWAZULU-NATAL

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ABSTRACT

The aesthetic appeal of beaches has made coastal properties prime sites for development. However, this development has been mismanaged and is within the littoral active zone. Beaches retreat landwards as sea levels rise, but with current development trends, beaches are trapped in a coastal squeeze. Climate-change predictions include an increase in frequency and heightened intensity of storms, which can cause significant erosion. This study aimed to determine the ecological implications of sea-level rise and storms for beaches in KwaZulu-Natal (KZN), using geographic information systems (GIS) and beach sampling methods. The beaches were mapped in terms of physical and biological attributes. Spatial trends in these attributes showed that the coastline can be split into three – the northern, central and southern regions. Although 25 % of the coastline is protected by marine reserves, these are located in the Delagoa bioregion: 28 macrofauna species in the Natal bioregion are not protected. Storm impacts for beaches can be heterogeneous, depending on local coastal features, *e.g.*, nearshore reef and sand dunes, and represented a temporary disturbance to macrofauna communities. A GIS-based coastal recession model was derived from Bruun's rule, and applied for different scenarios of sea-level rise and coastal development. Coastal squeeze is concern, particularly in the southern region. Further, the 10-m elevation contour was not completely effective as a setback line, even for a low sea-level rise scenario. The coastal recession model was validated using data from a real event in KZN, where sea level rose temporarily by ~1.0 m. The model performed well, although the calibration possibly did not span a wide enough range of beach morphodynamic types, and under-predicted retreat for dissipative beaches. It was concluded that the Natal bioregion needs marine reserves, and that higher resolution spatial data are required for accurate beach modeling and the south coast railway line should be relocated proactively. Guidelines for sandy beach systematic conservation planning were outlined, and seated in a conceptual framework of managing beaches for resilience. Application of the proposed recommendations and frameworks could aid in determining a way forward in integrated coastal zone management for KZN, in the face of the uncertainties associated with climate change.

[354 words]

PREFACE

The experimental work described in this dissertation was carried out in the School of Biological and Conservation Sciences, University of KwaZulu-Natal, Westville, from January 2007 to December 2008, under the supervision of Professor David S. Schoeman, Doctor Ronel Nel and Mr Andrew A. Mather.

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 - PLAGIARISM

I, Linda R. Harris declare that:

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

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

3. This dissertation does not contain other persons' data, pictures, 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 dissertation does not contain text, graphics or tables copied and pasted from the Internet, unless specifically acknowledged, and the source being detailed in the dissertation.

Signed: ________________________________

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Any beach ecologist will know that sampling is truly a team effort! Thanks to everyone who helped me – even if it was under false pretences that it was going to be a fun day in the sun on the beach: Adrian Evans; Andrew Harris (even if it was only because Mom said you must, and because I promised the surfing afterwards would be great... I am sorry it was not...); “the Craig(e)s” (whose shoes melted from the hot sand!); Hayley Wain; Jeff Le Roux; Karien Bezuidenhout; Lauren Roodt; Malcolm Smale (the most not-dressed-for-the-beach sampler ever!); Marie Botha; Maryanne Roux; Nicola “Zoopy” Carrasco; Nicoleen Valentine; Ronel Nel; Ruan Gertenbach; Susan Flack; Tammy Jones; Thithi Sodi; and Vanessa Isaacs. And a very big thank you to the people who helped me to identify the macrofauna: Karien Bezuidenhout; Natasha Govender; and Renzo Perissinotto. I could never have done this without you all.

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ABBREVIATIONS AND DEFINITIONS

Abbreviations

4AR	Fourth Assessment Report (of the IPCC)
CD	Chart Datum
CSIR	Council for Scientific and Innovative Research
DAEA	Department of Agriculture and Environmental Affairs
DEAT	Department of Environmental Affairs and Tourism
DEM	Digital Elevation Model
EKZNW	Ezemvelo KwaZulu-Natal Wildlife
GDP	Gross Domestic Product
GIS	Geographic Information System
HAT	High Astronomical Tide
ICZM	Integrated Coastal Zone Management
IPCC	Intergovernmental Panel for Climate Change
MDS	Multidimensional Scaling
MPA	Marine Protected Area
MS	Microsoft
R1, R2, R3	Retreat scenario 1, 2 and 3
SCA	Systematic Conservation Assessment
SCP	Systematic Conservation Plan
SHWM	Spring High Water Mark
SLWM	Spring Low Water Mark
TAR	Third Assessment Report (of the IPCC)
UTM	Universal Transverse Mercator

Definitions

In all cases, the definitions provided here are the meaning of the terms used throughout this dissertation, unless otherwise indicated in the text by the use of a footnote, where an alternative definition is given.

Across-shore	The direction running perpendicular to a coastline.
Along-shore	Also – longshore. The direction running parallel to a coastline.
Attribute table	A table from which GIS layers are created. It can contain multiple data associated with the points, lines or polygons in the shapefile, including co-ordinates, lengths, areas, and location labels.
Back beach	The boundary between the backshore beach and the hinterland.
Backshore beach	The sandy area between the spring high water mark and the back beach.
Beach	The single geomorphic unit: the littoral active zone, including the nearshore surf zone, intertidal beach, backshore beach and sand dunes.
Beach width	The intertidal distance between the spring high and spring low water marks.
Closure depth	A term used in the Bruun rule defining the offshore point at which there is no net gain or loss of sediment.
Coastal defence	Any form of engineering that attempts to reduce or mitigate the effects of erosion and/or wave action.
Coastal squeeze	The phenomenon whereby beach area is reduced owing to rising sea levels on the seaward side, and fixing of the coastline due to development on the landward side.
Digital Elevation Model	A three-dimensional model used in GIS.
Digitizing	The process performed in GIS where the geographic locations of particular features are drawn onto a map. In the case of this dissertation, all digitizing was performed in ArcGIS 9.2, and based on SPOT 5 satellite imagery.
Hard engineering	Any form of coastal defence that uses concrete, bricks or rock, such as sea walls, piers, groynes, breakwaters and loffelstein.
Hinterland	The terrestrial land behind the beach.
Shapefile	A spatial layer used in GIS that can either be a point, a line or a

	polygon.
Point file/layer	A series of points with a particular geographic location used in GIS.
Polygon file/layer	A spatial layer in GIS that comprises two-dimensional shapes to represent areas with a specific geographic location.
Polyline	Another name for a line shapefile, that uses georeferenced lines to represent features.
Setback line	A line, usually scientifically determined, used in coastal management that defines the seaward boundary of coastal development, prohibiting development seaward of that line.
Singleton	A species occurring at only one site.
Soft engineering	Practices such as sandy beach nourishment, retreat or coastal realignment that do not require construction with concrete – not to be confused with softer armouring, which refers to the use of sand bags and dune reconstruction as a coastal defence strategy.
Virtual transects	Transects created in a GIS that were not created in the field.
WGS84 projection	A way of representing a three-dimensional earth on a two-dimensional plane, such that areas and distances are not distorted.

STUDY SITE: THE KWAZULU-NATAL COASTLINE

KwaZulu-Natal is one of four coastal provinces in South Africa. It is located on the east coast of the country, bordered by Mozambique in the north and the Eastern Cape in the south. The coastline is approximately 560 km long and is split into two bioregions (Delagoa and Natal) at Cape Vidal.

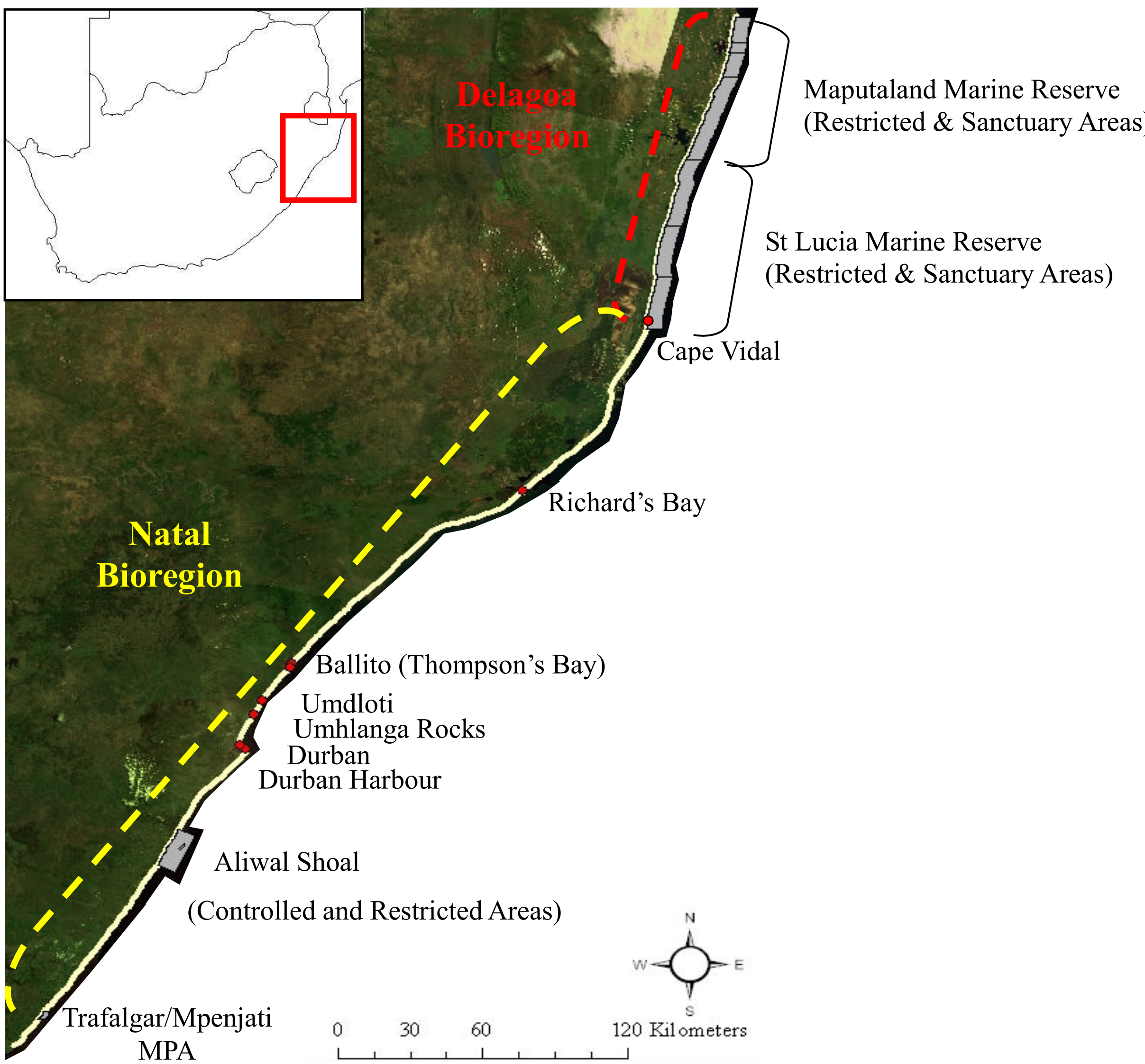

Figure 0.1. SPOT 5 satellite-image map of the KwaZulu-Natal (KZN) coastline (pale yellow line), showing important localities (red dots) and marine protected areas (MPAs, grey shapes) that are mentioned in this dissertation. The two bioregions in KZN are the Delagoa (red dashed line) and the Natal (bright yellow dashed line). Insert shows the location of KZN with respect to South Africa.

CHAPTER 1

CONTEXTUALIZING SANDY BEACH ECOLOGY IN A WORLD OF CLIMATE CHANGE

Introduction

Sandy beaches have an intrinsic natural beauty, representing a juxtaposed ecosystem of tranquillity and risk; rest and adventure. It is no wonder that people worldwide are drawn to the coast. As a holiday destination, sandy beaches attract the largest number of tourists (Davenport & Davenport, 2006) and in KwaZulu-Natal (KZN), beach visiting is ranked third as the preferred activity by foreign tourists, and first by domestic tourists (Tourism-KZN, 2007). Overseas, annual statistics at Delaware (USA), for example, show that 5.1 million people visit the beach, spending approximately US$ 573 million (Daniel, 2001). Furthermore, coastlines globally have attracted a number of investors and developers, to the end that 20.6 % of people live within 30 km of the coast, and 37 % within 100 km (Klein, 2001).

In spite of their high rankings as a tourist attraction, sandy beaches as coastal ecosystems have an extremely low public profile. A paper by Duarte *et al*. (2008), which addresses the imbalance in public awareness of coastal systems, did not include beaches! In reality, sandy beaches harbour unique biotic assemblages and perform many important, under-appreciated ecological processes and services (McLachlan & Brown, 2006; Beaumont *et al.*, 2007), *e.g.,* filtering sea water (McLachlan, 1989), mineralizing organic matter (McLachlan, 1983), and buffering against the extreme wave action associated with storms (Beaumont *et al.*, 2007). Sandy beaches also provide nesting and/or foraging sites for threatened vertebrate species, such as sea birds (*e.g.,* African black oystercatchers – *Haematopus moquini*) and turtles (*e.g.,* loggerheads – *Caretta caretta* and leatherbacks – *Dermochelys coriacea*). But the small size and cryptic nature of the resident biota, and the seeming lack of traditional ecological structures (McLachlan & Dorvlo, 2005), *e.g.* food webs, have created a common misperception that beaches are no more than sand to build castles in, and waves to surf.

Consequently, the ecological implications of coastal management interventions are rarely considered. In addition, beach conservation extends no further than the maintenance of the physical features, such as sediment budgets (Schlacher *et al.*, 2008): essentially maintaining beaches for tourism. In light of the predicted climate change impacts that threaten to be superimposed on an already stressed system, the paradigm that sandy beaches need to be conserved in a pristine state only for tourists needs to be shifted (Brown & McLachlan, 2002).

Beaches

Structure

Sand on the beaches originates primarily from inland erosion and is transported to beaches via river systems. The sand grains can range in size from 0.05 mm – 2 mm and comprise mainly the minerals silica and quartz, and to a lesser extent volcanic basalt and feldspar (Brown & McLachlan, 2002). Some sand particles may have marine biogenic origins, such as shell fragments, skeleton pieces and sponge spicules (Brown & McLachlan, 2002). These are washed up onto the beach by wave action. The littoral active zone is a single geomorphic unit (McLachlan & Brown, 2006), which comprises the coupled near shore, beach and dune system where sand is highly mobile (Brown & McLachlan, 2002). There are close linkages between these three adjacent systems (Jones *et al.*, 2007), as shown in Figure 1.1 below.

A breakdown in the linkages within the littoral active zone can lead to erosion. About 70 % of beaches worldwide are eroding (Bird, 2000). On the whole, this has been promoted by inappropriately implemented ecosystem management practices. In particular, the amount of sand supplied to many beaches has been reduced. This has been caused by: damming of rivers, which reduces the amount of sediment coming down estuaries onto the beach; preventing the movement of sand from dunes to the beach by developing the foredune or constructing sea walls immediately behind the beach (Fig. 1.1); and interrupting longshore drift of sediment by building groynes, piers and breakwaters. Consequently, beaches are generally sediment starved.

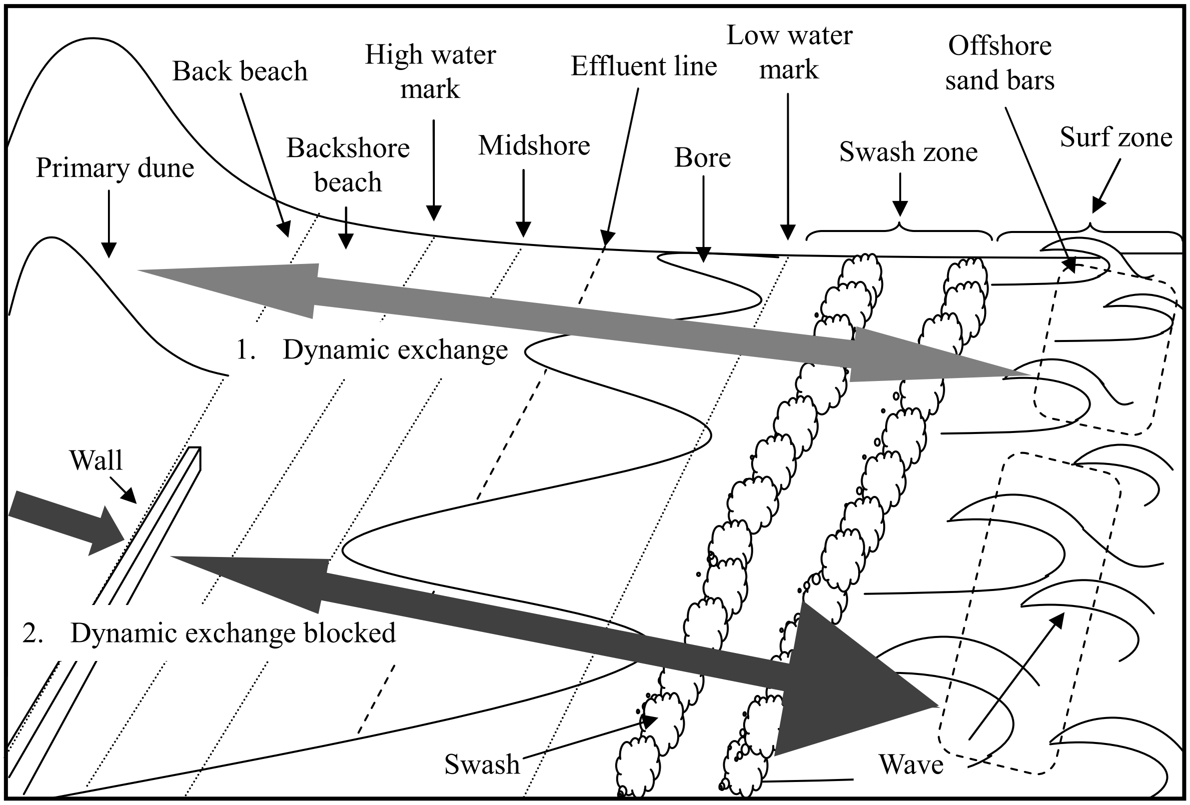

Figure 1.1. The salient features of a sandy beach and the dialectical relationships in the littoral active zone among the surf zone, sandy beach and dunes for dynamic sediment transport within these coupled systems. The light grey arrow indicates the dynamic exchange of sediment between the dunes, beach and offshore sand bars. The dark grey arrow indicates the effect that retaining walls (or any other hard engineering, *e.g.,* roads, houses or railway lines) may have on natural sand movement, with the larger arrow head indicating that this generally leads to eroding beaches.

Two major beach zonation patterns emerged during early studies on sandy beaches: a three-zone scheme presented by Dahl (1952) based on the distribution of characteristic crustaceans, and a four-zone scheme presented by Salvat (1964) based on the changes in sand moisture content. Dahl's zones from land to sea are: sub-terrestrial fringe – area above the driftline; midlittoral – intertidal beach between the driftline and the effluent line; sublittoral fringe – area below the effluent line. Salvat's zones from land to sea are: drying zone – land above the driftline; retention zone – intertidal beach up until just before the effluent zone; retention zone – a zone of beach over the effluent line; saturation zone – the area seaward of just below the effluent line. These and other zonation schemes were reviewed by McLachlan and Jaramillo (1995). The evidence in their paper and in Defeo and McLachlan (2005) supported the zones proposed by Dahl. However, the number of zones and their nature is variable depending on the beach morphodynamic type (McLachlan & Brown, 2006).

Morphodynamic types

Owing to the dynamic nature of sandy beaches, there is no single morphological form. On wave-dominated beaches (Short, 1999), the drivers of beach morphodynamic types, described below, can place a beach anywhere along a continuum of states, from dissipative to reflective (Wright & Short, 1984). Dissipative beaches tend to be macrotidal (McLachlan & Dorvlo, 2005), and are characterized by: gentle beach slopes (Short, 1999; Brown & McLachlan, 2002; Benedet *et al.*, 2004); fine sand of less than 200 µm (McArdle & McLachlan, 1992; Short, 1999; Benedet *et al.*, 2004); a wide surf zone (Brown & McLachlan, 2002) that comprises large, spilling breakers, which dissipate their wave energy in the surf zone (Short, 1999; Brown & McLachlan, 2002;Benedet *et al.*, 2004), so that gentle bores run far up the beach. Reflective beaches on the other hand, tend to be microtidal (McLachlan & Dorvlo, 2005) with a steep sloped beach face (Short, 1999; Benedet *et al.*, 2004), coarse sand larger than 1 000 µm (McArdle & McLachlan, 1992; Short, 1999; Benedet *et al.*, 2004) and have no true surf zone (Brown & McLachlan, 2002). The small, plunging breakers break onto the beach face (Short, 1999; Benedet *et al.*, 2004), reflecting most of the wave energy back to sea (McArdle & McLachlan, 1991).

In between these two extreme states, there are four broad categories of intermediate beaches (Short & Wright, 1983; Short, 1999, 2006). These are characterized by the presence, location and morphology of sand bars in the surf zone, rip currents, and cusps on the beach. The most dissipative-like intermediate beach is the longshore bar – trough morphodynamic state, followed in the continuum by the rhythmic bar and beach morphodynamic state, the transverse bar and beach morphodynamic state, with the ridge-runnel or low tide terrace form being the most reflective-like morphodynamic type (Short & Wright, 1983; Short, 1999, 2006). These intermediate beach forms are very temporally variable (McLachlan & Brown, 2006), and for spatial classification purposes, simply classifying beaches as intermediate is more appropriate.

Although not really relevant to the KZN beaches, the true extreme states in the beach morphodynamic type continuum are beaches where tides are more important than waves in shaping the beach form. These are tide-modified or tide-dominated beaches (Masselink & Short, 1993; Short, 2006). The states range from tidal flats and ultra-dissipative beaches, to ultra-reflective beach forms (Masselink & Short, 1993; Short, 2006).

Several indices have been developed to determine beach morphodynamic type, including: (1) Dean's parameter (Ω), which measures the waves' ability to move sand (Wright & Short, 1984); (2) the beach state index (BSI) which measures the ability of waves and tides to move sand (Defeo & McLachlan, 2005); (3) the beach index (BI), which allows beaches of different widths to be compared based on their maximum spring tide range and beach slope (McLachlan & Dorvlo, 2005); and (4) the beach deposit index BDI, which measures the slope and sand properties of a beach (Soares, 2003).

$$(1)\ \Omega = \frac{H_b}{W_s \times T_w} \qquad \text{…Eqn. 1.1}$$

$$(2)\ BSI = \Omega \times TR \qquad \text{…Eqn. 1.2}$$

$$(3)\ BI = Log_{10}\left(\frac{M_z \times TR}{S}\right) \qquad \text{…Eqn. 1.3}$$

$$(4)\ BDI = \left(\frac{1}{S}\right) \times \left(\frac{a}{M_z}\right) \qquad \text{…Eqn. 1.4}$$

Where: H_b = wave height (m); W_s = sediment fall velocity (m.s^{-1}); T = wave period (s); M_z = grain size (mm; φ +1 for BI to avoid negative values); TR = tide range (m); S = average intertidal slope; a = 1.03125 mm and is the median grain size of the sediment classification scheme.

Abiotic drivers

For wave-dominated beaches, the abiotic factors that drive beach morphodynamic types can be split into two categories: primary-ultimate and secondary-proximate drivers. The primary drivers include three principle factors: sand grain size; wave climate; and tidal regime, which interact to give the range of beach morphodynamic types we observe (McArdle & McLachlan, 1992; Short, 1993, Short, 1999; Benedet *et al.*, 2004; Defeo & McLachlan, 2005; McLachlan & Dorvlo, 2005; Short, 2006). The interactions among these drivers relate largely to the processes that move sand, *i.e.,* sediment transport (from along-shore to across-shore patterns by either wind or water), which can lead to erosion and/or accretion. Of the three primary drivers, wave action and sand grain size are generally considered most important (McLachlan, 1983), which is also evident in Figure 1.2 below. However, relatively speaking (under natural circumstances), the grain size of a beach varies very little with time, so most temporal variation in beach morphodynamic type is due to changes in wave height, and to a lesser extent, wave period (Wright *et al.*, 1985).

The role of the secondary drivers is to shape the beach within the morphodynamic state that is dictated by the primary drivers. However, these effects are more subtle and can accumulate, leading to a shift in beach morphodynamic type directly. Alternatively, their influence on one or more of the three primary drivers could imply an indirect role in driving the local beach morphodynamic type. These secondary drivers include:

1. Extrinsic drivers
    a. Storm impacts: storms move large volumes of sand from the upper beach into the surf zone (Brown & McLachlan, 2002; Hill *et al.*, 2004).
    b. Storm frequency: the amount of time between storm events determines if the beach has enough time to return to pre-storm conditions before the subsequent storm hits (Costas *et al.*, 2005).
    c. Local wind fields: winds influence wave conditions and associated processes (Gómez-Pujol *et al.*, 2007), and the aeolian transport of sand (Brown & McLachlan, 2002; Hesp, 2002). The prevailing wind direction would also be an important consideration in this factor (Brown & McLachlan, 2002; Hesp, 2002).
    d. Astronomical phenomena: the cyclic alignment of planets, stars and moons, for example, can influence sea levels and tides (Mather & Vella, 2007; Smith *et al.*, 2007a; Smith *et al.*, 2007b; Mather, 2008).
    e. Sea-level rise: it promotes the erosion of beaches (Brown & McLachlan, 2002).
2. Intrinsic drivers
    a. Nature and source of the sediment: this influences how easily the sand is eroded (Jackson *et al.*, 2005).
    b. Physiographic factors (*i.e.,* local coastal topography): it affects the incident angle of wave attack (Gómez-Pujol *et al.*, 2007).
    c. Opening and closure of inlets or estuaries: estuaries can alter cross-shore sand movements (Costas *et al.*, 2005) and sand grain size on the beach

d. Local bathymetry, including the presence of rocky shore platforms (Schoonees *et al.*, 2006; Anfuso *et al.*, 2007): this affects waves, currents and sediment transport (Ruessink *et al.*, 2007).
e. Water table height: it can change the erosion/accretion tendency of a beach (Horn, 2002).

The extent of the individual and cumulative impacts of the secondary drivers often depends on the nature of the environment immediately behind the beach, and how intact the littoral active zone is. The back beach type can range from extensive sand dunes, to intensive coastal development and sea walls. This in turn influences the dynamics of the sediment movement among the dunes, beach and surf zone (Fig. 1.1). If the naturally dynamic beach processes in the littoral active zone are impeded by hard structures, the magnitude of the secondary drivers' erosive impacts can be heightened. This will be exacerbated if beaches are sediment starved, as discussed above.

The relationships among the primary and secondary drivers of beach morphodynamic types are illustrated in Figure 1.2 below. A component of the model below that is missing is the magnitude of the relationships between the different factors – mainly because they are mostly unknown. However, it is predicted that a 10 % increase in wind speeds can lead to an increase in the rates of other coastal processes of up to an order of magnitude, and a 26 % increase in wave heights can result in a 40 – 100 % increase in sediment transport processes (Hewitson, 2006). Another study showed a 50 % increase in wave height caused a 300 % increase in the rate of longshore sediment transport (Miller, 1999). Although exact numbers cannot be added to the model, the principle is that each driver can have a significant effect in determining local conditions, and hence the prevailing beach morphology.

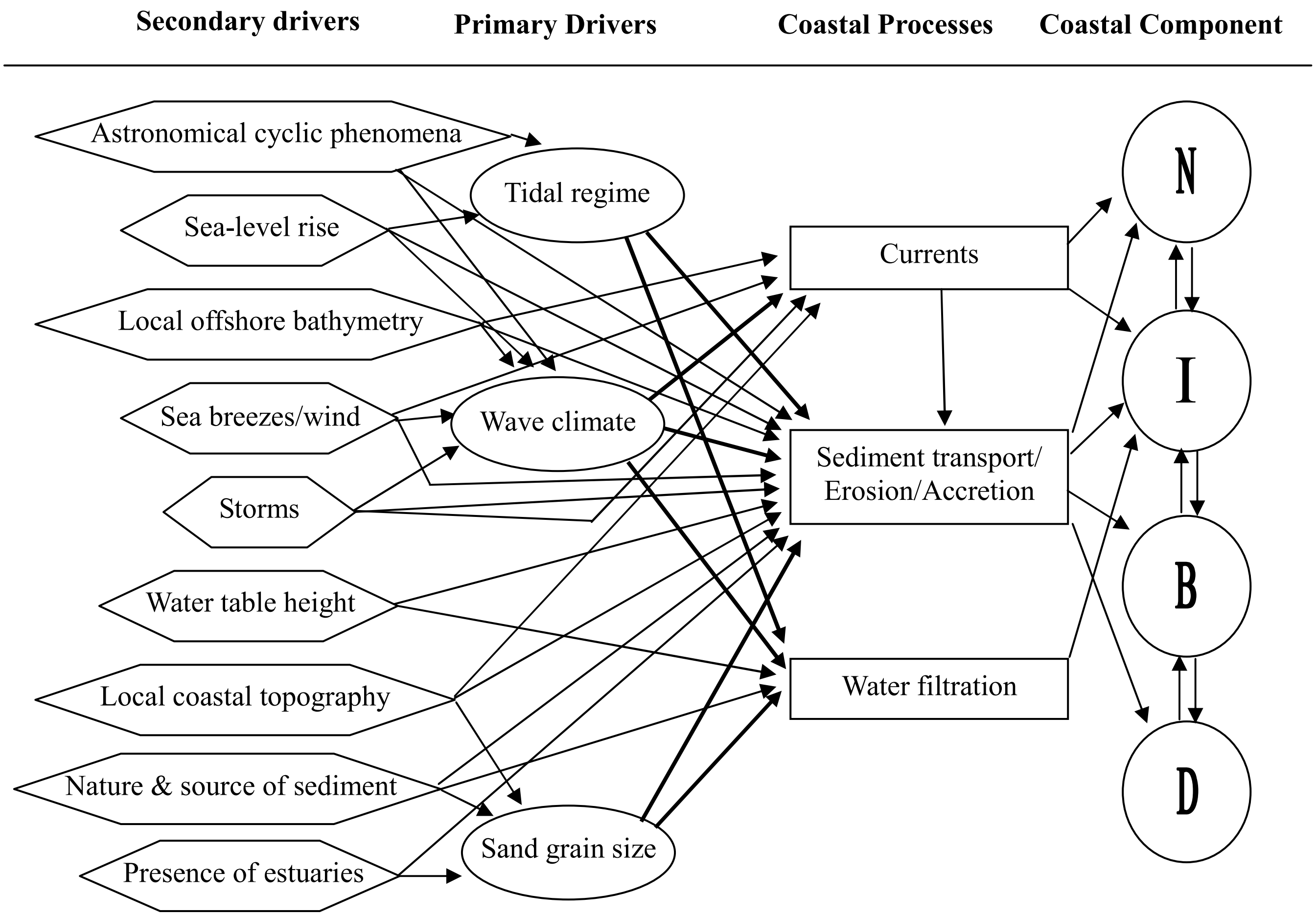

Figure 1.2. The interrelationships between the primary (oval) and secondary (hexagonal) abiotic drivers of coastal processes (rectangles) that influence the morphology of the different coastal components (circles), where: *N* is the nearshore, subtidal region; *I* is the intertidal beach; *B* is the backshore beach; and *D* is the sand dunes. The greater role of wave climate and sand grain size is highlighted, as are the dominant morphological processes of sediment transport, erosion and accretion in the physical structuring of sandy beaches.

Biota

The organisms that are found on a sandy beach range in size from microscopic, resident bacteria, to large, visiting leatherback turtles, with abundance of animals generally decreasing with increasing size. Owing to the harshness of the physical environment that these organisms inhabit, the autecological hypothesis proposed by Noy-Meir (1979) was applied to sandy beaches by McLachlan *et al.* (1993). This infers that beach-organism distributions are more as a response to the physical habitat than to biological interactions. Recent studies, however, suggest that biological interactions may be more important in shaping biotic communities on beaches than previously thought (Defeo *et al.*, 1997), particularly on dissipative beaches where animal densities are high (Dugan *et al.*, 2004).

There are distribution patterns of sandy beach fauna at a macroscale (latitude), mesoscale (along- and across-shore) and microscale (patch) (Defeo & McLachlan, 2005). Several hypotheses have been formulated to try and explain species distribution patterns (see McLachlan & Brown (2006) for a review), including: the swash exclusion hypothesis (McLachlan *et al.*, 1993); the multicausal environmental severity hypothesis (Brazeiro, 2001); the habitat harshness hypothesis (Defeo *et al.*, 2001; Defeo *et al.*, 2003); the sand and swash exclusion hypothesis (McLachlan, 2001; Nel *et al.*, 2001); and the hypothesis of macroscale physical control (McLachlan & Dorvlo, 2005). Almost all these hypotheses attempt to explain why reflective beaches have a lower species richness than dissipative beaches. However, there are physical features that appear to influence species richness on beaches, regardless of morphodynamic type: beach length (Brazeiro, 1999; Deidun & Schembri, 2008); beach area – although this might be a beach morphodynamic type artefact (McLachlan & Dorvlo, 2007); and intensity of urbanization (Veloso *et al.*, 2008). These latter three factors are important to consider in terms of beach community conservation. In order for a beach community to comprise a maximum local biodiversity, beaches need to be long enough, wide enough and have as low impact human development pressures as possible.

Zonation of sandy beach fauna does not show sharp boundaries and as the tide rises, individuals migrate or enter the water column, and the zones compress (McLachlan & Brown, 2006). However, McLachlan & Brown (2006) detail three broad zones that fauna are divided into, although this can change depending on beach morphodynamic type.

1. Supralittoral zone (the landward zone in Dahl's (1952) and Salvat's (1964) schemes)
    - Characterized by any of the following: talitrid amphipods; oniscid isopods (*Tylos*); ocypodid crabs; cirolanid isopods (*Excirolana*); and insects
    - These macrofauna live in dry sand, but may return to the swash for feeding and reproduction
2. Littoral zone (Dahl's middle zone, and Salavat's two central zones – although not always including the resurgence zone)

  - Characterized by the following macrofauna: cirolanid isopods (including some species of *Excirolana*); other isopods; haustoriid or other amphipods; spionid polychaetes; and ophelid polychaetes.
  - These species are truly intertidal and are not normally found in the surf zone. These species are not found on coarse-grain reflective beaches.
3. Sublittoral zone (Dahl's and Salvat's lowest zones)
  - Characterised by: hippid crabs; mysids; donacid bivalves or equivalents; nephtyid polychaetes; glycerid polychaetes; idoteid amphipods; oedicerotid amphipods; haustoriid amphipods.
  - These species extend into the surf zone and are generally absent on reflective beaches.

In light of climate change scenarios that threaten to inundate large sections of the coastline, another salient point for effective conservation of beach communities is beach connectivity. This is particularly so for reflective beach communities. Most sedentary benthic populations function as metapopulations, where each spatially separated population is connected by pelagic larvae (Caddy & Defeo, 2003). Current thought is that sandy beach populations could function as metapopulations: dissipative beaches being biodiversity sources, and reflective beaches being sinks (Caddy & Defeo, 2003; Defeo & McLachlan, 2005). Reflective beach biodiversity therefore depends on: the connectivity with dissipative beaches (Defeo & McLachlan, 2005) by the local- and large-scale hydrographic features that influence the rate and direction of larval dispersal; and on the richness and abundance status of the source populations (Caddy & Defeo, 2003). It is difficult to test this hypothesis for sandy beaches because of the many other factors affecting temporal species abundances (Defeo & McLachlan, 2005). However, recent studies are also beginning to question the validity of the connectivity hypothesis and have concluded that it requires further investigation (McLachlan & Dorvlo, 2007).

Ecosystem goods and services

In South Africa, coast-related products contribute 35 % of the country's Gross Domestic Product (White Paper for Sustainable Coastal Development, 2000). However, there are a number of goods and services provided by sandy beaches that do not necessarily confer a direct economic value, and are subsequently underappreciated. The goods include (Martínez *et al.*, 2007):

1. Food for humans and animals
2. Salt, mineral and oil resources
3. Construction materials
4. Biodiversity, including a genetic stock that could have applications in medicine and bioprospecting

The primary ecosystem services are (Defeo *et al.*, 2008; Schlacher *et al.*, 2008):

1. Sediment storage and transport
2. Wave dissipation and associated buffering against extreme events
3. Dynamic response to sea-level rise (within limits)
4. Breakdown of organic materials and pollutants
5. Water filtration and purification
6. Nutrient mineralisation and recycling
7. Water storage in dune aquifers and groundwater discharge through beaches
8. Maintenance of biodiversity and genetic resources
9. Nursery areas for juvenile fishes
10. Nesting sites for turtles and shorebirds, and rookeries for pinnipeds
11. Prey resources for birds and terrestrial wildlife
12. Provision of scenic vistas and recreational opportunities
13. Supply of bait and food organisms
14. Functional links between terrestrial and marine environments in the coastal zone

It is estimated that the global coastal and marine ecosystem goods and services are worth US$ 21 trillion per annum (Krelling *et al.*, 2008). Sandy beaches are therefore exceptionally valuable ecosystems, deserving of far more conservation priority than they have previously been afforded.

Threats

Owing to the combination of a lack of understanding of beach ecosystems (particularly amongst management authorities), approval of inappropriately-placed development initiatives, and poor public awareness, sandy beaches are exposed to a number of pressures (Brown & McLachlan, 2002; Schlacher *et al.*, 2006; Schlacher *et al.*, 2007; Defeo *et al.*, 2008; Schlacher *et al.*, 2008). Most of these are human-related, and include: disruption of sand transport; pollution; trampling; recreational activities, including use of off-road vehicles; litter; beach cleaning; mining; groundwater changes; bait collecting; and fishing pressures (Brown & McLachlan, 2002; Schlacher *et al.*, 2006; Schlacher *et al.*, 2007; Defeo *et al.*, 2008; Schlacher *et al.*, 2008). This has led to the overexploitation of resources and modification of the coastline to the extent that these unsustainable practices have reduced the resilience of this ecosystem to natural disturbances (Klein, 2001), and have impacted beach fauna communities (*e.g*., Thomas *et al.*, 2001; Dugan *et al.*, 2008; Veloso *et al*., 2008).

In synergistic addition to these current stresses, the implications of climate change for sandy beaches threaten only to exacerbate damages. As mentioned above, about 70% of beaches are already eroding (Bird, 2000). The added erosive force of rising sea levels and increased intensity and frequency of storms will aggravate this coastal problem. This could lead to additional crises (*e.g.* beaches eroding down to bedrock; or beach nature significantly changing due to high rubble inputs from infrastructure failure during big wave events), potentially forcing local ecosystems into a cascading series of disastrous consequences. These could include large declines in biodiversity, biomass and abundance of beach fauna, and concomitant suppression (or complete loss) of ecosystem services.

Climate change

Causes/drivers

It is imperative to have an understanding of the causes and drivers of climate change, in order to fully grasp the long-term implications of this phenomenon. For a stable climate system to be maintained, the amount of incoming and outgoing radiation must be equal (Naidu *et al.*, 2006). An imbalance in this can cause the surface temperature of the earth to change (Naidu *et al.*, 2006; IPCC, 2007). There are essentially two principle forces driving climate variability: solar forcing from the sun (*e.g.,* Beer *et al*., 2000; Soon *et al*., 2000; Cubasch *et al.*, 2006); and radiative forcing from greenhouse gases (Naidu *et al.*, 2006; IPCC, 2007). In the last 400 years, solar variability has been responsible for 59 – 74 % of decadal average surface temperature change (Palmer *et al.*, 2004). However, in the last 100 – 150 years, the relative contribution of solar forcing has been reduced, and the amount of radiative forcing from greenhouse gases is increasing beyond previous levels (Beer *et al.*, 2000; Soon *et al.*, 2000; Cubasch *et al.*, 2006).

The reason for the recent increase in the radiative forcing contribution is the exponential increase in the concentration of greenhouse gases in the atmosphere, largely initiated by the Industrial Revolution (mid-18th – 19th centuries). The IPCC (2007) state that the amount of carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) in the atmosphere has increased from pre-industrial concentrations of 280 ppm, 714 ppb and 270 ppb, to 379 ppm, 1774 ppb and 319 ppb in 2005, respectively. Further, the annual increase of CO_2 has been higher in the last decade (1995 – 2005) than any of the decades since 1960, when direct, continuous assessments were first started (IPCC, 2007). The high global warming potential of these gases (Naidu *et al.*, 2006; IPCC, 2007), coupled with their long residence times (*e.g.,* CO_2 = 200 – 450 years) (Naidu, *et al.*, 2006) in the atmosphere, gives climate change its strong inertia. This implies an ongoing warming effect on the earth, even if emissions were stopped completely (Klein, 2001; Naidu *et al.*, 2006; IPCC, 2007).

General consequences of climate change

The most obvious effect that increased solar and radiative forcing has on the global climate is an increase in temperature. The IPCC (2007) record that average global temperatures have risen by 0.74 º C since 1850. At the time of publication of the latest IPCC (2007) report, 11 of the previous 12 years (1995 – 2006) had been the warmest years since 1850. However, the global increase in temperature is not uniform: for example, average Arctic temperatures have increased at more the twice the rate of global averages over the last century (IPCC, 2007). Not only have averages increased, but extreme temperatures as well. Over the last 50 years, the number of cold days, nights and frost events has decreased, and the number of hot days, nights and heat waves has increased (IPCC, 2007). Certainly for ecosystems, the changes in extremes are likely to be of greater consequence than changes in averages.

Raised global temperature has a number of consequences, manifesting at all scales. At a large scale, these include melting of the polar ice caps and glaciers (Zwally *et al.*, 1983; Oppenheimer, 1998; Arendt *et al.*, 2002; Arrigo & Thomas, 2004; Vaughan, 2005; Joughin, 2006) and increased sea surface temperatures (Gille, 2002; Hegerl & Bindoff, 2005; IPCC, 2007). Both of these concomitantly contribute to: sea-level rise (Douglas, 1995; Cabanes *et al.*, 2001; Church, 2001; Edwards, 2005; Church & White, 2006; Mather, 2007; Rahmstorf, 2007; Rahmstorf *et al.*, 2007); decreasing ocean salinity (Munk, 2003; IPCC, 2007); decreasing ocean pH (Caldeira & Wickett, 2003); changes in storm and precipitation patterns (Benavente *et al.*, 2006; Huntington, 2006; Naidu *et al.*, 2006; IPCC, 2007); possible increases in tropical cyclone activity (Knutson *et al.*, 1998; Webster *et al.*, 2005; Hoyos *et al.*, 2006; Landsea *et al.*, 2006; IPCC, 2007); and potential shutdown of thermohaline circulation (Keeling & Peng, 1995; Broecker, 1997; Broecker *et al.*, 1999; Clark *et al.*, 2002; Wunsch, 2002; IPCC, 2007). Of the consequences listed here, sea-level rise and changes in storm patterns will be considered in this study.

Consequences of climate change for sandy beaches

Sea-level rise is caused primarily by the thermal expansion of the ocean (Chemane *et al.*, 1997; Cabanes *et al.*, 2001; California Coastal Commission, 2001; Edwards, 2005; Naidu *et al.*, 2006; IPCC, 2007) in response to global surface temperature increases (IPCC, 2007), melting of polar ice caps and other subsidiary sources (*e.g.,* Munk, 2003). Currently, global rates of sea-level rise are accelerating (Church 2001; Church and White 2006; Rahmstorf 2007; Rahmstorf, *et al.,* 2007), following the upper limits predicted by the IPCC (Church & White, 2006; Rahmstorf, 2007; Rahmstorf *et al.*, 2007). The latest sea-level rise predictions by the IPCC are 18 - 59 cm by 2100 (IPCC, 2007). Rahmstorf (2007) suggests that, given the current observational data, the sea-level rise predictions for 2100 made by the IPCC (2007) may be too conservative, and that it would not be unrealistic to expect a one-meter rise in sea level.

Some of the consequences of sea-level rise include: increased beach erosion, dune blowout formation and ultimately, landward beach retreat (Hesp, 2002); intensified flooding; and increased saline intrusion into groundwater (Gambolati *et al.*, 2002). It has been predicted that sea-level rise itself will not affect the highly adaptable, mobile beach species, but the loss of habitat that it causes will (Brown & McLachlan, 2002; Dugan *et al.*, 2008).

Storms are important in shaping beaches because they move large quantities of sand from the upper shore and deposit it in the surf zone. This sand is moved back slowly to the beach and dunes during calmer conditions (Brown & McLachlan, 2002; Costas *et al.*, 2005; Anfuso *et al.*, 2007).

Consequently, many coastlines display erosion-accretion cycles (Anfuso *et al.*, 2007). Depending on the intensity of the erosion event and the local wave energy, recovery of beaches from storms can take up to a decade (Anfuso *et al.*, 2007), and some beach profiles may not fully recover (Costas *et al.*, 2006; Anfuso *et al.*, 2007). If the return period of extreme storms decreases as is predicted (IPCC, 2007) and insufficient time is available for recovery from a preceding storm event, then there could be severe implications for beaches. This would be of particular concern for those beaches that are currently sediment starved and already in a critical state of erosion.

The combination of storms (a pulse disturbance) and sea-level rise (a press disturbance) thus represents a synergistic erosive force for beaches. This, in conjunction with changes in sediment transport patterns from management interventions, is the greatest long-term threat to sandy beaches virtually worldwide (Brown & McLachlan, 2002). Eroding beaches generally migrate landwards (Bray *et al.*, 1997; Brown & McLachlan, 2002; Hesp, 2002; Schlacher *et al.*, 2006), which confers a significant risk on infrastructure located too close to the beach. If a beach is lined with development, walls or other hard structures, the beach cannot retreat. The intertidal area is subsequently forced into a "coastal squeeze" as sea levels rise (Bray *et al.*, 1997; Brown & McLachlan, 2002; Hesp, 2002; Schlacher *et al.*, 2006). The ultimate consequence is loss of beach habitat by inundation.

From an ecological perspective, losing beach area through coastal squeeze means sequentially losing the species associated with the beach zones, starting with the most landward zone, the supralittoral (*e.g.,* Dugan *et al.*, 2008). In addition, it means some ecosystem goods and services will be compromised, or even lost. This can include the nesting sites of endangered turtles (Fish *et al.*, 2008). Owing to the significant value of sandy beaches, albeit under-appreciated, it is important that the effects of coastal squeeze are minimized as much as possible. This essentially means managing and regulating coastal development landward of the beach.

Coastal development: past and current practices

It is predicted that coastlines globally will bear the brunt of climate-change impacts from sea-level rise and storms (Schlacher *et al.*, 2006; Jones *et al.*, 2007). This is largely because many structures have been built too close to, if not in, the littoral active zone, with the subsequent removal or restraining of the local foredunes, and concomitant breakdown in the linkages between dune systems and the beach, causing erosion problems. Two thirds of the world's largest cities are located on coasts (Cicin-Sain & Belfiore, 2005), many of which are unsustainable and at an increasing risk from natural hazards (Yeung, 2001). The concern lies not only in the risk to the coastal development and the society associated with it, but in the amount of coastal squeeze that it will cause. Additionally, international trends show that coastal human populations are expanding more rapidly than inland populations (Schlacher *et al.*, 2008). As these populations increase, the more difficult it is to attain sustainability in natural ecosystems (Halpern *et al.*, 2008). Some reports even suggest that the socio-economic scenario is of greater consequence than the climate change scenario when looking at the predicted effects for the next century (*e.g.,* Nicholls, 2004; Jollands *et al.*, 2007).

A South African perspective

Determining the implications of climate change for the KZN beaches is of particular importance, given the predicted consequences of climate change for the rest of South Africa. The western half of the country gets less than 500 mm rainfall per annum, which by international standards is arid. Climate change predictions include a decreased rainfall in this western half, and increased rainfall along the eastern escarpment (Naidu *et al.*, 2006). This implies that living conditions along the east coast will be far more favourable than in the west and thus, it is predicted that the future east coast population will be particularly large (Naidu *et al.*, 2006). Increasing populations threaten to put a strain on already limited resources, and have serious implications for land use change. In KZN, the last 12 years have already seen a 22 % increase in coastal urbanization in the 100-m strip inland of the high water mark (Celliers, in prep.). Additionally, maps of the conservation status of vegetation types in KZN show a band of about 50 km from the coast (excluding the northern third of the province) that has mostly been transformed from endangered to critically endangered in the last five years (Kohler, 2005). Unless managed appropriately, KZN will be particularly at risk of losing its beaches to coastal squeeze, along with the associated biodiversity, ecosystem goods and ecosystem services.

Sandy beach conservation in South Africa is particularly well legislated. There is the White Paper on Sustainable Coastal Development (2000) and the recently tabulated Integrated Coastal Management Bill (2007) that can be applied to managing the coastline and regulating coastal development. The latter, once enacted, will replace the Sea Shore Act (1935). In KZN, there has been a recent ban of off-road vehicle (ORV) driving on sandy beaches (Celliers *et al.*, 2004), apart from in specific recreational areas (*e.g.,* Sodwana Bay, but only in the allowed area) and at boat launch sites. Thus, in spite of the poor public awareness, and general lack of understanding of sandy beaches as ecosystems by most people, there is some recognition of the importance to conserve beaches, even if this is motivated largely by human interests in the coast.

Problem identification

This dissertation is the first step towards a coastal conservation management plan for KZN. The aim is to determine the ecological implications of sea-level rise and storms for the KZN beaches. The broad objectives are:

- to map the KZN beaches in terms of morphodynamic type, biodiversity, nature of the back beach and proximity of development, and examine the spatial trends;
- to determine the consequences of a high-impact erosion event from a storm for sandy beach macrofauna;
- to determine the vulnerability of the KZN coastline to, and potential consequences of sea-level rise under different scenarios of climate change and coastal development;
- to test the predictive model (from the objective above) against the effects of a real storm that coincided with a high astronomical tide, simulating a scenario of 1 m sea-level rise; and
- to make recommendations for beach management in KZN based on the results of the preceding objectives.

Research Philosophy

This study is a synthesis of data from a variety of both published and unpublished sources. The sampling that was done was in order to fill in specific gaps in the existing data. This was followed by compiling the data in a geographic information system (GIS; ArcGIS 9.2) for a desktop analysis. Because this is the first study of its kind for KZN, areas of further research, required conceptual development, and suggestions for the focusing of future efforts are highlighted.

Dissertation structure

I have written this dissertation by starting with a detailed introduction, followed by four chapters that are written up as separate papers, and thus, some information is repeated across the chapters. Although each chapter could stand alone, they complement one another in logical sequence, which, together, address the issue of sea-level rise and storm impacts for the KZN sandy beaches. The conclusion is written in a similar style to the introduction.

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CHAPTER 2

CHARACTERIZING THE PHYSICAL AND BIOLOGICAL NATURE OF THE KWAZULU-NATAL BEACHES

Abstract

Ecosystems are losing species at an unprecedented rate, largely because of unsustainable human activities. In addition, climate change is predicted to be the greatest threat to ecosystems, sandy beaches in particular, in the next century. Formulation of conservation plans requires knowledge of local systems so that priority areas can be identified for conservation. In this paper, the current physical and biological characteristics of the KwaZulu-Natal (KZN) coastline are described, in terms of beach morphodynamic types, coastal development and macrofauna diversity. The physical characteristics were mapped using satellite imagery and oblique aerial photography in ArcGIS 9.2. Biological characteristics were determined by sampling for macrofauna diversity along across-shore transects, at 13 sites along the coast. Based on the spatial heterogeneity of coastal development in KZN, and the dominant beach morphodynamic type, the coastline can be broadly split into three regions: north; central; and south. The northern region comprises mostly pristine, undeveloped dissipative and intermediate beaches. The central region has nodes of intensive urban development very close to the beach, with strips of natural vegetation in between the nodes, and beaches tend to be intermediate. The southern region is developed at a low to intermediate intensity and is characterized by pocket beaches that are rocky and reflective, with a few longer intermediate beaches also present. There was a distinction in macrofauna communities based on beach morphodynamic type and on bioregion. The paradigm that species richness increases from reflective to dissipative beaches was proven to apply to the KZN sandy beaches. Most of the northern region falls in the Delagoa bioregion, and is currently protected by the St Lucia and Maputaland Marine Reserves. Although these reserves extend along 25 % of the KZN coastline, there are 28 species of macrofauna that occur only in the Natal bioregion and are largely unprotected in formal reserves. It is recommended that sandy beach marine protected areas (MPAs) are proclaimed in the central and southern regions as a matter of urgency, given the current extent and intensity of development in these two regions, and the rate at which development is occurring.

Introduction

Recently there has been an emphasis on biodiversity, and a drive to increase the awareness of, and thus reduce the alarming rate of species loss (*e.g.*, Chapin III *et al.*, 2000). In most instances, the decline in biodiversity has been related to human activities, such as habitat destruction and overexploitation of resources (Forester & Machlis, 1996; Chapin III *et al.*, 2000). In the next century, unmitigated, anthropogenically-accelerated climate change will potentially be the greatest modern threat to ecosystems globally (IPCC, 2007). This is because climate is an integral component of the abiotic foundation that all ecosystems are built upon. Any change at this most basic level has implications for the survival of the organisms within the habitat, particularly if the changes are too rapid to allow for adaptations by the various species.

In light of this, organizations world-wide are developing conservation management plans to protect as much biodiversity, and associated goods and services provided by intact ecosystems, as possible. In order to develop effective conservation strategies, there needs to be a good understanding of local environments, both in terms of the abiotic elements that drive habitat type and/or biodiversity, and in terms of the biodiversity itself. Once these characteristic features have been determined, one can make predictions of how the ecosystem will respond to climate change and hence, what the most suitable proactive strategies will be to ensure conservation.

In the sandy beach context, determining ecosystem characteristics essentially means knowing the extent of the different beach morphodynamic types within the study area. This is because beach morphodynamic type can be used as a proxy for other features of beaches, both physical – such as slope and sand grain size (Soares 2003), and biological - such as macrofaunal diversity (Jaramillo *et al.*, 1993; Defeo & McLachlan, 2005). The different beach morphodynamic types arise out of the interactions among the various abiotic drivers (refer to Chapter 1 for details).

The primary drivers that dictate beach morphodynamic type include: wave climate, tidal regime and sand grain size (Brown & McLachlan, 2002; Benedet *et al.*, 2004; Defeo & McLachlan, 2005; McLachlan & Dorvlo, 2005). The secondary drivers determine beach morphology within the beach morphodynamic type, and include: storms (Brown & McLachlan, 2002; Hill *et al.*, 2004; Costas *et al.*, 2005); local wind fields (Brown & McLachlan, 2002; Hesp, 2002; Gómez-Pujol *et al.*, 2007); astronomical phenomena (Mather & Vella, 2007; 2008; Smith *et al.*, 2007a; Smith *et al.*, 2007b;

Mather, 2008); sea-level rise (Brown & McLachlan, 2002); nature and source of the sediment (Jackson *et al.*, 2005); physiographic factors (Gómez-Pujol *et al.*, 2007); inlets or estuaries (Costas *et al.*, 2005); local bathymetry (Schoonees *et al.*, 2006; Anfuso *et al.*, 2007; Ruessink *et al.*, 2007); and water table height (Horn, 2002). In some cases, the effects of the secondary drivers can accumulate, leading to a shift in beach morphodynamic type directly, or influence the three primary drivers, thereby changing the beach morphodynamic type indirectly.

The beach morphology that emerges from shaping by these abiotic drivers can fit in anywhere along a continuum of states that ranges from macrotidal ultra-dissipative to microtidal reflective (McLachlan & Dorvlo, 2005; Short, 2006). Several indices have been developed to determine beach morphodynamic type, including: (1) Dean's parameter (Ω), which measures the ability of waves to move sand (Wright & Short, 1984); (2) the beach state index (BSI) which measures the ability of waves and tides to move sand (Defeo & McLachlan, 2005); (3) the beach index (BI), which includes measures of the intertidal area, swash climate and sand grain size (McLachlan & Dorvlo, 2005); and (4) the beach deposit index BDI, which measures the slope and sand properties of a beach (Soares, 2003).

$$(1)\ \Omega = \frac{H_b}{W_s \times T_w} \qquad \text{…Eqn. 2.1}$$

$$(2)\ BSI = \Omega \times TR \qquad \text{…Eqn. 2.2}$$

$$(3)\ BI = Log_{10}\left(\frac{M_z \times TR}{S}\right) \qquad \text{…Eqn. 2.3}$$

$$(4)\ BDI = \left(\frac{1}{S}\right) \times \left(\frac{a}{M_z}\right) \qquad \text{…Eqn. 2.4}$$

Where: H_b = wave height (m); W_s = sediment fall velocity (m.s^{-1}); T_w = wave period (s); M_z = grain size (mm; φ +1 for BI to avoid negative values); *TR* = tide range (m); *S* = average intertidal slope; *a* = 1.03125 mm median grain size of the sediment classification scheme. Each of the morphodynamic states has a very specific morphology and set of characteristics associated with it, purely based on the way in which the physical drivers interact. Table 2.1 below compares the characteristics of three broad beach morphodynamic types found on wave-dominated beaches (Wright & Short, 1984; Short, 1999).

Table 2.1. Comparisons between the physical characteristics of the three major beach morphodynamic types: dissipative, intermediate and reflective. (References cited on the next page).

	Dissipative	Intermediate	Reflective
Morphology	Gentle beach slopes [1,2,3] with multiple low relief bars [2,3]	Intermediate slopes and surf zone characterized by sand bars, channels and rip currents. [1,4] Can have reflective lower shores and dissipative upper shores. [1]	Steep beach profile with no bars. [2,3]
Sediment characteristics	Fine sand [2,3,5,6] (<200 μm)	Fine to medium sand [2-4] (200 μm-1000μm)	Coarse sand [2,3,5] (>1000 μm)
	Limited shoreline mobility but high backshore mobility [2,3]	Rhythmic shoreline features with highly variable shoreline position and moderate backshore mobility [2]	Relatively limited shoreline and backshore mobility. [2,3] Show greater profile mobility than other states when exposed to direct wave attack [2,7]
	Most erosional beach state[8]		Most accretional beach state [8]
			Limited sediment transport with bedload as the dominant mode [2,3]
Wave and tidal characteristics	High wave energy [1] although can also be low [9]	Moderate to heavy wave action [4], can also be low [9]	Can be low wave energy [9]
	Wave energy dissipated in the surf zone [1,6,8]		Waves break on the beach face [1,8] reflecting most of the wave energy back to sea [10, 7, 9]
	Wide surf zone [1]		No true surf zone [1]
	Spilling breakers [2,3]	Plunging to spilling breakers [2]	Plunging breakers [2,3]
	Large wave heights [2,3]	Medium wave heights [2]	Small wave heights [2,3]
	Tend to be macrotidal [9]	Range of tide types [4]	Tend to be microtidal [9]
Swash characteristics	Control of swash climate by the beach slope [5]	Control of the swash climate by beach slope and wave height [5]	Control of the swash climate by wave height [5]
	Swash period and upwash time is longer [5,8] due to interference between swashes that can lead to infragravity bores and thus less than one swash per wave [5]		Short swash period [8] with one swash per wave, each upwash complete before the next begins so no infragravity bores [5]
	Benign, non-turbulent swash climate [8]		Harsh, turbulent swash climate [1,8]
	Most swashes not above the effluent line [8]		Many swashes running above the effluent line [8]
Interstitial environment	Filter the lowest volume of sea water per unit area [5,6,10]	Filter 0.5-0.8 times more sea water than dissipative beaches per unit area [6]	Filter 100 times more sea water than dissipative beaches per unit area [6,10]
	Filtration driven by tides [5]		Filtration driven by waves [6]
	Filter the most particulate organic matter per unit area[11]		Filter the least particulate organic matter per unit area[11]
	Higher water table [5,6] thus high saturation on the beach face [3]		Lower water tables therefore lower saturation [10]
	Stagnant interstitial conditions, thus low oxygen tensions [6,10]		Dynamic interstitial conditions and high oxygen tensions [10]

From Table 2.1 above: 1 = Brown & McLachlan (2002); 2 = Benedet *et al.* (2004); 3 = Short (1999); 4 = McLachlan (1990); 5 = McArdle & McLachlan (1992); 6 = McLachlan (1989); 7 = Klein *et al.* (2003); 8 = Defeo & McLachlan (2005); 9 = McLachlan & Dorvlo (2005); 10 = McArdle & McLachlan (1991); 11 = Jones (2008).

Beach morphology in turn determines the biological community structure, zonation of the fauna and overall ecosystem functioning (Brown & McLachlan, 2002; Dahl, 1952; McLachlan & Brown, 2006). This is largely because intertidal macrofauna experience the beach through three dynamic variables: sediment composition and sand movement (de la Huz *et al.*, 2002; Defeo *et al.*, 1997; Dorgan *et al.*, 2006; Dugan *et al.*, 2004; McLachlan *et al.*, 1995; Nel *et al.*, 1999; Nel *et al.*, 2001); the swash climate (McArdle & McLachlan, 1991, 1992); and the exposure/moisture gradient (McLachlan, 1989), which all vary according to the morphodynamic state of the beach. Species richness patterns therefore relate to beach morphodynamic type, with dissipative beaches supporting far more species than reflective beaches (Defeo & McLachlan, 2005; Lercari & Defeo, 2006; McLachlan, 1996; McLachlan & Dorvlo, 2007; McLachlan *et al.*, 1995).

Biodiversity patterns among different beach morphodynamic types are more complex than previously thought. Firstly, there is evidence suggesting that there are biological interactions on dissipative beaches, both within and between species (Defeo *et al.*, 1997; Dugan *et al.*, 2004; McLachlan & Dorvlo, 2007; Schoeman & Richardson, 2002). These can influence community structure and patterns of biodiversity within beaches (Dugan *et al.*, 2004). Secondly, current thought is that sandy beach populations might function as metapopulations: dissipative beaches being biodiversity sources, and reflective beaches being sinks (Caddy & Defeo, 2003; Defeo & McLachlan, 2005), although it has been recognized that this requires further testing (McLachlan & Dorvlo, 2007). Physical dimensions are also important on sandy beaches. Evidence suggests that beaches longer (Deidun & Schembri, 2008; Rodil *et al.*, 2006) than 2 km (Brazeiro, 1999) and beaches that are wide (McLachlan & Dorvlo, 2007) might be able to maintain a greater diversity than a series of narrow pocket beaches. These complexities have implications for conservation plans, particularly under various scenarios of climate change and potential beach habitat loss through inundation and erosion (Roberts *et al.*, 2003).

As mentioned above, development of conservation plans requires baseline information, and there is currently very little published data on the KZN beaches. The aim of this chapter is therefore to determine the physical and ecological characteristics of sandy-beaches along the KZN coastline. Respectively, this will provide an understanding of the scope for natural resilience to erosion and inundation of beaches from climate change, and the spatial distribution of beach biodiversity. The objectives are, firstly, to characterize the hinterland in terms of: the extent to which the coastline is developed; location of development; extent of development; and the nature of the back beach. Secondly, the extent of the different beach morphodynamic types along the coast will be mapped; and beach macrofauna diversity will be determined. Various baseline statistics that will be useful for conservation planning will also be calculated.

Materials and methods

Data collection

Hinterland characterization of the KZN coastline

A combination of SPOT 5 satellite imagery and a continuous series of oblique photographs (both obtained from Ezemvelo KwaZulu-Natal Wildlife (EKZNW)) were used to map the physical features of the hinterland along the KZN coastline in ArcGIS 9.2 (ESRI). This included characterizing the back beach type; and determining patterns of development. The latter was performed by mapping the intensity of the development, ranging from pristine to intensive, and the location of the development, ranging from back beach to tertiary dune, or an equivalent "tertiary dune" area where dunes were absent. For both of these exercises, the mapped features were represented as polylines of the KZN coast, which were projected into Universal Transverse Mercator (UTM) using the WGS84 projection.

Table 2.2. The characteristics of the back beach and the coastal development that were used to define the hinterland classification scheme of: back beach type; location of development; and intensity of development.

Classification	Code	Description
Back beach type	Natural	Vegetation, grass, sand dunes
	Estuary/Harbour mouth	Estuarine, river or harbour port inlet
	Softer armouring	Including: geofabric sand bags; other sand bags; and dune reconstruction efforts
	Hard armouring	Including: wall; loffelstein; dolosse/rubble; harbour breakwaters; tourism amenities; road; and rock
Location of development	None	No development present
	Back beach	Immediately behind the backshore beach
	Lower foredune	Small patch of vegetation or dune between backshore beach and the development
	Low to mid foredune	Development located from half way up the foredune to the top of the foredune
	Mid to back foredune	Development located from the top of the foredune to the base of the second dune
	Secondary dune	Development located anywhere on the secondary dune
	Tertiary dune	Development located anywhere on the tertiary dune
	Beyond tertiary dune	Development in the picture is evident beyond the first three sand dunes
	Top of ridge	Development is located on the top of a bluff, cliff or other sharply rising topographic feature that is not a sand dune
Intensity of development	None	No development present
	Sparse	Very few buildings sporadically present
	Low	Much higher proportion of vegetation compared to development
	Medium	Patchy development with approximately equal proportions of natural vegetation and development
	High	Many buildings located very close to one another such that only very small patches of natural vegetation are present
	Intensive	Nothing left of the natural coastal environment – complete transformation of the area

Ecology of the KZN sandy beaches

Beach morphodynamic types

An incomplete polyline of the KZN coastline was obtained from EKZNW, where the beach morphodynamic types had been mapped based on field-based assessments (by Dr. Ronel Nel). The few, small sections of the polyline that were not mapped were filled in using a combination of local knowledge, satellite imagery and a point shapefile of beach transects collected by EKZNW[1]. This point shapefile had calculated beach morphodynamic types using equations 2.1 – 2.4, which were used to verify beach morphodynamic types in areas where local knowledge was limited. There were seven different categories used in the beach classification: dissipative beach; intermediate beach; reflective beach; dissipative estuary beach; intermediate estuary beach; reflective estuary beach; and rock.

S***andy beach macrofauna***

The beach macrofauna diversity was determined by performing transects at 13 sites along the KZN coastline, from Island Rock in the north, to Trafalgar in the south (Fig. 2.1). Sampling took place during spring tides so that the entire intertidal area was accounted for. Raw data from the northern ten sites were obtained from Nel and Bezuidenhout (2008). The three southern sites were selected to get better coverage of the whole coast, and because none of the other ten beaches that were sampled represented the intermediate to reflective range of beaches. These were sampled using the same methods as these authors, so that biodiversity values could be accurately compared.

Across-shore transects were performed in triplicate with a 10 m interval between them (see Fig. 2.2 below, and Schlacher *et al*. (2008) for further details on this sampling design). Each transect was set up between the drift line (which was used as a proxy for the spring high water mark – SHWM) and the spring low water mark (SLWM – which is the lowest point that the tide recedes to, and is evident as a small ridge in the sand: the low tide trough). The total distance that this intertidal transect spanned was measured and divided up into ten equidistant levels. At each level, a total of 0.1 m^2 was sampled by taking four cylindrical cores of 0.025 m^2 each, to a depth of 0.3 m. The sand from the core was placed into a 1-mm mesh bag and sieved in the swash to remove all sand grains that were smaller than 1 mm.

[1] In 2006, EKZNW performed 307 across-shore transects along the KZN coast, with the key factors being measured including: profile data (*i.e*., height and distance data between specific points across the beach); relative density of ghost crabs; abundance of sanderlings and plovers; grain size; and data relating to the wave climate (*i.e*., wave height and period).

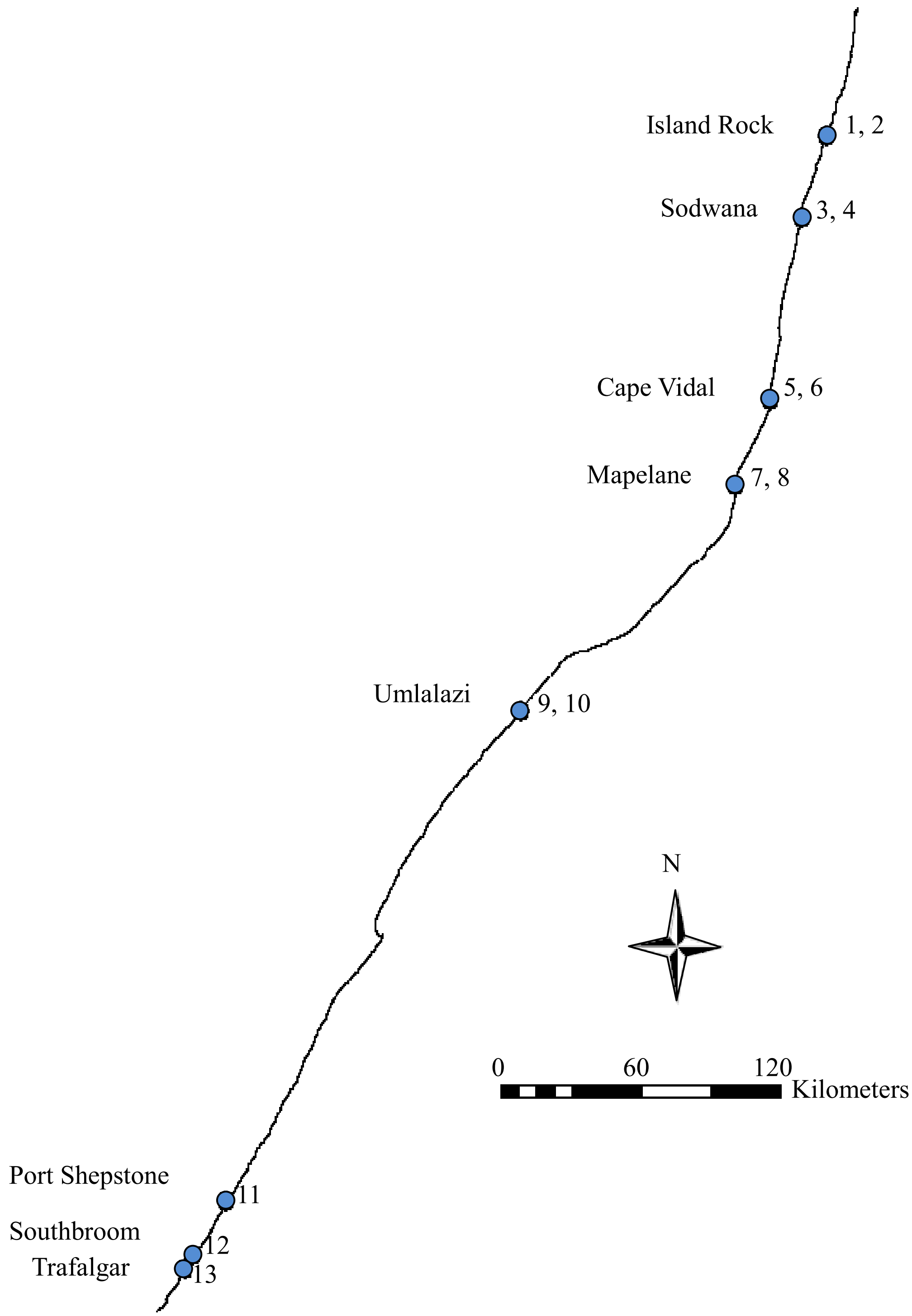

Figure 2.1. Location of the 13 sampling sites along the KZN coast: site name and number shown per location.

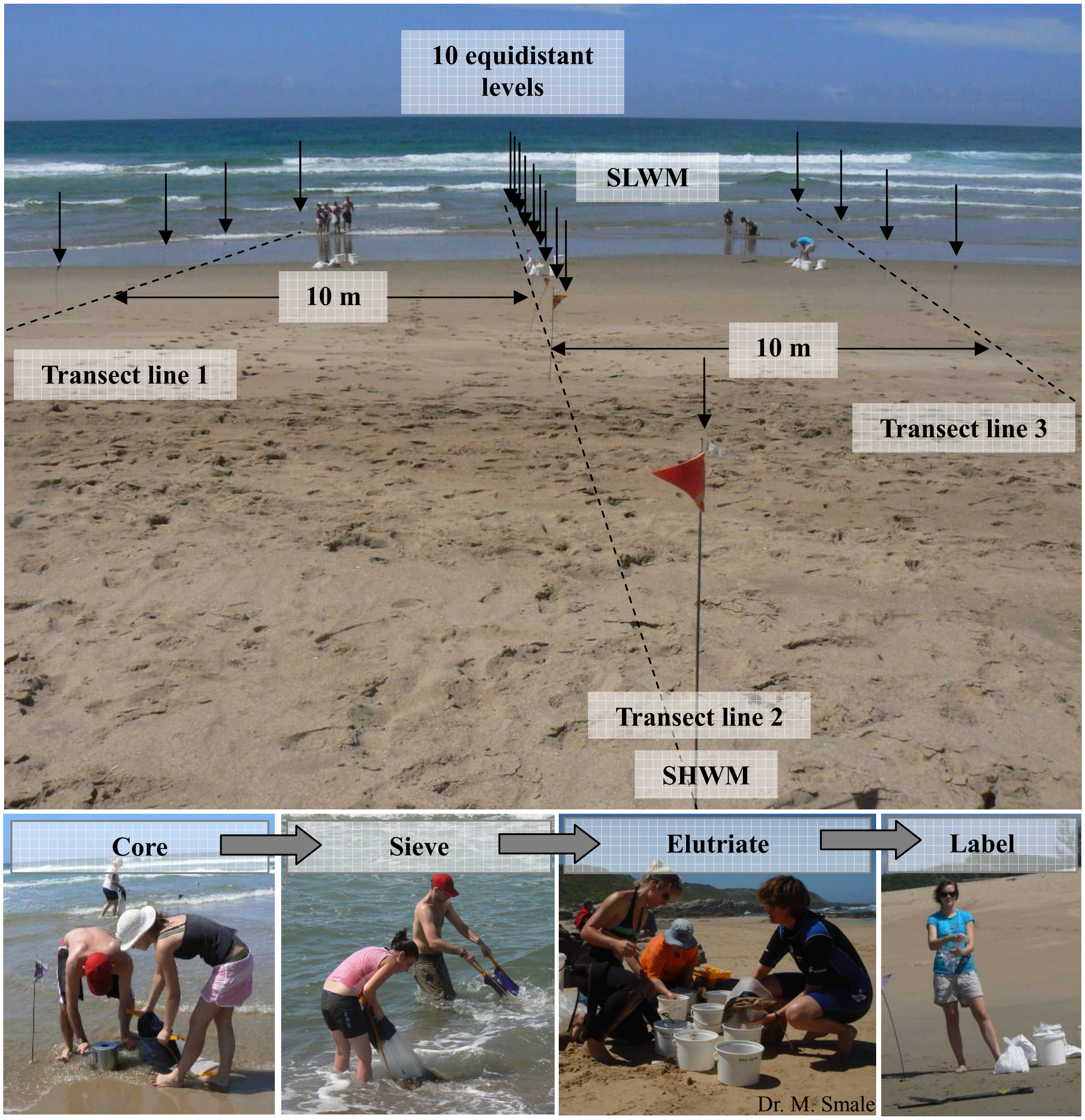

Figure 2.2. Photographs showing the macrofauna sampling-design and associated methods on the beach.

The macrofauna were elutriated out of the sand using the “stir and pour” method, which is based on the principle that macrofauna are less dense than sand. Each sand sample was emptied into a bucket of water and the mixture was stirred until all sediment was in suspension. The macrofauna remained in the water column and the sand settled rapidly. The stirred water was poured through a 1-mm mesh sieve to retain the organisms, while still allowing the water to pass through the sieve; and the process was repeated five times per sample. This number of repeats has been proven to be efficient when elutriating macrofauna (Govender, in prep.). The sieve was washed down with water to aggregate all the animals at the bottom of the net. These animals, and any retained sand, were placed into labeled jars and fixed with 4 – 5 % formalin. In the laboratory, each sample was scanned under a dissecting microscope to pick out all the macrofauna. These animals were identified to the lowest taxonomic level (if not species, then morphospecies), counted and preserved in 80 % ethanol.

The dry mass of the macrofauna was determined by oven-drying approximately half of the animals of each taxon at 60 ° C for 24 h. The samples were weighed on a four-decimal-place balance and an average value per taxon was determined. These were multiplied by the abundance data to give a total value of dry mass per taxon per beach. Note that separate values were determined for adults and juveniles; and exceptionally large specimens were weighed individually so that they did not skew the average weight per taxon. For the very small macrofauna (*e.g.,* the marine Collembolan, *Anurida maritima*), several animals were pooled into one sample, and the dry mass was divided by the number of individuals.

While sampling on the beach, several physical features of the beach were measured, including: wave height; wave period; intertidal beach width; elevation; and beach profiles. Sand samples were also taken from the beaches from the high-, mid- and low-shore. These were oven-dried at 60 ° C for 24 h. Sand fractions were determined by passing the sand through a series of sieves with sequential mesh sizes of: 2 000 µm; 1 000 µm; 500 µm; 250 µm; 125 µm; 53 µm, and a collecting tray for sediment that was finer than 53 µm. These different fractions were weighed on a three-decimal-place balance, and average grain size per beach was determined. The sorting and skewness statistics were calculated using GRADISTAT (Blott & Pye, 2001). All these data were collated into a table of the respective beaches' physical characteristics. These values were used to determine beach morphodynamic type by calculating: Dean's parameter (Ω, Eqn. 2.1); the beach state index (BSI, Eqn. 2.2); the beach index (BI, Eqn. 2.3); and the beach deposit index (BDI, Eqn. 2.4).

Data analysis

Hinterland and beach morphodynamic type characterization of the KZN coastline

The summary statistics tool in ArcGIS 9.2 (ESRI) was used to interrogate the attribute tables of the four respective polylines of the KZN coast: back beach type; extent of development; location of development; and beach morphodynamic type. In this analysis, the summed distance along the coastline that each unique value comprised was determined. These values were represented as proportions in MS Excel to get a preliminary assessment of the state of the coastline. Maps of the four polylines were created to determine spatial patterns of distribution of the respective factors per polyline.

The beach morphodynamic type, beach width[2], back beach type, extent of development, location of development and latitude were all correlated in SPSS 15 using the Spearman's rank correlation to determine relationships between all pair-wise combinations of these variables. This was based on 305 randomly created points along the coast. If one beach morphodynamic type showed a tendency to be highly developed, it would highlight the need for currently undeveloped sites of this beach morphodynamic type to be conserved. If there were patterns between any of the development scenarios and latitude, this could highlight areas where specific conservation efforts need to be concentrated. Beach width was also included to determine if the highly developed beaches were narrower than the other beaches, as a result of coastal squeeze.

Ecology of the KZN sandy beaches

Raw data from sampling in Nel and Bezuidenhout (2008) were combined with the data from the sampling in this study, and compiled into a single table of beach biodiversity. Abundance per running meter (m^{-1}) was calculated by the following equation, and added to the table:

$$Abundance\ per\ running\ m = \frac{\#\ individuals}{total\ area\ sampled}\ x\ beach\ width \qquad \text{…Eqn. 2.5}$$

This calculation was repeated for dry mass, and dry mass per running meter values were also added to the table.

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[2] In this case, beach width refers to the intertidal and backshore beach widths combined.

The macrofauna abundance data and related physical beach data were entered into the multivariate statistical package, Primer 6. The Shannon-Weiner index was used to calculate biodiversity at the 13 different sites, and included in the biodiversity table mentioned above. A Bray-Curtis resemblance matrix was constructed to represent similarities among the 13 beach sites, based on macrofauna biodiversity data. Multidimensional scaling (MDS) plots were created from this resemblance matrix and overlaid with site similarity clusters to visually represent the statistical groupings of the beaches. A BEST BIOENV test was performed to determine the physical characteristics that were most responsible for the patterns of macrofauna diversity among the different beaches. The result of this test was used as the factor by which the MDS was plotted.

A scatter-plot graph was created to determine whether or not the KZN beach communities conform to the swash exclusion hypothesis (McLachlan *et al.*, 1993), and thus determine if beach morphodynamic type can be used as a proxy for macrofauna diversity. The data used in this graph were the data from this dissertation, compared with data from McLachlan and Dorvlo (2005). All beaches that had a similar tide range to the KZN beaches were selected from this recent publication. Physical data from the beaches (McLachlan & Dorvlo, 2005) were used to calculate the Dean's parameter (Eqn. 2.1). These beach morphodynamic type data were plotted against the corresponding species richness data, for both the KZN and other beaches.

Results

Hinterland characterization

Location and intensity of development

More than half of the coastline is undeveloped (56.27 %), but a significant proportion of the coastal foredune has been developed to some extent, ranging from sparsely (7.49 %) to intensively (1.82 %) (Figs. 2.3 and 2.4). Most of the coastal development ranges from low (15.78 %) to medium (11.45 %) intensity, with smaller proportions of sparse (7.49 %), high and intensive development (9 % summed). Almost 80 % of all coastal development has its seaward boundary on the primary dune, which translates into a third of the primary dune extent along the KZN coastline being developed.

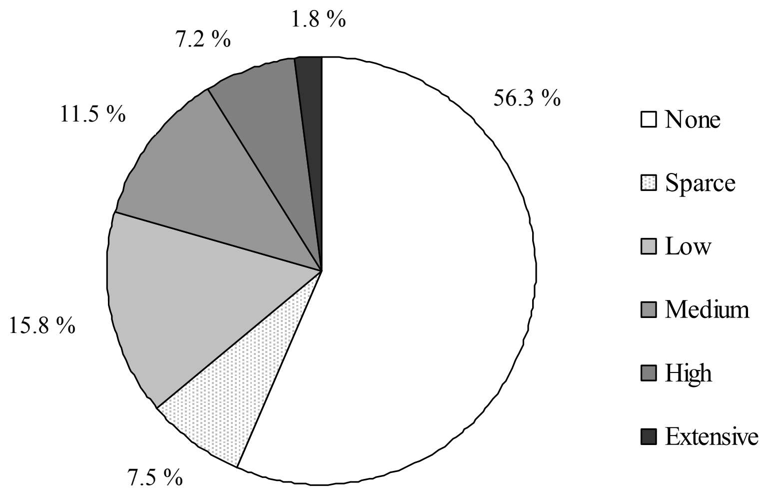

Figure 2.3. The intensity of development along the KZN coastline.

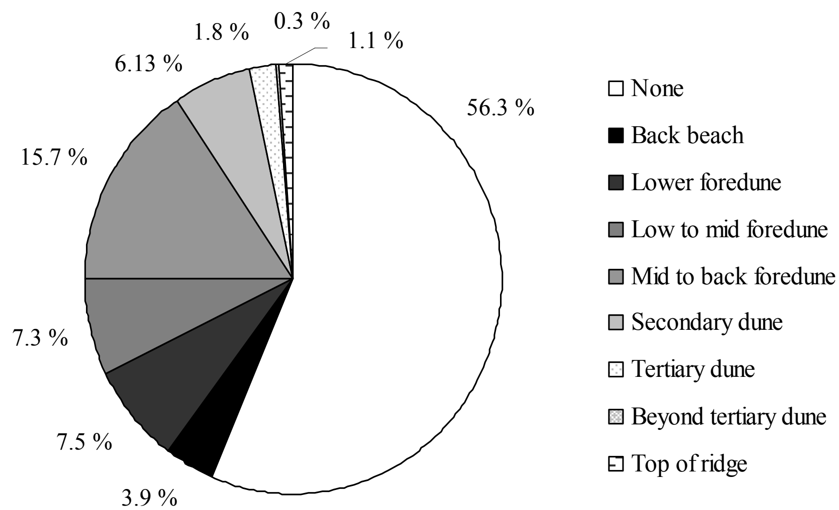

Figure 2.4. The location of development along the KZN coastline.

Back beach types

The majority of the KZN coastline is immediately unconstrained (91.31%), meaning that most of the coastline has natural vegetation or sand dunes immediately behind the beach. By combining the results in this figure (Fig. 2.5) with the two figures above (Figs. 2.3 and 2.4), it is clear that this band of natural vegetation does not necessarily extend too far landwards because 43 % of the coast is developed to some degree. Most of the armouring of beaches is currently hard armouring (3.45%), which is least favourable from a beach conservation perspective. Softer armouring comprises a small fraction of the coastline (1.55 %), and estuaries and harbour mouths make up the final 3.69 %.

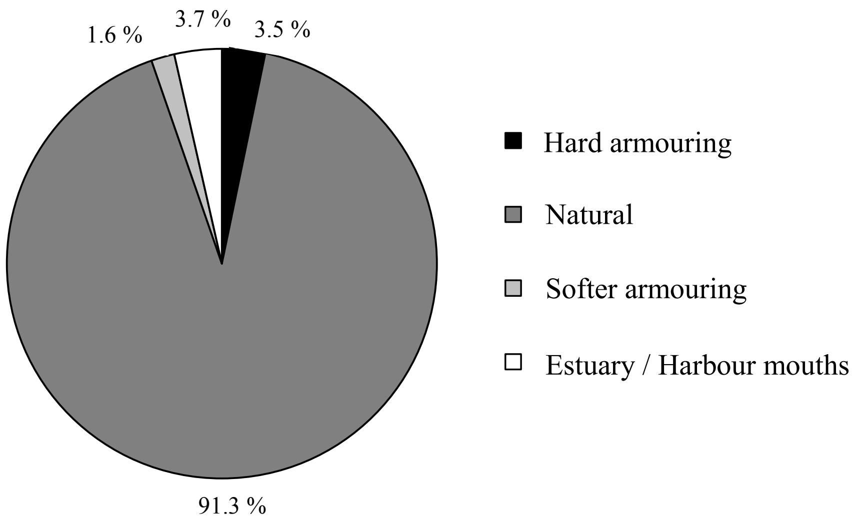

Figure 2.5. The proportions of the different back beach types along the KZN coastline.

Beach morphodynamic types

The KZN sandy beaches are dominated by intermediate beaches (44.39 %) and rock (33.05 %; Fig. 2.6). Approximately equal proportions of dissipative (10.80 %) and reflective (9.12 %) beaches exist. Estuarine beaches make up 2.65 % of the coastline, comprising mostly intermediate beaches (2.09 %), with very small contributions from dissipative (0.21 %) and reflective (0.34 %) beaches.

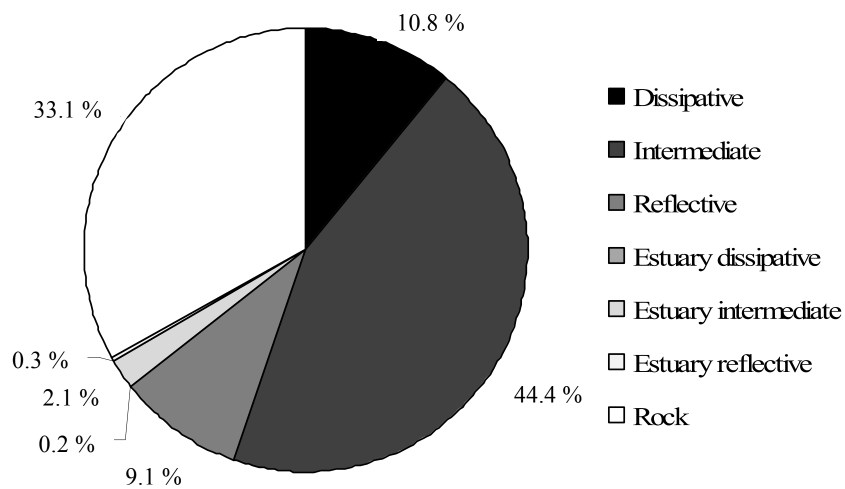

Figure 2.6. The proportions of the different beach morphodynamic types along the KZN coastline.

Spatial patterns in coastal development and beach morphodynamic types

There is a pattern in the physical beach characteristics that it is evident and supported statistically, because all four physical factors (beach morphodynamic type, location and intensity of development and back beach type) were correlated with latitude (Table 2.3). Based on these patterns, the coastline can be divided into three regions (Fig. 2.7):

1. Northern region: from north of approximately Richard's Bay to the KZN northern border
2. Central region: from Richard's Bay to the Durban harbour
3. Southern region: south from the Durban harbour to the KZN southern border

This is particularly clear in terms of development (Figs. 2.8b-d). The northern region is largely undeveloped and is nearly all pristine beaches. The central region has several highly to intensively developed areas (*e.g.*, Ballito, Umdloti, Umhlanga Rocks, Durban), interspersed with either natural coastal land or low-development areas. The southern region has a consistent, lower-intensity development of the foredune across the whole region, with a few, small high-intensity development hotspots. Figure 2.8d shows no armouring in the north, and hotspots of hard and softer armouring associated with the highly developed areas the central region. The southern region has much more armouring along the coast, and the least natural back beach of the three regions.

Figure 2.7. Photographs of a typical (a) northern, (b) developed central, (c) undeveloped central, and (d) southern region beach scene. All photographs by Roddy Ward (2007 – 2008).

The morphodynamic states (Fig. 2.8a) show a less obvious pattern than the development layers (Figs. 2.8b-d). What is evident is the majority of the dissipative beaches in KZN are in the northern region and the central region is dominated by intermediate beaches. The southern region comprises much shorter beaches of all types, mainly reflective, and is far rockier than the other regions. There are also many more estuarine beaches in this region.

The correlations between each of the development factors and latitude, beach morphodynamic type[3] and beach width[4] show interesting results. As described above, all development factors were significantly correlated with latitude ($n = 305$; $p < 0.001$ in all cases). Beach morphodynamic type showed a similar relationship. This means that, from north to south: the location of development gets closer to the beach; the extent of development increases; the nature of the back beach becomes more armoured; and beach morphodynamic types become more reflective. Beach width was not significantly correlated with any of these factors. There is a non-significant relationship between beach width and back beach type ($n = 305$; $p = 0.062$): it is predicted that this will become significant as sea levels rise and beaches become narrower. All three development factors are significantly correlated, suggesting that as development is closer to the back of the beach, it becomes more intensive, and beaches are armoured to protect the development. The location of development is negatively correlated with beach morphodynamic type, meaning that development is closer to the beach as conditions become more reflective.

Table 2.3. Results from Spearman's rank correlations between development types (back beach = back beach type, Ext. Dvpt = extent of development, and Loc. Dvpt = location of development), beach characteristics (beach morphodynamic type (Morph. Type), and beach width) and latitude (n = 307 in all cases). Significant correlations are highlighted in bold, n = 305 in all cases.

		Morph. Type	**Beach Width**	**Back Beach**	**Ext. Dvpt**	**Loc. Dvpt**
Beach Width	r =	-0.043				
	p =	0.458				
Back Beach	r =	0.098	0.107			
	p =	0.088	0.062			
Ext. Dvpt	r =	-0.068	-0.400	-0.479		
	p =	0.236	0.483	**<0.001**		
Loc. Dvpt	r =	-0.128	-0.032	-0.559	0.778	
	p =	**0.025**	0.576	**<0.001**	**<0.001**	
Latitude	r =	0.147	0.030	0.503	-0.665	-0.622
	p =	**0.010**	0.595	**<0.001**	**<0.001**	**<0.001**

[3] Dean's parameter was used to represent beach morphodynamic type in the correlation analyses.
[4] Note: in this case, beach width is the combined intertidal and backshore beach width.

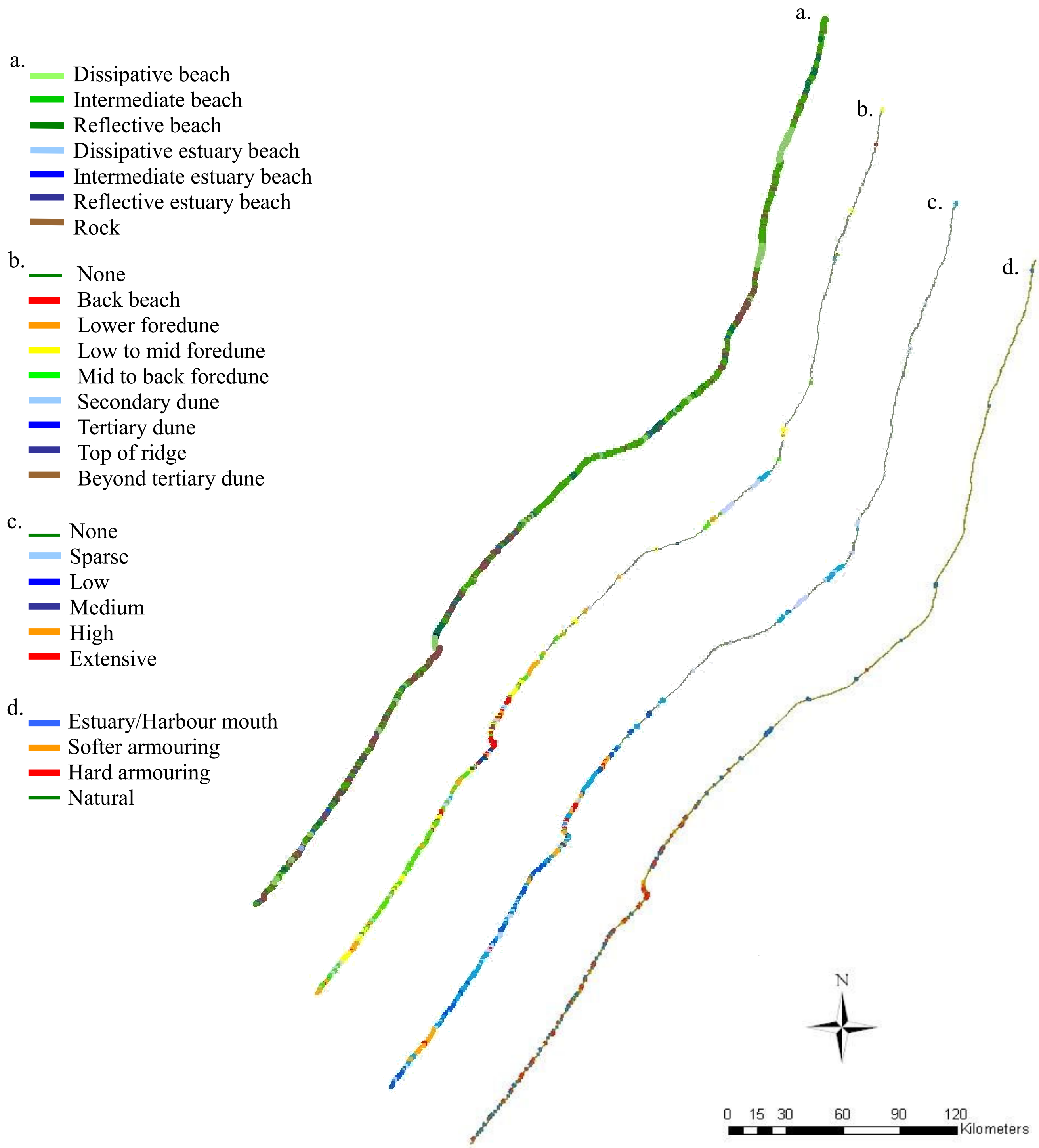

Figure 2.8. The physical nature of the KZN coastline, mapped according to: (a) morphodynamic state; (b) location of development; (c) extent of development; and (d) back beach type.

Macrofauna communities of the KZN sandy beaches

Physical characteristics of the beaches

The physical parameters that were recorded at the 13 sampled sites showed largely similar conditions (Table 2.4), and did not cover a significant range of morphodynamic states (see Nel & Bezuidenhout, 2008). Most of the beaches had medium sized (250 – 500 µm), well sorted, sediment and similar wave climates (H_b ~ 1.5 m, T_w ~ 12 s). Sites 3 and 4 (Sodwana) had the finest sand (264 – 270 µm), largest wave heights (3.3 - 4.0 m), longest wave periods (36 – 45 s), and flattest slopes (*1/S* = 31), with Site 3 representing one of the most dissipative of the intermediate beaches. Site 11 stood out as an ultra-reflective beach, with very coarse (> 1 mm), poorly sorted sand and the steepest slope (*1/S* = 12). Sites 1, 2, 6, 12 and 13 are intermediate beaches, and the rest of the sites are reflective beaches. Many of these physical characteristics are extremely dynamic in the short-term, particularly those that relate to the wave climate, and should be compared with caution.

Macrofauna biodiversity

From Table 2.5, Site 6 had the greatest species richness (16 species), with Sites 4, 7 and 13 having the second highest (15 species). The highest overall diversity (richness and evenness taken into account) was found at Sites 3-6 (*H'* = 2.0-2.3). Sites 9-13 had the greatest abundances per running meter, but not necessarily the most biomass. The largest biomass per running meter was at Site 12, with 2 large *Emerita austroafricana* individuals contributing to most of the biomass on this beach. *Scolelepis squamata* and *Excirolana natalensis* were most commonly found, being present at all but one of the sites. Twenty seven of the 58 species (47 %) recorded were only found at a single site (singletons). Of these singletons, eight were from the northern six sites (Delagoa bioregion[5]) and 18 from the southern seven sites (Natal bioregion). There were 12 species that were found only in the Delagoa bioregion, and 28 species that were found only in the Natal bioregion.

[5] See study site section for further information on the biogeographic break and bioregions.

Table 2.4. Physical characteristics of the thirteen beaches, arranged from north to south (after Nel and Bezuidenhout, 2008). Dotted line indicates biogeographic break: Delagoa bioregion = Sites 1-6; Natal bioregion = Sites 7-13.

	Isl. Rock (1)	Isl. Rock (2)	Sodw. (3)	Sodw. (4)	C. Vidal (5)	C. Vidal (6)	Mapel. (7)	Mapel. (8)	Umlalazi (9)	Umlalazi (10)	P.Shep. (11)	S'broom (12)	Trafalgar (13)
Date	29/01/06	29/01/06	30/01/06	30/01/06	31/01/06	31/01/06	01/02/06	01/02/06	02/02/06	02/02/06	08/03/08	09/03/08	24/03/08
Width (m)	48.0	52.0	72.0	79.0	43.0	89.0	32.0	79.0	62.0	63.0	55.0	63.0	75.0
Elevation (m)	2.5	3.8	2.3	2.6	2.0	2.1	2.3	2.9	2.4	2.1	4.5	2.6	2.4
1/Slope	19.0	14.0	31.0	31.0	22.0	43.0	14.0	28.0	26.0	30.0	12.0	24.0	31.0
H_b (m)	1.5	1.1	4.3	3.3	1.2	4.0	1.7	1.3	0.8	1.2	1.5	1.6	1.3
T_w (min)	5.3	4.3	1.7	1.3	4.7	1.7	5.0	5.0	2.7	4.7	4.0	5.7	5.0
T_w (s)	11.3	13.9	36.0	45.0	12.9	35.3	12.0	12.0	22.5	12.9	15.0	10.6	12.0
M.Grain (µm)	295.0	326.0	264.0	270.0	403.0	340.0	638.0	502.0	458.0	472.0	1037.0	301.0	279.0
M.Grain (φ)	1.8	1.6	1.9	1.9	1.3	1.6	0.6	1.0	1.1	1.1	-0.1	1.7	1.8
GS Category	MF	MF	MF	MF	MC	MF	C	C	MC	MC	VC	MF	MF
Sorting	WS	WS	WS	WS	WS	WS	WS	MS	WS	WS	PS	MS	WS
Skewness	NS	NS	NS	NS	FS	NS	NS	NS	NS	NS	FS	NS	NS
Tide (m)	1.8	1.8	2.0	2.0	2.1	2.1	1.9	1.9	2.0	2.0	2.0	2.0	2.0
W_s ($cm.s^{-1}$)	3.8	4.3	3.3	3.4	5.6	4.5	9.3	7.2	6.5	6.7	15.0	3.9	3.5
RTR	1.2	1.6	0.5	0.6	1.8	0.5	1.2	1.5	2.4	1.7	1.4	1.2	1.5
DFV (Ω)	3.4	1.8	3.7	2.2	1.6	2.5	1.5	1.5	0.6	1.3	0.8	4.0	3.2
Beach State	Inter	Refl	Inter	Inter	Refl	Inter	Refl	Refl	Refl	Refl	Refl	Inter	Inter
BSI	6.0	3.2	7.3	4.3	3.3	5.2	2.9	2.9	1.2	2.6	1.6	8.0	6.4
BDI	66.4	44.3	121.1	118.4	56.3	130.4	22.6	57.5	58.5	65.5	11.9	82.2	114.6
BI	2.0	1.8	2.3	2.2	2.0	2.4	1.6	2.0	2.0	2.1	1.4	2.1	2.2

Width = Beach Width; *Elevation* = Beach Elevation; H_b = Breaker Height; T_w = wave period; T_s = swash period; *M.Grain* = Mean Grain Size; *GS Category* = Grain Size Category; W_s = Sediment Fall Velocity; *RTR* = Relative Tide Index; *DFV* = Dimensionless Fall Velocity (Dean's parameter); *BSI* = Beach State Index; *BDI* = Beach Deposit Index; *BI* = Beach Index; *MF* = Medium-Fine; *MC* = Medium Coarse; *C* = Coarse; *VC* = Very Coarse; *WS* = Well Sorted; *MS* = Medium Sorted; *PS* = Poorly Sorted; *NS* = Normally Skewed; *FS* = Fine Skewed; *Inter* = Intermediate; *Refl* = Reflective.

Table 2.5. The biological features and macrofaunal composition of the beaches (after Nel & Bezuidenhout, 2008). Dotted line indicates biogeographic break: Delagoa bioregion = Sites 1-6; Natal bioregion = Sites 7-13.

	Beach Site Number												
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**
# Species	11	7	14	15	14	16	15	11	12	12	13	13	15
Abundance (#.m^{-1})	709.3	265.8	376.0	693.4	248.4	791.1	184.9	210.7	2149.3	1841.0	9893.9	1372.0	1875.0
Biomass (g.m^{-1})	3.2	0.6	1.1	10.2	21.8	2.3	0.4	0.6	17.2	3.9	3.8	81.3	18.6
Singletons	1	1	0	2	2	2	5	3	0	0	6	3	2
H'	1.4	1.5	2.1	2.2	2.3	2.0	1.9	2.1	1.1	0.9	0.9	1.9	1.9
Amphipod sp. F						1							
Amphipod sp. Z							1						
Anurida maritime											15		
Bullia mosambicensis						1			1				1
Bullia natalensis						1							
Caprellidea							1						
Carabidae larva												1	
Cavolina sp.											1		40
Chilopoda											4		
Crab megalope / juvenile								1					
Dermestidae											1		
Donax madagascariensis			1	1									
Donax spat			4	2		4						8	
Dorvillea sp.											191	51	3
Emerita austroafricana	5		5	4	6				222	203		4	19
Eurydice kensleyi		4	7	8	2	4							
Eurydice longicornis	2	4	1	19	6	5			8	4			2
Eurydice sp. C	8	1	1		5		10	3	2	2			
Eurydice sp. D	3								2				
Eurydice sp. E						1				1			
Excirolana natalensis	59	14	16	12	15	7	23	7	11	7		23	26
Exosphaeroma hylecoetes						1							2
Flabellifera		1											
Gastrosaccus bispinosa	48	20	1	14	1	3		2	45	36			
Gastrosaccus longifissura						1			1	4			
Gastrosaccus sp. A	1												
Glycera natalensis					2								

Table 2.5. continued.

	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**
Glycera papillosa					1	1							
Glycera sp. 1												3	1
Glycera sp. 2											1	4	
Glycera sp. A			1	1			1						
Glycinde sp.				3									
Goniadopsis sp. A	2	2	1	4	4	2	3	2	4	3			
Goniadopsis sp. B							1			1			
Lumbrineris coccinea											90		
Lumbrineris tetraura							2	1					
Mollusc larvae												1	
Ocypode juvenile			1				1	1					
Oligochaete sp. 1													1
Oligochaete sp. 2													2
Pisione africana											62	14	2
Pisionidens indica	1		1		1		2	1	2	1	1200	15	10
Polychaete sp. A							1						
Polychaete sp. F				1	2		1						
Polychaete sp. R								1					
Polychaete sp. S				1									
Polychaete sp. Y							1						
Pontogeloides latipes									6	3			3
Sciaridae											1	6	
Scolelepis squamata	4		6	7	5	35	3	7	6	2	1	3	63
Staphylinidae											23		
Symphyla											1		
Unidentified crustacean												1	
Urothoe grimaldi			1	1	1	12		1					1
Urothoe sp.				1		1							
Worm sp. A					1								
Worm sp. B								1					
Worm sp. C							1						

Macrofauna community characterization

Multi-dimensional scaling of beach site similarity shows four groups that are best explained by their beach morphodynamic types (Fig. 2.9), as calculated by Dean's parameter (Eqn. 2.1). Group 1 is Site 11, which is a reflective beach, but at the ultra-reflective end of the morphodynamic state continuum. Group 2 comprises Sites 9 and 10: these are two reflective beaches. Groups 3 and 4 are the intermediate beaches. None of the beaches that were sampled were truly dissipative, but Group 3 (Sites 1, 6, 12 and 13) were the closest, being in the "dissipative-intermediate" category. Group 4 represents the remaining sites that are reflective-intermediate/intermediate. The beaches are not clearly split by bioregion, which suggests that at a small scale, sandy beach communities in KZN are driven more by beach morphodynamic type than by biogeographic patterns.

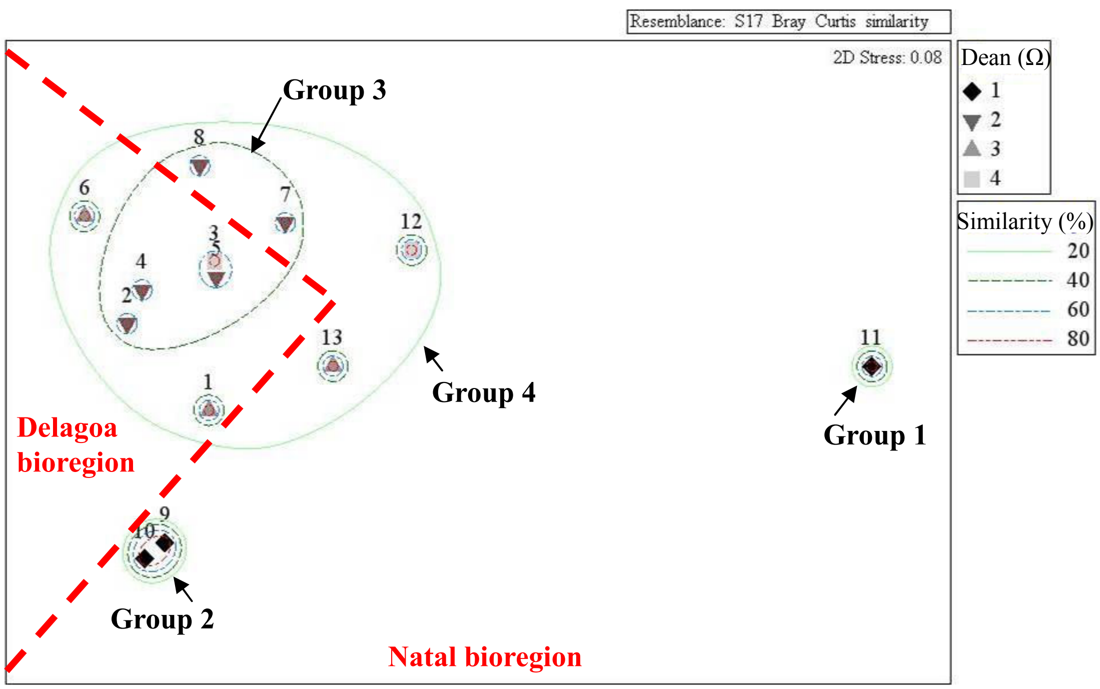

Figure 2.9. MDS of the thirteen beach sites based on a Bray-Curtis resemblance matrix, represented by one of the most significant factors (Dean's parameter, Ω), and overlaid with a cluster diagram of site similarity (%). Red dashed lines indicate the biogeographic break between the sites in the Delagoa bioregion and the Natal bioregion.

The paradigm in sandy beach ecology that species richness increases from reflective to dissipative beaches (McLachlan *et al.*, 1995; McLachlan *et al.*, 1996; Defeo & McLachlan, 2005; Lercari & Defeo, 2006; McLachlan & Dorvlo, 2007) does not show a particularly strong relationship in the figure (Fig. 2.10) below, and there is a lot of scatter, particularly around the reflective to intermediate beaches. The KZN beach sites used in this dissertation sit perfectly within the range of data from other sandy beach sites in the world with the same tidal range (from McLachlan & Dorvlo, 2005). Although the KZN sites cluster comparatively close to the global (blue) trend-line, the relationship between Dean's parameter and species richness (red trend-line) is very weak (r^2 = 0.038). However, the sites used in this dissertation span a very narrow section of the full beach morphodynamic type continuum, and it is not appropriate to scale up to true dissipative beach biodiversity based on the limited KZN samples. Furthermore, Dean's parameter (Eqn. 2.1) may not be the most accurate estimate of beach morphodynamic type given the snap-shot estimates of wave height (H_b) and wave period (T_w), which are extremely variable parameters. Given the position of the KZN data points within the cloud of data points of the global beaches, it can be assumed that the swash exclusion hypothesis (McLachlan *et al.*, 1993) holds true for the KZN beaches.

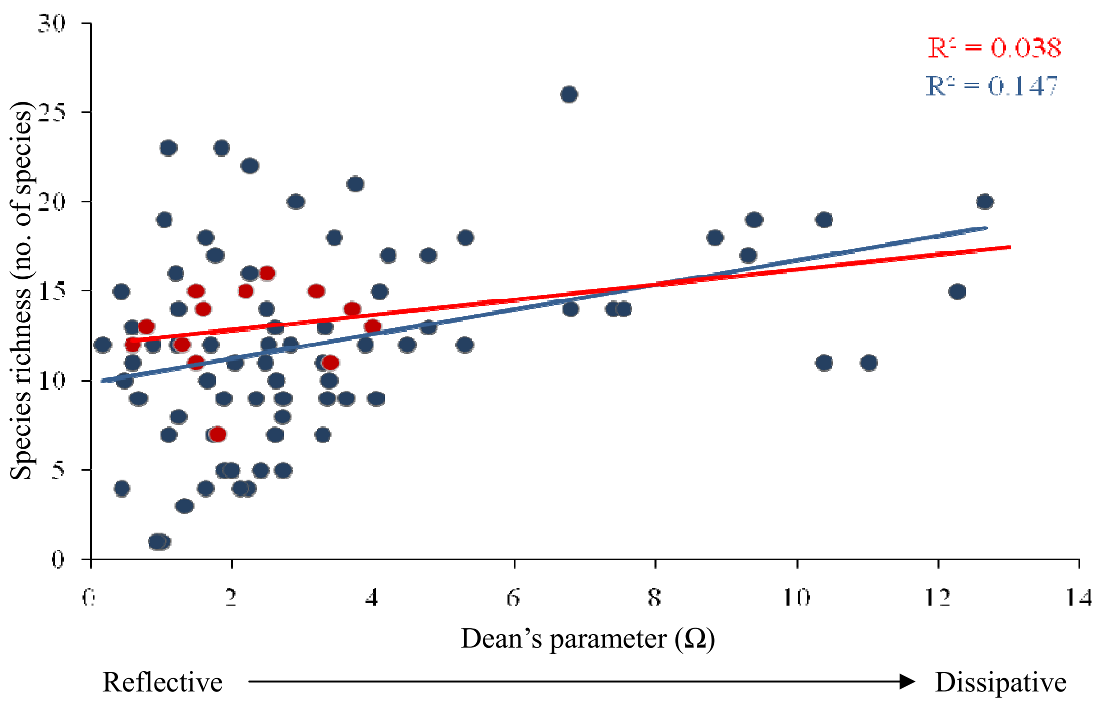

Figure 2.10. The relationship between species richness and beach morphodynamic type as measured by Dean's parameter (Ω) for the KZN beaches (data points in red, n = 13) and for other sandy beaches in the world (McLachlan & Dorvlo, 2005) with a similar tide range to KZN (data points in blue, n = 76). Blue trend-line based on blue, global data points given in black, with r^2 = 0.147; red trend-line based on the red, KZN data points (r^2 = 0.038).

Discussion

Hinterland and coastal development

The KZN coastline is split broadly into ~ 56 % undeveloped, of which almost half comprises the St Lucia and the Maputaland Marine Reserves in the north region, ~ 33 % developed on the primary dune, and ~ 10 % developed beyond the primary dune. The majority of the coastal development in KZN is in the southern region, and is mainly built around the railway line that runs mid-way up the primary foredune for most of the length of the coastline in this region. The highly to intensively developed areas, however, are mainly in the central region where the major urban nodes, *e.g.*, Durban, Umhlanga Rocks, Umdloti and Ballito, are located. Development intensity is varied, with about half the developed areas falling in the sparse to low categories, and the other half split nearly equally between medium, and high to intensive categories. Perhaps the most important point to make here is that, as development is built closer to the beach, it becomes more intensive, and subsequently, beaches become armoured – usually with hard defences – to protect the high-value infrastructure. From both an ecological and economic point of view, this provides a strong case for not developing too close to sandy beaches: ecologically, because it promotes erosion and coastal squeeze (Jolicoeur & O'Carroll, 2007; Schlacher *et al.*, 2007; Schleupner, 2008) and economically because of the financial implications of holding back the sea and repairing damages to defences after high-impact events like storms (Smith *et al.*, 2007b).

In spite of the spatial heterogeneity in coastal development along the KZN coastline described above, broad patterns can be identified. The northern region is largely undeveloped, comprising near-pristine beaches for most of the length of the region, with almost all of the province's dissipative beaches found here. The majority of the coastline in the north is protected by the St Lucia and Maputaland Marine Reserves. The intact, natural sand dunes in this region and lack of constraining development are suggestive of the fact that these beaches have a high adaptive capacity and inherent resilience to possible implications for sea-level rise, which is explored in later chapters of this dissertation.

The southern and central regions are potentially far more ecologically compromised in the face of climate change compared to the north. This is because of the higher prevalence of coastal infrastructure closer to the beach in these two regions, which confers greater threats of coastal squeeze in response to sea-level rise. The central region has nodes of intensively developed coastal urban areas, interspersed with undeveloped strips of coastline. The southern region is more uniformly developed at a medium intensity, with the seaward boundary of the development approximately half way up the primary foredune. In spite of the development in these regions, there are still some undeveloped areas, particularly in the central region. These could prove to be exceptionally valuable from a sandy beach conservation point of view, given that the only formally protected coastline in these two regions is in the Trafalgar-Mpenjati Marine Reserve. This reserve barely comprises 1 % of the KZN coastline.

Patterns in macrofauna communities, and ecological implications for the KZN sandy beaches

The diversity of sandy beach macrofauna compared favourably with other beaches of a similar tide range (McLachlan & Dorvlo, 2005), such that the paradigm of increasing species richness with increasing dissipative-like beach state (McLachlan *et al.*, 1995; McLachlan *et al.*, 1996; Defeo & McLachlan, 2005; Lercari & Defeo, 2006; McLachlan & Dorvlo, 2007) can be applied to the KZN beaches. By inference, the beaches in the northern region, the most dissipative in the province, could be argued as more important to conserve. This, not only from a macrofauna perspective, but also because these beaches are important turtle nesting grounds in KZN. It has been coincidental that these high conservation priority (based on macrofauna diversity) beaches are protected by the St Lucia and Maputaland Marine Reserves, which together form nearly 25 % of the KZN coastline. However, these beaches fall into a separate bioregion (the Delagoa) compared to the rest of the KZN beaches (Lombard *et al.*, 2004). Apart from a small marine reserve at Trafalgar/Mpenjati, there is no formal protection of the sandy beaches in the KZN southern and central regions. Considering that there are 28 species that are only found in this region, 18 of which only occurred at single sites, it is clear that there is a need for the proclamation of marine protected areas (MPAs) or reserves in this bioregion.

If the metapopulations hypothesis holds true that dissipative beaches function as source beaches and seed reflective beaches with fauna (Caddy & Defeo, 2003), then it could be argued that the northern region beaches might seed the more southern, reflective beaches thereby reducing the need for more MPAs to be proclaimed. This is not the case because the predominant direction of local currents and longshore drift in KZN is south to north (Schoonees, 2000), and by implication, the beaches in the northern region will have virtually no effect on the diversity of the beaches further south of them. This provides even more of a case for the need of MPAs in the central and southern regions. The metapopulations hypothesis is more applicable to these beaches in the south that are predominantly reflective and rocky pocket beaches, although there are still some longer intermediate beaches interspersed between them. The implications are that these more dissipative-like beaches are very important in maintaining the biodiversity on the reflective beaches, not only because of their morphodynamic state (McLachlan *et al.*, 1995; McLachlan *et al.*, 1996; Defeo & McLachlan, 2005; Lercari & Defeo, 2006; McLachlan & Dorvlo, 2007), but also because they are longer beaches (Brazeiro, 1999; Deidun & Schembri, 2008). Subsequently, these longer, intermediate beaches should receive high conservation priority status.

Admittedly, sandy beach biodiversity extends beyond macrofauna. While conservation of reflective beaches may not seem to be too much of a priority for macrofauna, it could be important for other groups, like meiofauna. These other groups may perform different ecosystem services compared to macrofauna, which are also important considerations for sandy beach conservation plans. For example, the higher proportion of estuarine beaches in the south region compared to the rest of the province could mean that these beaches have additional or alternative functions and fauna than the other regions. It was beyond the scope of this study to consider the faunal groups other than macrofauna for the KZN beaches, and this is highlighted as an avenue for possible future research in the province.

Conclusion

There is a need for sandy beach MPAs in the south and central regions, based on macrofauna diversity. This was also identified in the National Spatial Biodiversity Assessment (Lombard *et al.*, 2004), where they highlighted areas in these two regions for intertidal conservation priority, although this was based on rocky shore and seaweed communities. It is thus apparent that the intertidal habitats (both sandy beach and rocky shore) in the Natal bioregion are under-represented in formal protection areas, and this needs to be addressed.

Coastal management plans need to carefully consider the location of sandy beach MPAs. The implications of developing close to the beach, particularly if this development is in the littoral active zone, is that it prevents the dynamic movement of the coastline in response to erosion events, like storms, and in response to sea-level rise. The beach gradually becomes inundated, which is known as coastal squeeze, causing not only a loss in beach habitat, but in its associated biodiversity, ecosystem goods and ecosystem services. Thus the MPA sites need to have some scope for natural processes to occur if the beach is to be resilient, and to be able to respond to climate change with limited negative impacts on the beach and its faunal communities.

The hinterland analyses revealed that there is still a lot of undeveloped coast, and half of the areas that are developed, are only developed at a sparse to low intensity. By implication, there is some scope for proclaiming MPAs in relatively pristine areas, *i.e.*, where the beach is backed by natural vegetation and sand dunes, or areas that could possibly be rehabilitated to this state. While most of the undeveloped coast lies in the northern region, there are still some sites in the central and southern regions that would be suitable for MPA proclamation. However, options in the southern region are exceptionally limited, because nearly the entire region is developed within the littoral active zone. The central region has more options for MPA sites, because development in this region is predominantly high-intensity developed urban nodes with natural coastline in between. However, development in the coastal zone is ever-increasing. In the last 12 years there has be a 22 % land-use change, from natural vegetation to urban development, in the 100-m strip inland from the high water mark (Celliers, in prep.).

Given the need for MPA proclamation in the central and southern regions, the already limited options for MPA sites based on current development, and the high rate of coastal development that threatens to reduce MPA site options in the future, a coastal conservation management plan for KZN needs to be formulated and implemented as quickly as possible. Not only will this maximize conservation efforts, but it will minimize the financial costs of implementation. The proclamation of MPAs will form only a part of a greater coastal management plan that is required for the whole province. As the global sea level rises at an accelerated rate (Church & White, 2006, Rahmstorf, 2007; Rahmstorf et al., 2007), and storms threaten to increase in frequency and intensity as a result of climate change (IPCC, 2007), coastlines are at risk of the impacts associated with these phenomena. These have implications not only for sandy beach ecology, but for the coastal development and infrastructure immediately behind the beaches. It is therefore obvious that an integrated way forward to solve these problems, at a local scale, is needed.

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CHAPTER 3

THE PHYSICAL AND ECOLOGICAL IMPLICATIONS OF STORMS FOR SANDY BEACHES

Abstract

Climate change predictions for the coming century include an increase in storm intensity and frequency. The effect of storms on beaches is well studied. However, the majority of the research has concentrated on the physical impacts, with very few publications concerning storms and beach fauna and none (that the author is aware of) that consider the implications for coastal ecosystem goods and services. This study aims to begin filling this gap in the literature by examining the effect of a large storm on sandy beach macrofauna communities. Two sites at Sardinia Bay (Port Elizabeth, Eastern Cape) were sampled for beach macrofauna following standard sampling methods, and physical site characteristics were also recorded. Sampling took place approximately four months before the storm, and six weeks after the storm. The beach morphology and macrofauna community at Site 1 showed greater impacts following the storm than Site 2 did. These impacts were expressed mainly in terms of sand eroded and a decrease in macrofauna biomass per species (excluding species that were not present before the storm). This was largely attributed to the presence of a nearshore reef at Site 2, which buffered a lot of the wave energy during the storm, as well as the presence of sand dunes behind Site 2 that ameliorated the effects of erosion by replacing the eroded sand. Although there was some degree of rearrangement in the macrofauna communities at the two sites, neither community was completely removed. Storms thus represent a short-term infrequent disturbance for undeveloped sandy beaches, through which macrofauna can persist. Further research is required to determine the impact of storms on developed coasts, on other taxa and on ecosystem goods and services in order to complete the picture of the ecological effects of storms. This information is required for effective conservation management of beaches into the future.

Introduction

Sandy beaches are extremely dynamic environments. The animals that live in this habitat thus have to be well adapted to be able to survive the harsh conditions (McArdle & McLachlan, 1992; McLachlan *et al.*, 1995), particularly when large waves pound the sandy shores (Brown, 1996). These high-energy waves threaten to dislodge fauna from their burrowed localities, and wash them out to sea along with sand eroded from the beach face (Brown & McLachlan, 2002). This principle is encapsulated in the swash exclusion hypothesis, for example. The hypothesis suggests that the distribution of species on beaches of different morphodynamic types is because faunal groups are able to survive only in a certain swash climate (McLachlan *et al.*, 1993). However, what happens when the waves are significantly larger and more energetic than the average conditions individuals have to endure?

When considering the impact of large storms on sandy beaches, the majority of the literature concerns changes in beach profiles and effects on dunes and dune vegetation (*e.g.,* Leatherman, 1979; Bryant, 1988; Morton *et al.*, 1994; Leadon, 1999; Forbes *et al.*, 2004; Hill *et al.*, 2004; Aagaard *et al.*, 2005; Costas *et al.*, 2005; Anfuso *et al.*, 2007), with far fewer publications examining the impacts of storms on beach fauna (Crocker, 1968; Saloman & Naughton, 1977). From some studies we can infer the latter, *e.g.,* where summer-winter comparisons of beach fauna communities have been made (*e.g.,* Degraer *et al.*, 1999), because many beaches have a summer (calm weather) and a winter (stormy weather) state (*e.g.,* Basco *et al.*, 1997). On the whole, however, the ecological implications of storms are largely unknown.

All studies listed above that examined the physical impact of storms on beaches showed that there was a significant amount of erosion that took place. Dunes were found to be an important store of sand during these times (Leatherman, 1979; Morton *et al.*, 1994), and it was only on beaches with dunes that full profile recovery could take place (Morton *et al.*, 1994). Beaches were found to take several years to return to their pre-storm physical conditions (Leadon, 1999), with some beaches only partially recovering (Morton *et al.*, 1994; Hill *et al.*, 2004; Costas *et al.*, 2005). The few studies on intertidal beach fauna have shown that there was little impact on the communities, in spite of changes in habitat morphology (Crocker, 1968; Saloman & Naughton, 1977). This contrasts with impacts on intertidal sessile, nonscleratinian fauna on coral reefs, which were shown to have a lower diversity with storm activity (Walker *et al.*, 2008).

An opportunity to gain insight into the ecological impacts of storm-induced erosion presented itself in the Eastern Cape. A big-wave pulse resulting from a large storm at sea pounded into the South African south coast on 1 September 2008. Even the most sheltered bays in Port Elizabeth had very large waves that significantly eroded the beaches and caused structural damage to tourist amenities. In some areas, waves were breaking over roads located behind beaches, to the point that the national highway linking Cape Town, Port Elizabeth and Durban (the N2) was temporarily closed. Four to five months prior to this event, two sites at Sardinia Bay had been sampled for macrofauna. This provided background data that could be compared with the state of the beach macrofauna community shortly after the storm.

If beaches are to be managed for resilience in a world of climate change, understanding the impacts that storms have on beach-fauna communities is important. This is because climate change predictions include an increase in the intensity and frequency of large storms (*e.g.,* IPCC, 2007), and successful management strategies can only be formulated from empirical knowledge. The aim of this chapter is therefore to investigate the impact of a large-scale erosion event on sandy beach macrofauna communities. The objectives are: to determine the changes in biomass, abundance, species richness and species distribution, by comparing the before- and after-storm data; and to determine if there are physical drivers of any patterns identified.

Materials and methods

Study site

Two sites, Site 1 (34° 02.089’ S; 25° 30.133’ E) and Site 2 (34° 02.019’ S; 25° 29.530’ E) at Sardinia Bay (Fig. 3.1) were sampled for macrofauna 4 and 5 months before the storm, respectively, and six weeks after it. Physical differences between Site 1 and Site 2 are illustrated in the photographs below (Fig. 3.2a-f). Site1 is at the edge of the beach and thus, very close to a rocky headland. It is backed by a car park and surf life-saving club house. Site 2 is 1.7 km west of Site 1 and is protected to some degree by nearshore reef. On the landward side of the beach, Site 2 is backed by dunes formed from wind-blown sand and are not stabilized with vegetation.

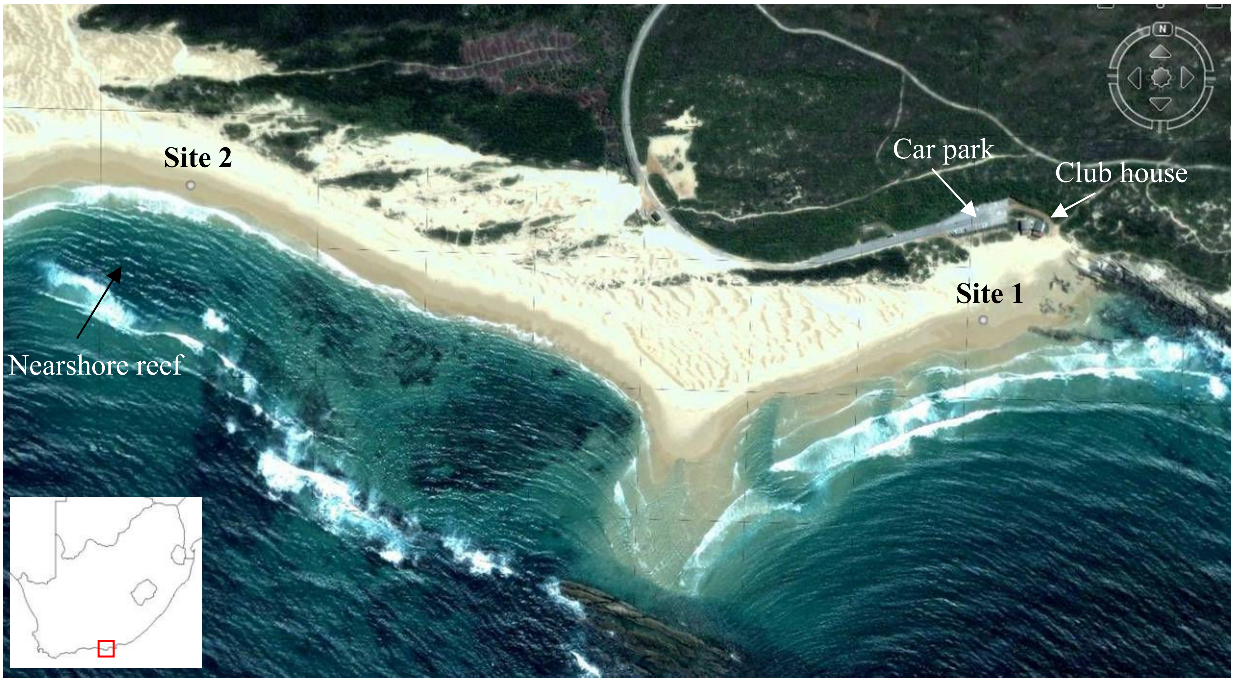

Figure 3.1. Google Earth Map showing the study sites and salient site features at Sardinia Bay, with a country location map insert.

Data collection and analysis

Sampling was performed using the same methods described in Chapter 2 and the data were similarly analyzed in Primer 6. A Bray-Curtis resemblance matrix was constructed to represent among-site similarities. This was visually represented as an MDS plot, and overlain by a cluster analysis of the data. A BEST BIOENV test was run to identify the physical features of the beach that might be driving the changes in the beach communities before and after the storm.

The total volume of sand eroded (V_{SE}) per site per running meter (m^{-1}) was determined by calculating the area of the cross section of the beach and multiplying by 1 m (Eqn. 3.1, Fig. 3.3), for before and after the storm. The estimated sand volume for the before-storm profile was subtracted from the after-storm profile in order to get the total volume of sediment removed.

$$V_{SE} = \left(\frac{1}{2}\right) \times \left(BW \ x \ BE\right) \times 1 \qquad \text{…Eqn. 3.1}$$

Where BW = beach width and BE = beach elevation.

Figure 3.2. Photographs of the Sardinia Bay sites before and after the storm. (a) Site 1 nine months before; (b) Site 1 the day after the storm; (c) Site 1 six weeks after, on the day of sampling; (d) Site 2 (in the distance) nine months before; (e) Site 2 (in the distance) the day after the storm; (f) Site 2 six weeks after, on the day of sampling.

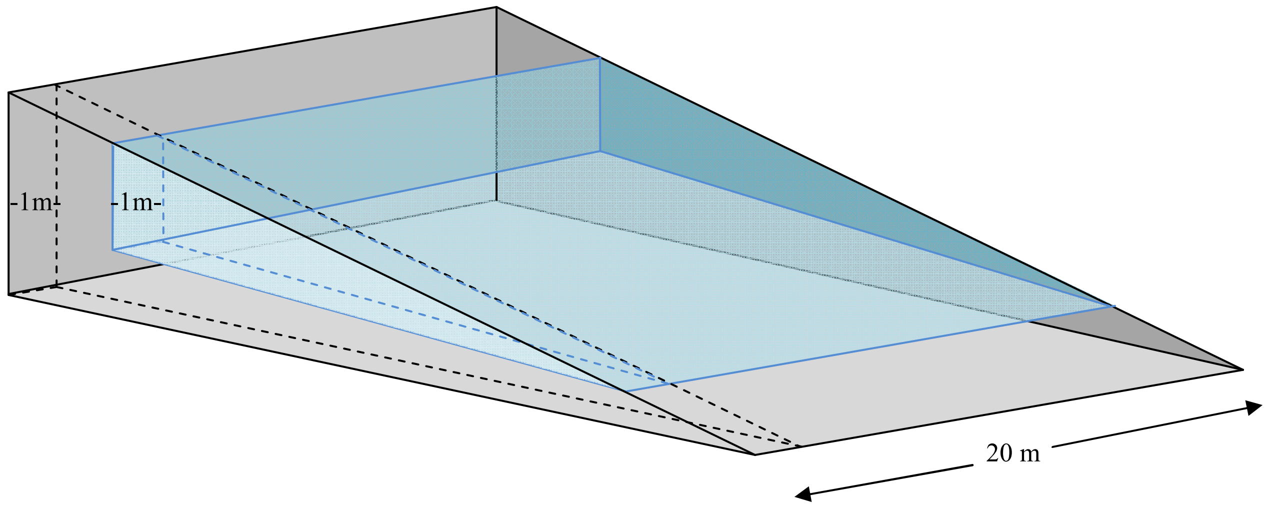

Figure 3.3. Diagram illustrating how the amount of sand eroded was calculated, both per running meter (m^{-1}) and for the whole site (distance per running meter multiplied by the total along-shore distance, 20 m). The amount of sand in the blue wedge (pre-storm profile) was subtracted from the grey wedge (post-storm profile) in order to determine the total amount of sand eroded during the storm.

Results

Physical changes

The comparative data (Table 3.1) show a trend throughout the parameters that the first site displayed greater physical impacts than the second site. Although there was more retreat at the second site, evidenced by the marginally greater increase in beach intertidal width, there was more vertical erosion (and hence total erosion) in the first site because of the relatively large change in slope and elevation. This translated into a greater volume of sediment removed: for the 20 m (alongshore distance) sites, 1404 m^3 sand was removed at Site 1 (70.2 $m^3.m^{-1}$) and 386 m^3 sand at Site 2 (19.3 $m^3.m^{-1}$). The erosion at Site 1 exposed bedrock that had previously been covered with sand. In addition, some areas of Site 1 had bedrock that was covered by less than 30 cm of sand, which became evident while the cores were being taken. The implications of the erosion and shallow sand layer are a reduced habitat for the sandy beach macrofauna. There are changes in the sediment properties for Site 1, but it is unlikely that these changes are large enough to be driving changes in the macrofauna that are present.

When comparing the physical characteristics of each site between the two sampling events, the majority are fairly similar. This is particularly true at Site 2 where, for example, sand grain size varies by only 0.37 mm. The greatest apparent changes are in the beach indices of relative tide range (RTR), Dean's parameter (DP) and the beach state index (BSI). However, these are driven by the change in wave height. This is an extremely variable parameter, and the difference reported here would not necessarily reflect the effect of the storm on these beaches. Changes in the beach deposit index (BDI) and beach index (BI) are driven by changes in the beach slope.

Table 3.1 A comparative table of the physical site characteristics at Site 1 and Site 2, before and after the storm.

	Site 1 before	**Site 1 after**	**Site 2 before**	**Site 2 after**
Date	04-Apr-08	17-Oct-08	07-Apr-08	17-Oct-08
Intertidal width (m)	84.60	85.50	81.90	83.70
Elevation (m)	2.10	3.72	4.23	4.60
1/Slope	40.29	22.98	19.36	18.20
H_b (cm)	70.50	100.00	221.00	108.50
T_w (s)	7	12	15	15
T_s (s)	18	10	5	13
Mean grain size (μm)	276.59	260.00	265.57	265.20
Mean grain size (φ)	1.85	1.94	1.91	1.91
Sorting	WS	WS	VWS	VWS
Skewness	FS	S	FS	FS
Tide (m)[6]	1.57	1.57	1.77	1.77
W_s ($cm.s^{-1}$)	3.47	3.19	3.29	3.28
RTR	2.23	1.57	0.80	1.63
DP (Ω)	3.02	4.66	4.55	2.24
Beach state	Inter	Inter	Inter	Inter
BSI	0.84	1.01	1.04	0.77
BDI	150.20	91.16	75.19	70.76
BI	2.26	2.03	2.00	1.97

Width = Beach Width; *Elevation* = Beach Elevation; H_b = Breaker Height, T_w = wave period; T_s = swash period; W_s = Sediment Fall Velocity; *RTR* = Relative Tide Range; *DP* = Dean's Parameter; *Beach state* = Beach Morphodynamic State based on Dean's Parameter; *BSI* = Beach State Index; *BDI* = Beach Deposit Index; *BI* = Beach Index; *WS* = Well Sorted; *VWS* = Very Well Sorted; *FS* = Fine Skewed; *S* = Symmetrical; *Inter* = Intermediate.

[6] Used tidal difference for Port Elizabeth for each day for two tidal cycles

Biological changes

Species richness and abundance

Eurydice longicornis was the dominant species at both sites, before and after the storm, because it was the most abundantly occurring at all times. There was a decrease in its total abundance after the storm (reduced by 16 % at Site 2), particularly at Site 1 (reduced by 66 %). There were two outstanding changes in the macrofauna communities (Fig. 3.4): at Site1, the number of *Armandia* sp. individuals was reduced by 95 % of previous abundance; at Site 2 the number of *Urothoe coxalis* individuals increased by 1327 %. This increase meant *U. coxalis* became the dominant species at Site 2. *Armandia* sp., *E. longicornis* and *U. coxalis* were the only species that were present at more than 500 individuals per running meter, both spatially and temporally.

Overall species richness[7] remained a constant nine at Site 1, with four of those species present both before and after the storm: *Armandia* sp.; Diptera; *E. longicornis*; and *Pontogeloides latipes*. Total abundance per running meter was reduced from 5076 to 1967, *i.e.,* a 62 % decrease. The following species were no longer present in our samples at Site 1 after the storm: *Bullia rhodostoma*; *Gastrosaccus psammodytes*; Polychaete sp. A; and *U. coxalis.* The insect nymph was also absent, but in its place there was an insect larva. Species that appeared at Site 1 after the storm include: *Donax serra*; *Exosphaeroma sp*; *Scolelepis squamata*; *Urothoe serrulidactylus* and *Urothoe* sp. (Fig. 3.4a).

At Site 2, species richness was reduced from ten to nine, with seven of these species present both before and after the storm. These species include: *B. rhodostoma*; Coleoptera; *E. longicornis*; *Excirolana natalensis*; *G. psammodytes*; *P. latipes*; and *U. coxalis*. Total abundance per running meter increased marginally, by 2 %, from 3722 to 3807. Notable decreases were evident in *E. natalensis* (by 66 %), *G. psammodytes* (by 74 %), and *P. latipes* (by 74%). Species that were no longer present after the storm are: Amphipod sp. A; Insect larva; and *Talorchestia capensis*. *S. squamata*; Talitridae sp. A.; *U. serrulidactylus*; and *Urothoe* sp. appeared at Site 2 after the storm (Fig. 3.4b).

[7] Note: *Urothoe sp.* was not counted as an additional species. This particular individual is suspected to be *U. serrulydactilus* but the species could not be confirmed because the individual was damaged. It is unlikely to be the only one of a different *Urothoe* species present at either of the Sites at either time and thus it was excluded from species richness.

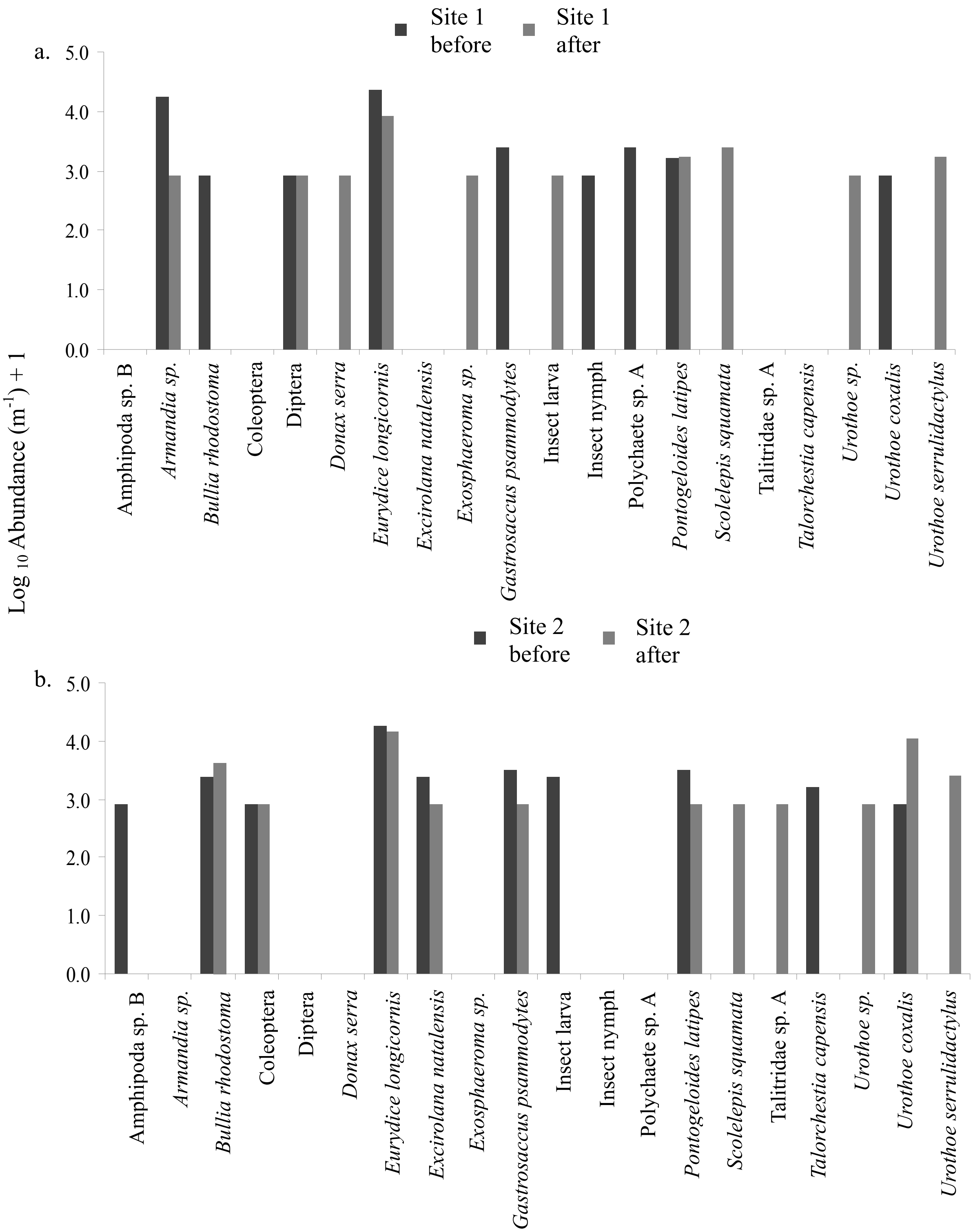

Figure 3.4. The log abundance per running meter of the species found on the beach before and after the storm at (a) Site 1 and (b) Site 2

Dry biomass

At Site 1, *Armandia* sp. showed a decrease to 28 % of pre-storm biomass. There was a 28 % increase in the biomass of *E. longicornis* and a 2063 % increase in the biomass of *P. latipes*. The species identified from Fig. 3.4 above that were no longer present at Site 1 obviously showed a 100 % decrease in biomass after the storm. Likewise, the species that appeared after the storm showed increases in biomass compared to before the storm. The most significant of these increases were for *S. squamata* and *D. serra*, which increased from zero to 1.49 $g.m^{-1}$ and 0.98 $g.m^{-1}$ respectively (Fig. 3.5a).

At Site 2, the isopods *E. longicornis* and *E. natalensis* increased in biomass after the storm by 65 % and 2370 %, respectively; *P. latipes* decreased by 84 %. The other species at this site showed changes in their biomass of less than 0.5 $g.m^{-1}$. In spite of being present in relatively low abundance (Fig. 3.4 above), *Bullia rhodostoma* at Site 2 was notably the most dominant contributor to biomass. This is because of the relatively large size of *B. rhodostoma* compared with the other sandy beach macrofauna present at Sardinia Bay (Fig. 3.5b).

Comparing site similarities, before and after the storm

The grouping of the sites was based on a few of the physical features as input variables: beach intertidal width; beach elevation; intertidal slope; and sand grain size. These features are the most likely to drive the differences among sites. All features relating to waves were excluded because of the extreme variability that could artificially induce groups. In this MDS plot (Fig. 3.6), both Site 2 states were relatively closely related. Site 1 after the storm was weakly related to the Site 2 states, while Site 1 before the storm emerged as a distinct state. This shows that there was a significant difference in the physical state of Site 1 after the storm compared to before, and no significant difference in Site 2. The results from the BEST BIOENV test showed that all the features were responsible for the groups, with beach intertidal width, intertidal slope and grain size emerging as the most important values.

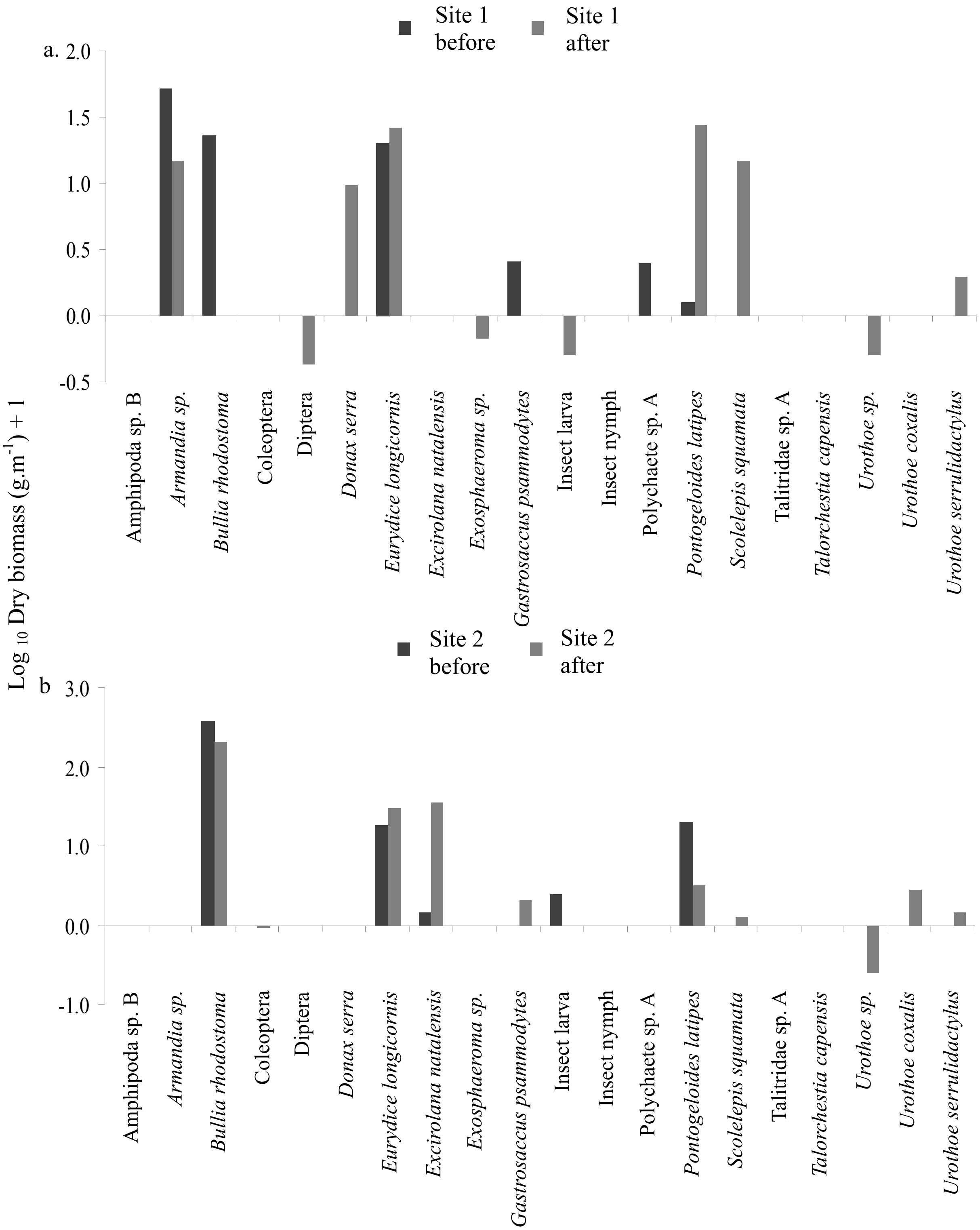

Figure 3.5. The log dry biomass per running meter of the species found on the beach before and after the storm at (a) Site 1 and (b) Site 2

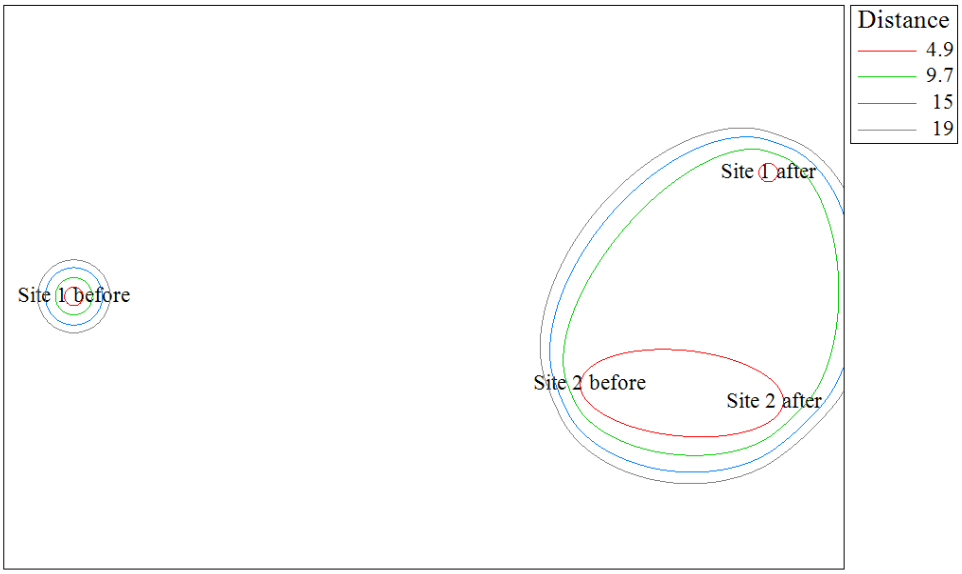

Figure 3.6. A MDS plot of the site similarity based on physical characteristics among the four beach states: before and after the storm at Site 1 and Site 2.

Macrofauna communities before and after the storm

The two MDS plots below (Fig. 3.7a, b) show that the Site 2 macrofauna communities (hereafter, communities) were more closely related to one another than the Site 1 communities were. The groupings based on abundances (Fig. 3.7a) show weaker relationships, but reveal that the communities at Site 2 were more related than those at Site 1 because they lie closer to one another in the MDS plot. This pattern was more evident in Fig. 3.7b, where the Site 2 communities lie close together, showing an 80 % similarity compared to Site 1 that only has a 20 % similarity.

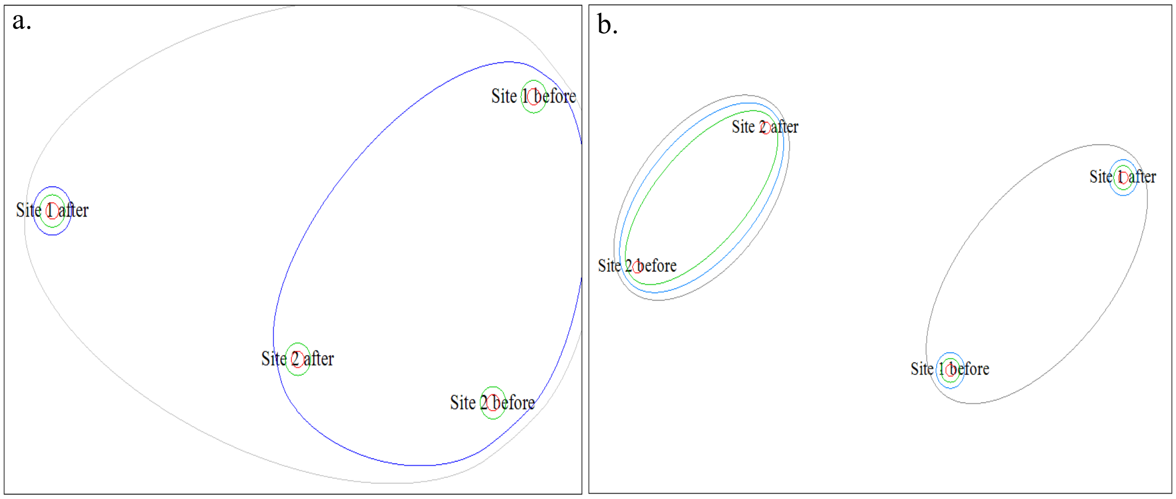

Figure 3.7. A MDS plot of the site similarity among the four beach macrofauna communities: before and after the storm at Site 1 and Site 2 to determine the extent of storm impacts on (a) the abundance (m^{-1}) and (b) biomass ($g.m^{-1}$) of the sandy beach macrofauna. Similarity lines: red = 80 %; green = 60 %; blue = 40 %; grey = 20 %.

Macrofauna across-shore distribution changes

In terms of species distributions on the beach (Fig. 3.8), Site 1 shows a clear trend of species moving further down the beach towards the low-water mark after the storm, with no individuals present landwards of Level 5-6 (Fig. 3.8a). This trend was obvious for all of the species represented by coloured bars, which were the species that occurred at Site 1 both before and after the storm. The species that were removed from the beach by the storm (species represented by grey-shaded bars in Fig. 3.8a) were all mid- to low-shore species, which were replaced with similarly distributed species (species represented by grey-shaded bars in Fig. 3.8b).

At Site 2 (Fig. 3.9), Level 10 was not sampled before the storm (owing to injured samplers and adverse conditions at the beach) and thus it cannot be assumed that this level did not contain species as is suggested by the species distribution plots (Fig. 3.9a). What is evident, however, is the increased abundance of individuals around the midshore mark (Fig. 3.9b). The species that were removed from the beach after the storm were all related with the highshore and those that appeared after the storm were predominantly associated with the midshore.

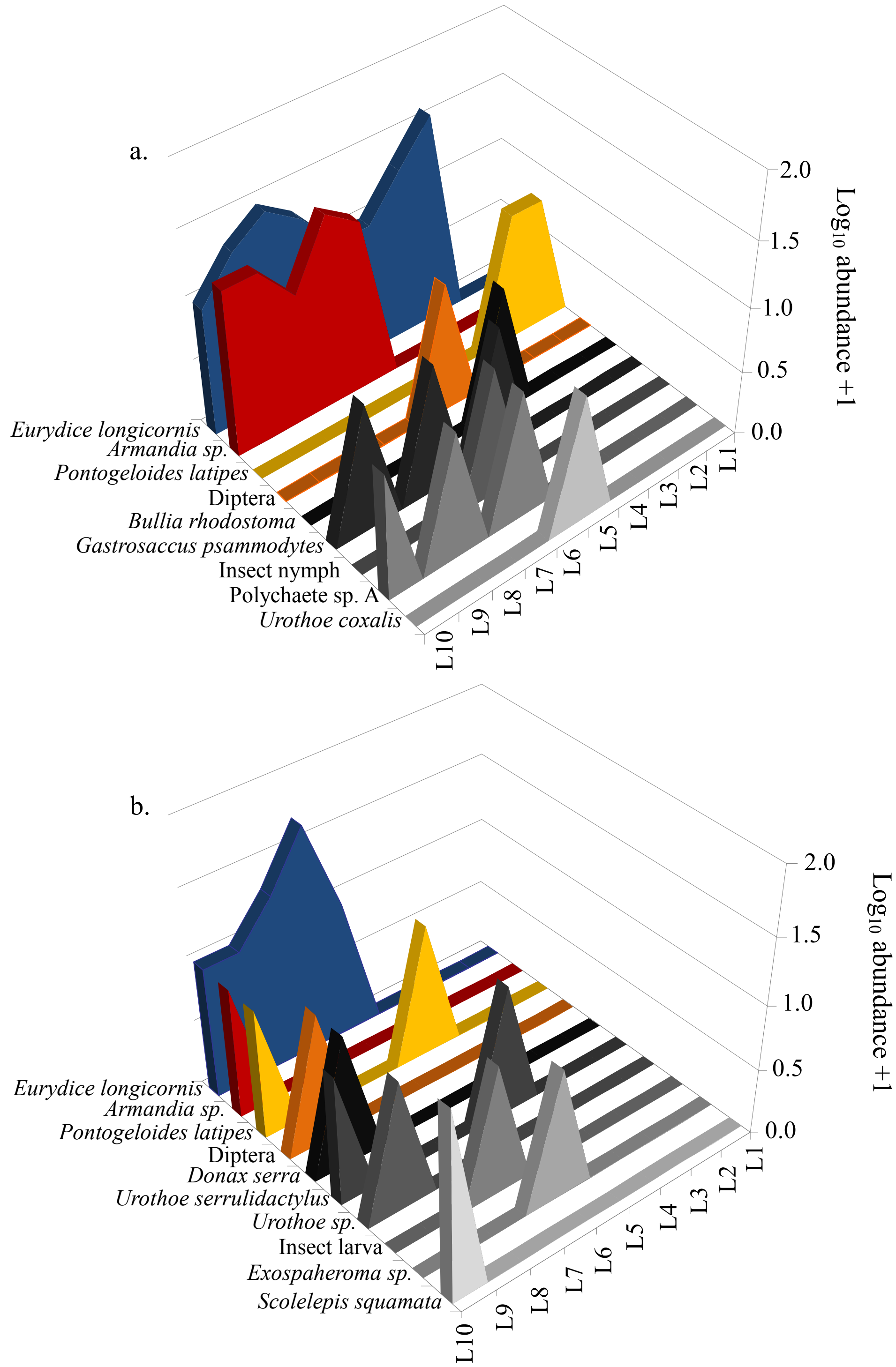

Figure 3.8. The species distributions (in log number of individuals per level) at Site 1 (a) before and (b) after the storm. Note that coloured distribution maps correspond between (a) and (b), representing the species that persisted on the beach after the storm. The grey-shaded distribution maps are of species that either were removed from the beach by the storm, or appeared on the beach after the event. Level 1 (L1) represents the high water mark and Level 10 (L10) represents the spring low water mark.

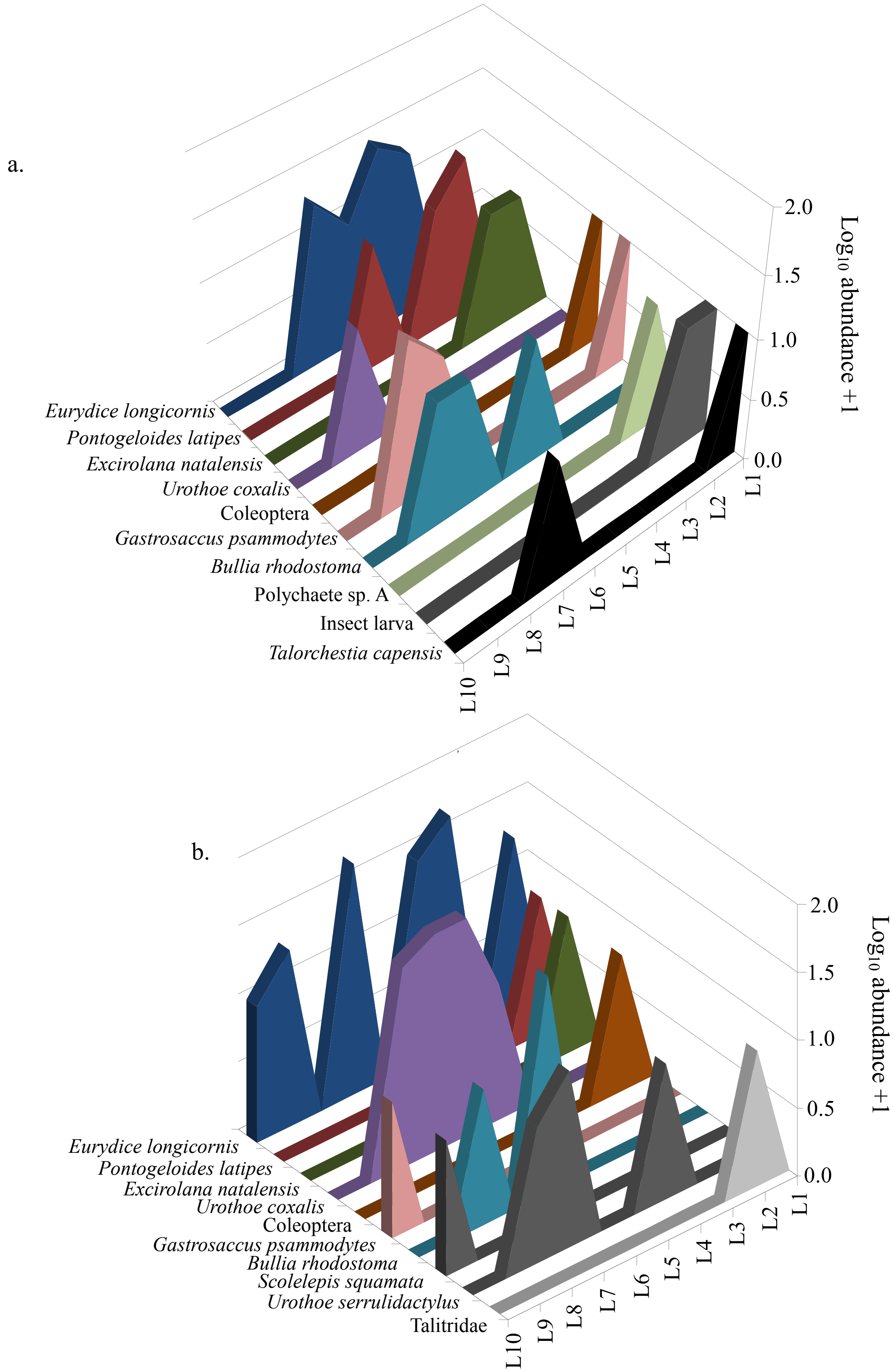

Figure 3.9. The species distributions (log of the number of individuals per level) at Site 2 (a) before and (b) after the storm. Note that coloured bars correspond between (a) and (b), representing the species that

persisted on the beach after the storm. The grey-shaded bars are of species that were either removed from the beach by the storm, or appeared on the beach after the event. Level 1 (Ll) represents the high water mark and Level 10 (L10) represents the spring low water mark. Note that the high spikes of the bars in the foreground in (b) do not block any spikes in the bars displayed behind them.

Discussion

The effect of the storm on the physical state of the beach sites

Storm-impact amelioration by sand dunes and reef

There were greater impacts from the storm at Site 1 than at Site 2, shown by the changes in the physical morphology of the beach. The major reason for this result is very likely the nearshore reef that offered protection to Site 2 by dissipating some of the wave energy during the storm, reducing the erosive ability of the waves and hence, reducing the overall impacts. The reef could have also trapped the eroded sand closer to the shore, which meant it could have returned to the beach more readily than if it had been washed further offshore. Additionally, Site 2 is backed by sand dunes, which meant that when the beach was being eroded, there was a store of sand that could be drawn on to replace that which was lost. This effect has been established in previous studies (*e.g.,* Leatherman, 1979; Morton *et al.*, 1994). The sand from the dunes would have reduced the amount of vertical erosion on the beach and minimized the overall change in the intertidal beach profile.

In comparison, Site 1 was more exposed to direct wave energy because there is no reef protecting it. It is also more susceptible to erosion from terminal scouring because it is at the edge of the Sardinia Bay beach and hence is a more dynamic site in terms of its profile and fauna. This site it is backed by a car park. With no available store of sand behind the beach, more vertical erosion would have been anticipated. There are also many shallow-lying rocks in the Site 1 intertidal zone that became more and more exposed as the beach eroded. As this happened it would have promoted further erosion by terminal scouring around the edges of the rocks, thereby exacerbating the situation. Consequently, the three-dimensional habitat available for sandy beach macrofauna would have decreased substantially. During the sampling, for example, some of the cores were not taken down to the full 30 cm because we hit bedrock before this depth.

Ecological implications of storms for beaches

The effect of the storm on the Site 1 macrofauna community

At Site 1, there was a large decline (65 %) in overall abundance, but only a small reduction in biomass (4 %). This suggests that many of the smaller individuals were washed away during the storm, and only the larger individuals were able to persist. Examples of the pattern are shown in *Armandia* sp. and *Eurydice longicornis*. *Armandia* sp. abundance decreased by 95 % but the biomass decreased by only 72 %. For *E. longicornis* there was 65 % reduction in abundance, but a 25 % increase in biomass. The overall increase in biomass of *E. longicornis* suggests that large individuals that were not previously present at this site might have come onto the beach after the storm.

There is a consistent species distribution pattern at Site 1 that shows no species occupying the mid- to highshore zones after the storm. This was partly expected because the location of the intertidal zone – and hence the sampling area – had shifted landwards as a result of the storm (confirming the trend noted by Bryant (1988)), and now included a portion of the previous backshore beach at Site 1, which would previously have been void of intertidal fauna. However, it was six weeks after the storm, which was more than enough time for species to inhabit this area. The granulometric analysis showed only a small increase in grain size from the lowshore to the highshore. Personal observations of the sand at Site 1 were that there was a significant amount of rubble, small rocks and very coarse sand at these levels as a result of erosion of the back beach and damage to the surf life-saving club house. It is possible that this highshore beach environment is not suitable for the resident beach fauna and they are forced to live further down the intertidal zone. A previous study has shown that kelp can act as an agent of disturbance for *Donax serra* (Soares *et al*., 1996). It is possible that the rubble here acts in a similar manner.

The effect of the storm on the Site 2 macrofauna community

Owing to the limited physical impacts on this beach because of ameliorating effects from the reef and sand dunes, it was expected that the biological impacts would be far less pronounced, as has been shown in other studies (*e.g.*, Croker, 1968). At Site 2, there was a 2 % increase in abundance, but a total reduction in biomass by 32 %. This trend is driven by the changes in *Bullia rhodostoma*, with a large decline in their biomass, in spite of a small increase in abundance. The

MDS plots showed a high similarity between the macrofauna communities before and after the storm at Site 2. There is no obvious pattern at the Order level either: within an order some species increased, others decreased, some appeared and some were removed. In terms of species distributions, there seems to be a trend of increased abundance in the midshore zones after the storm. However, without baseline data regarding the naturally dynamic shifts in species abundances and distributions, it is difficult to say if this is significant or not.

Ecosystem goods and services

Other considerations which require future investigation include the effect of storms on ecosystem goods and services. We can speculate the effect of storms on some of these goods and services, although, it is likely that storms would cause only temporary changes, for most in the short-term, although others may be longer-lived. In terms of ecosystem goods, storms could suppress food supplies to local harvesters (Kyle *et al.*, 1997), for example, by reducing the biomass of macrofauna on the beach. In terms of ecosystem services, storms and/or unusually high tides that: wash over turtle nests; scour them out; or expose the eggs, will destroy the nests, thus reducing the number of recruits significantly (Martin, 1996; Ross, 2005 and references therein). Even just periods of excessive rainfall can destroy turtle nests (Ragotzkie, 1959; Kraemer & Bell, 1980). Further, if storms decrease the abundance of intertidal invertebrates, this can impact on shorebird communities that rely on beaches as a source of prey items. Certainly the ecosystem service of sand storage and storm-impact buffering is highlighted during storms. This study confirmed that sand dunes buffer the effect of storms and act as a store of sand to ameliorate the effects of erosion during storms. However, if development is built in the littoral active zone, *e.g.*, the surf life-saving club house behind Site 1 at Sardinia Bay, then this service is compromised, as was evidenced by the structural damage to the surf life-saving club house.

Potential confounding factors

There are several confounding factors in this study. Firstly, it is not known whether the reef or the sand dunes played a greater role in ameliorating the effects of the storm. Secondly, the sampling was only a single replicate before and after the storm, and the differences in macrofauna communities could be as a result of temporal variation more than the effect of the storm. This temporal variation could be a seasonal effect, where the before-storm sampling was at the end of summer when abundance would be higher, compared to the after-storm sampling which was at the end of winter when abundance would have been lower. However, this seasonal effect would have affected both sites, and thus differences are assessed as relative, comparative effects. Likewise, thirdly, there is a potential recreational pressure that requires relative comparisons to be made. Site 1 has a higher recreational pressure than Site 2 because it is closer to the car park, and thus accessed more frequently. However, the same relative tourist pressures would have been applied at both sites before and after the storm, and thus cannot account for the post-storm changes in the macrofauna community at Site 1. In order to improve the robustness of this experiment, more sampling of these sites in the future is required to determine whether or not the effects at Site 1 were from the storm, and not as a result of temporal variation.

General implications of storms for sandy beaches

It is difficult to make broad, substantial conclusions about the implications of storms for sandy beaches, owing to the limited number of sites that were sampled and also because of the relatively low diversity and biomass at Sardinia Bay even before the storm. However, the results presented here show that there was a general rearrangement in the macrofauna communities on both the beach sites, and that these communities were not completely removed. This is in concordance with Saloman and Naughton (1977), who showed both abundance and species richness of beach benthic invertebrates remained approximately the same before and after a hurricane. It therefore appears that sandy beach macrofauna can persist through storms with relatively low impacts on their communities. Furthermore, provided that the beach is not constrained by sea walls and is not subject to beach cleaning for tourists, storms could increase the amount of wrack on the beach (Jones *et al*., 2007). Wrack on beaches has been shown to increase the species richness, abundance and biomass of wrack-associated fauna and other selected taxa (Dugan *et al.*, 2003). Thus, to some degree, storms have the potential to confer benefits to beach communities.

One observation from this study is that storms can have localized impacts on the beach, depending on particular features on the beach at a relatively small scale. This observation was confirmed during the March storm in 2007 (see Chapter 5 for details). During this storm, one particular beach, Thompson’s Bay (Ballito, KwaZulu-Natal north coast), was eroded until the entire sandy beach had the underlying bedrock exposed: there was no sand left on the beach after the peak of the storm (see Chapter 5, Fig.5.1e). It is expected that the beach fauna communities at this site would have died, and that recolonization would have only occurred once the sand had returned to the beach. This highlights the heterogeneous impacts that storms have, and how important site characteristics are in determining the extent of these impacts and thus how much recovery would need to take place following the storm.

Previous studies on storm activity for beaches showed that only undeveloped beaches recovered to pre-storm morphology, with partial (7 – 71 %) recovery by developed beaches (Morton *et al.*, 1994). This could imply more significant impacts for sandy beach macrofauna on developed beaches following storms. From this speculative perspective, one crucial area of future research will be investigating storm effects on developed beaches, where erosion will be greater and profile recovery is lower. Coupled with recovery of beaches is the period of time in between storms. If storms occur frequently, with insufficient time for post-storm recovery on the beach (both in terms of physical characteristics and biological communities) then this could substantially impair the integrity of the system. This is a particularly important point given that there is a predicted increase in the frequency of extreme storm events (IPCC, 2007). The supply of sand to beaches under these conditions will be crucial for the system to recover.

This study is admittedly an incomplete analysis of the ecological implications of storms for sandy beach fauna because it considers only one size class: macrofauna. Certainly the implications of storms for other beach fauna need to be considered. In particular, studies are required of the supralittoral species, *e.g.*, cirolanid isopods or talitrid amphipods, which do not normally have to endure the wash-over effects of waves because they live in the dry, supra-littoral zone (McLachlan & Brown, 2006). Another area of future research that this study, and the Thompson's Bay example described above hint at, is the influence of low-lying bedrock and storms for sandy beaches, because this adds a third, vertical dimension of habitat loss on beaches.

Conclusion

Given that beach macrofauna are unique, highly specialized animals that are adapted to withstand exceptional fluctuation in their natural environment (McArdle & McLachlan, 1992; McLachlan *et al.*, 1995), it is not surprising that they are able to survive storm activity. This study confirmed that nearshore protection from reefs can significantly buffer the effects of a storm. It also confirmed that sand dunes provide a store of sand that can be drawn on during high erosion events, and can aid in maintaining the sediment at a local site in a comparable size class to before the storm. The latter can assist in ameliorating the impact of storms on macrofauna communities. However, it is uncertain as to which coastal feature conferred the greater effect: sand dunes or nearshore reef. This study has shown that the effect of storms on sandy beaches can be very heterogeneous, and is highly dependent on site-specific coastal features. In conclusion, storms are a temporary disturbance on undeveloped sandy beaches with no outstanding ecological implications for macrofauna communities. This pattern may or may not be true for developed-beach macrofauna communities.

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CHAPTER 4

SPATIAL VULNERABILITY OF THE KWAZULU-NATAL COASTLINE TO INUNDATION AND EROSION UNDER DIFFERENT SEA-LEVEL RISE AND DEVELOPMENT SCENARIOS

Abstract

The aesthetic appeal and economic incentives of the coastal zone makes the land in this area a prime site for development. However, this development has been largely mismanaged and is inappropriately located too close to the littoral active zone, such that natural beach dynamics are now severely hampered. Normally, beaches would retreat landwards under conditions of sea-level rise in order to maintain their equilibrium profiles. But, contemporary coastal development patterns restrict this and thus, beaches are trapped in a coastal squeeze. In this chapter, the Bruun rule was modified to include a measure of beach morphodynamic state, and used to create a tool for predicting coastal recession. This tool gives the new co-ordinates of beach features (such as the position of the back beach, spring high water mark or low water mark) for a user defined scenario of sea-level rise. It was used to predict: the area of retreat for the KwaZulu-Natal (KZN) coastline both with and without current defence structures; the extent of development at risk of impacts from coastal erosion; how much beach area is expected to be lost in front of current defences; and finally the efficacy of the proposed 10-m elevation contour as a setback line for KZN. All analyses were calculated for three scenarios of sea-level rise: 0.2 m; 1.0 m; and 1.8 m, based on 508 transects along the coast. The development at risk was further split into three development scenarios: current development; a 500 m buffer; and a 1 km buffer, around current development. The two buffers extended all around the current development, but did not extend further seaward than the current back beach. The results were calculated for the whole KZN coast, and per region (north, central and south). While the north is predicted to experience the greatest retreat, it also has the greatest adaptive capacity for these impacts, and hence there was no beach area loss predicted. The central and southern regions showed a large amount of retreat, development at risk and beach loss in front of hard coastal defences, and proactive relocation of

the south coast railway line is suggested. The area values for each of these analyses increased both with increasing development and sea-level rise, indicating that development scenarios are as important as the climate change scenarios. Debate over coastal recession modeling was encouraged because this is the only way that accurate, predictive management tools will develop.

Introduction

Coastal ecosystems provide mankind with significant economic benefits: from socio-economic opportunities (Daniel, 2001), to ecosystem goods and services (Beaumont *et al.*, 2007; Duarte *et al.*, 2008). However, the coastal zone, and sandy beaches in particular, is under threat from all angles (Brown & McLachlan, 2002; Anker *et al.*, 2003; Schlacher *et al.*, 2006; Schlacher *et al.*, 2007; Defeo *et al.*, 2008). The primary reason for the contemporary threats to beaches is the disproportionate human population growth along the coastline (Yeung, 2001; Cicin-Sain & Belfiore, 2005; Schlacher *et al.*, 2008). Currently, 70 % of the world's mega-cities are in the coastal zone (Duarte *et al.*, 2008) and it is predicted that by 2020, 75 % of the world's population will live within 60 km of the beach (UNCED, 1992).

This "coastal boom" has led to accelerating levels of development too close to the littoral active zone (Daniel, 2001). Two important consequences are: the construction of sea walls to protect the infrastructure immediately behind the beach (Jones *et al.*, 2007); and impacts from high levels of tourism (Veloso *et al.*, 2008). From an ecological perspective, coastal urbanization and tourism pressures have had a number of negative implications for sandy beach fauna, *e.g.,* talitrid amphipods (Veloso *et al.*, 2008), wrack-associated invertebrates, shorebirds (Dugan *et al.*, 2008), hawksbill turtles (Fish *et al.*, 2008; Harewood & Horrocks, 2008) and sanderlings (Thomas *et al.*, 2001). In addition, by effectively removing the potential for natural landward beach migration, development has increased the vulnerability of coastal ecosystems (and coastal cities) to pressures such as those relating to climate change (Arthurton, 1998; Klein, 2001).

One of the most significant predicted impacts of climate change that will affect sandy beaches is change in mean sea level. Sea-level rise is caused primarily by thermal expansion of the ocean (Chemane *et al.*, 1997; Cabanes *et al.*, 2001; California Coastal Commission, 2001; Edwards, 2005; Naidu *et al.*, 2006; IPCC, 2007) in response to global surface temperature increases (IPCC, 2007), melting of polar ice caps (Zwally *et al.*, 1983; Arendt *et al.*, 2002; Arrigo & Thomas, 2004; Vaughan, 2005; Joughin, 2006) and other subsidiary sources (*e.g.,* Munk, 2003). Currently, global rates of sea-level rise are accelerating (Church, 2001; Church and White, 2006; Rahmstorf, 2007; Rahmstorf *et al*., 2007) and following the upper limits predicted by the IPCC (Houghton et al., 2001; Rahmstorf, 2007; Rahmstorf *et al*., 2007). Specifically for Durban, and thus for KZN, the present rate of sea-level rise is 2.7 $mm.yr^{-1}$ (Mather, 2007). The latest IPCC report (Fourth Assessment Report: AR4) predicts that by 2100, sea level will rise between 18 and 59 cm (IPCC, 2007). This is considered to be an underestimate, and a 1-m rise in sea level is considered possible (Rahmstorf, 2007).

The implications of sea-level rise for coastal ecosystems are large-scale inundation and erosion (*e.g.,* Brown *et al.*, 2006; Schleupner, 2008; Snoussi *et al.*, 2008) as the beaches re-establish equilibrium profiles in response to adjusted mean sea level (Bruun, 1962), *i.e.,* landward migration (Davidson-Arnott, 2005). In most, if not all instances, coastlines around the world have high-value infrastructure in these erosion-prone zones, necessitating some form of a defence structure for protection. This leads to the prevention of natural beach migration (Bray *et al.*, 1997; Fish *et al.*, 2008), and ultimately beach reduction or loss, known as coastal squeeze (Schlacher *et al.*, 2007; Schleupner, 2008). Coastal squeeze has numerous implications for sandy beach ecology (*e.g.,* Defeo *et al.*, 2008; Dugan *et al.*, 2008; Fish *et al.*, 2008) and local tourism (Daniel, 2001).

Traditionally, beach management has aimed to maintain the physical and geomorphological aspects of the coastline, with little regard for ecological implications (Schlacher *et al.*, 2008). In many cases this involves the construction of sea walls. In addition to the negative ecological effects of hard engineering (*e.g.,* Dugan *et al.*, 2008), sea walls create erosion problems at their terminal ends, requiring wall extension and gradual coastal hardening (Jolicoeur & O'Carroll, 2007). Implementation of groynes also has drawbacks by impeding longshore transport of sediment: updrift of the groin there will be accretion, but downdrift-beaches become sediment starved, exacerbating existing erosion (Jolicoeur & O'Carroll, 2007). As a result, investment has been made in strategies that are perceived to be more favourable because they work with the natural beach processes to create more sustainable shorelines (Ferreira *et al.*, 2006; Phillips & Jones, 2006; Milligan *et al.*, 2008). The alternative options include: soft engineering practices like beach nourishment (Greene, 2002; Nordstrom, 2005); and coastal realignment through the implementation of conservative setback lines (Clark, 1997; Ferreira *et al.*, 2006). These interventions maintain beach area and, if implemented correctly, can preserve beach biodiversity, ecosystem goods and services, and tourism potential. However, coastal realignment is not always a feasible option, the maintenance costs of nourishment are high, correctly graded source sediment is not always available and can cause ecological impacts at the borrow sites, and armouring leads to coastal squeeze. So the question is: which strategy will be the most appropriate response to sea-level rise?

Coastal development intensity and location is spatially heterogeneous, and thus a "blanket management" approach is not appropriate. Locally-relevant strategies will need to be employed (Chemane *et al.*, 1997; Jolicoeur & O'Carroll, 2007) if both conservation and socio-economic outcomes are to be achieved (Phillips & Jones, 2006). Proactive integrated coastal zone management has the advantage of being cost-effective in the long-term (Nicholls, 2007), with other significant concomitant benefits, such as hazard avoidance and prevention of species extinctions. Thus, model studies of predicted impacts from sea-level rise and shoreline retreat are critical (Cooper & Pilkey, 2004b) for the development of effective, sustainable long-term coastal management plans.

The aims of this chapter are to develop a tool that can be used to predict the impacts of sea-level rise for coastlines in a geographic information system (GIS); and to use this tool to determine the vulnerability of the KZN coastline to the impacts associated with different scenarios of sea-level rise and coastal development. To achieve this, the objectives are to create a coastal recession model that will determine new co-ordinates of beach features for any given amount of sea-level rise. This model will be used to determine the areas that will erode in response to sea-level rise as beaches re-establish equilibrium profiles. The amount of development at risk will be determined from a best (current rate), intermediate and worst-predicted mean sea-level rise and beach retreat scenarios for 2100 under current (low), intermediate and high development scenarios, both with and without current defences. The area of beach loss will be determined per region and overall. Finally, the efficacy of the proposed 10-m elevation setback line under the different scenarios will be tested.

Methods

Conceptual framework

There are arguments both for (Schwartz, 1965, 1967; Dubois, 1975, 1976; Rosen, 1978; Zhang *et al.*, 2004) and against (Lowenstein, 1985; Pilkey *et al.*, 1993; List *et al.*, 1997; Pilkey & Cooper, 2004) the widely used Bruun rule (Bruun, 1962), to the point of rather heated debate amongst scientists (Nicholls & Stive, 2004; Cowell & Thom, 2006; Cowell *et al.*, 2006; Pilkey & Cooper, 2006; Cooper & Pilkey, 2007). From a beach ecologist's perspective, modeling coastal erosion depends largely on the beach's morphodynamic state. Beaches with fine sand, tending towards the dissipative end of the morphodynamic-state continuum, are more vulnerable to erosion than beaches with coarse sand at the reflective end (Defeo & McLachlan, 2005). Owing to the interactions between the sediment and swash, the latter type of beaches tends to accrete (Defeo & McLachlan, 2005). This could very well be one of the primary reasons why the Bruun rule has not always worked: beaches do not erode uniformly and the rule is too general to accurately predict landward retreat. This is echoed by Pilkey and Cooper (2004) who state: "*The Bruun rule is a "one model fits all" approach, unsuitable in a highly complex, natural environment with large spatial variations in shoreline retreat*". Thus, whilst acknowledging the many criticisms of the Bruun rule (*e.g.,* Pilkey et al., 1993; Pilkey and Cooper, 2004; Davidson-Arnott, 2005), I believe there is merit in the approach if the characteristics of the beach are included in the model.

In collaboration with Andrew Mather, the Bruun rule was modified. Work by Mather *et al.* (in prep.) on the Durban coastline revealed the distinction between the responses of beaches of different morphodynamic types. On basis of the beach indices (see Chapters 1 and 2) we decided to use beach slope as an indicator of beach morphodynamic type (which we could easily interpolate from a digital elevation model) using the beach index (BI) equation (McLachlan & Dorvlo, 2005):

$$BI = Log_{10}\left(\frac{M_z \times TR}{S}\right) \qquad \text{…Eqn. 4.1}$$

Where: M_z = grain size (mm); TR = tide range (m); S = average intertidal slope.

In KZN, there is a fairly uniform tidal range (of approximately 2 m) across the province, which allowed us to disregard this term. Many sources have cited a significant relationship between sand grain size and intertidal beach slope (Bascom, 1951; Bird, 1969; McLean & Kirk, 1969; King, 1972; Carter, 1988; Jackson *et al.*, 2005; McLachlan & Dorvlo, 2005; McLachlan & Brown, 2006), thus allowing the necessity of only one of these factors to predict beach morphodynamic type.

Bruun's rule (Fig. 4.1) is defined as:

$$R = \frac{L}{h+D} \times s \qquad \text{…Eqn. 4.2}$$

Where: R = the distance of shoreline retreat; L = the distance between the shoreline and the closure depth (m), h = closure depth (m), D = dune height (m) and s = the amount of sea-level rise (m).

An alternative way of representing the Bruun rule (Fig. 4.1) is (Cooper *et al.*, 2007; Daniel & Abkowitz, 2005):

$$R = \frac{s}{\tan\theta} \qquad \text{…Eqn. 4.3}$$

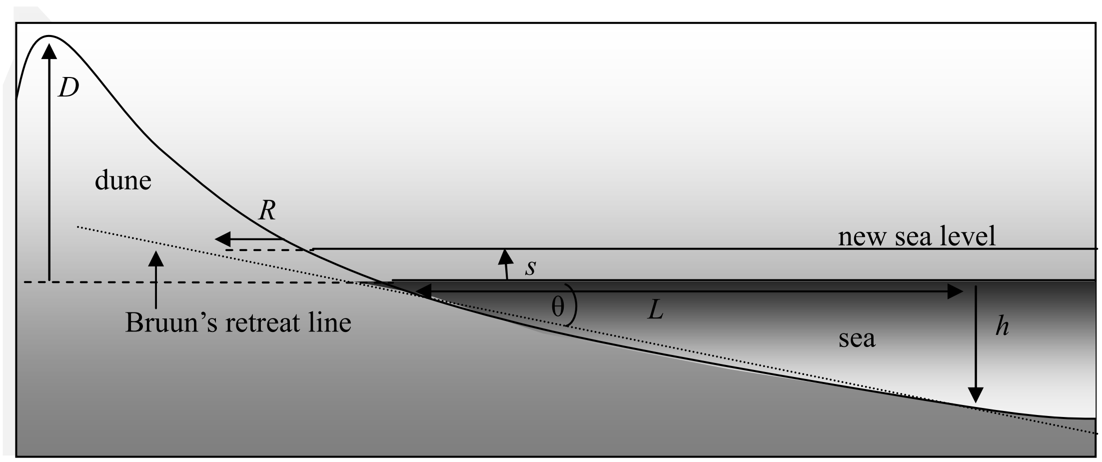

Figure 4.1. Diagram showing the Bruun rule, where the amount of retreat (R) is calculated based on values for: the closure depth (h) – the depth at which there is no net loss or gain of sediment, determined by the point along the offshore profile beyond which no temporal change in profile morphology is evident; the distance between shoreline and the closure depth (L); the distance measuring the vertical rise in sea level (s); and the height of the dune, measured from mean sea level to the highest part of the dune (D). Bruun's retreat line intersects the closure depth and the shoreline. A back-extrapolation of this line to intersect the new sea level gives the point where the new shoreline will be, at distance R back from the original shoreline.

Mather *et al*. (in prep.) showed that, in KZN, the average closure depth is approximately 18 m, confirming Theron (1994). Their calculations also showed a highly significant relationship ($r^2 = 0.98$) between sand grain size (G, D_{50} mm) and the slope of Bruun's retreat line (B_m, degrees), with a fitted power curve of:

$$B_m = 1.3107 \times G^{0.6522} \qquad \text{…Eqn. 4.4}$$

Therefore, by knowing either the intertidal slope of the beach or the sand grain size (because the two are significantly related and hence one can interpolate grain size from slope, and vice versa), it is possible to include a measure of beach morphodynamic state when applying the Bruun rule. By inference, this would significantly improve the applicability of the model.

Practically, it was not feasible to collect sediment samples of the province's entire coastline. A far simpler, less intensive method was to obtain beach intertidal slopes from a digital elevation model (DEM) of the KZN coast in ArcGIS 9.2 (ESRI). One could then interpolate sand grain size, based on the significant relationship between these two variables (Eqn. 4.4). A relationship of intertidal slope and sand grain size specific to the KZN coast was calculated because this, again, would improve the applicability of the model. Several years' worth of data were obtained from the CSIR of across-shore profiles (Theron, 2003) and sediment grain size[8] for the beaches in the eThekwini Municipal Area. The central beaches along the Durban Golden Mile were excluded from the analysis so as to eliminate the influence of the sand-pumping scheme in this area. A regression between the average sand grain size (G, D_{50} in mm) and intertidal beach slope (S, vertical height divided by horizontal distance) values revealed a significant relationship ($r^2 = 0.72$), with a fitted power curve of (Fig. 4.2):

$$G = 2.6661 \times S^{-0.6209} \qquad \text{…Eqn. 4.5}$$

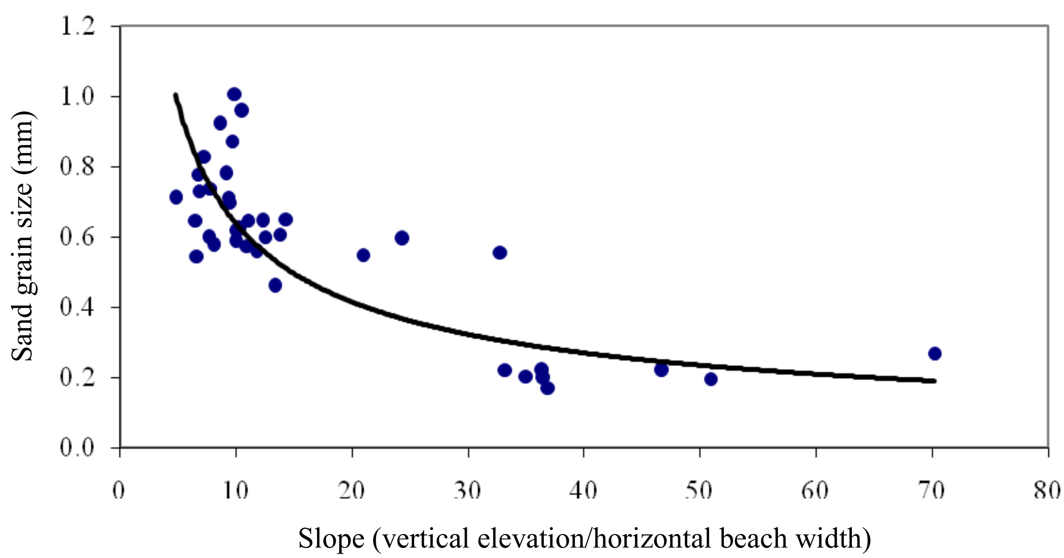

Figure 4.2. The relationship between slope and sand grain size based on data from the eThekwini Municipality Area (n = 65), showing that the grain size decreases significantly ($r^2 = 0.72$) as the profile slope flattens.

[8] Raw data collected by the CSIR obtained from eThekwini Municipality.

The coastal recession model

A 25 m x 25 m DEM of KZN was obtained from the Surveyor General (Department of Land Affairs: Chief Directorate Surveys and Mapping, Cape Town). This was the most accurate DEM that was available. I plotted 508 across-shore transects along the coastline, extending seaward of the spring low water mark and landward of the back beach. This translates into approximately one transect per kilometer of coastline. However, the density of transects in urbanized areas was set higher than in undeveloped areas in order to address the objective concerning the interplay between coastal development, inundation and retreat more accurately. Each transect was converted into a 3D polyline, based on the DEM, using the 3D analyst function. Beach profiles were created from these polylines, using the Easy Profiler extension v 9.03 (Huang, 2005). The values of cumulative distance and height for each profile were exported into MS Excel.

In ArcGIS, the co-ordinates of the three beach features: the spring low water mark (SLWM); spring high water mark (SHWM); and the back beach (BB), along each transect line were exported into the same Excel work book as the above data. Using the profiles data, beach-feature co-ordinates and Equations 4.3 – 4.9 (this chapter), a coastal recession model was formulated. A schematic version of the model process is described in Figure 4.3, and details on the trigonometric calculations in Figure 4.4.

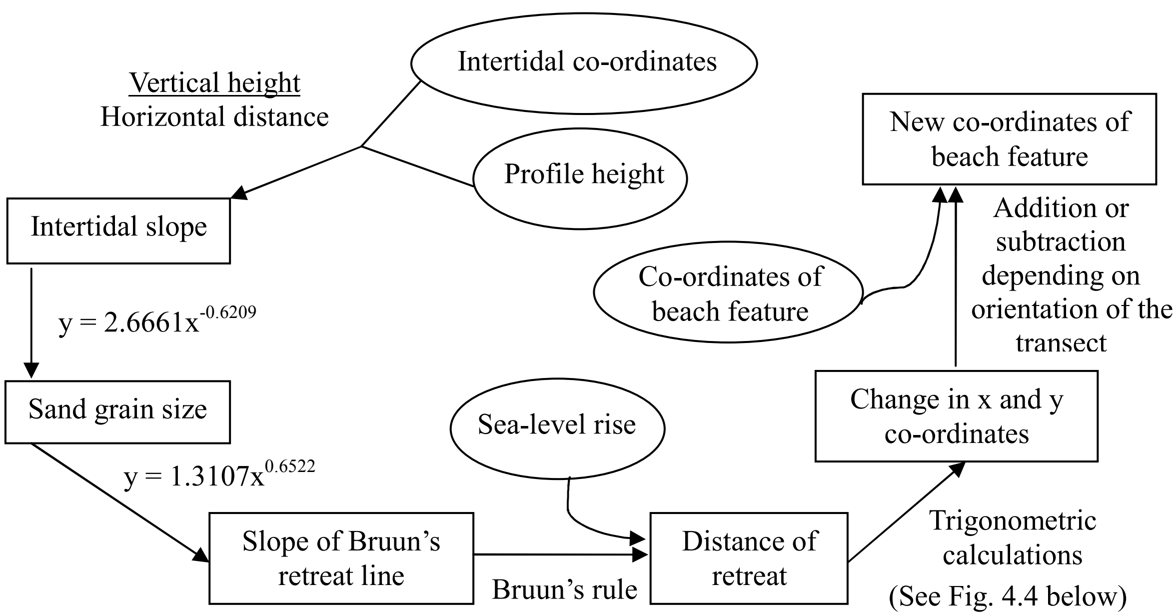

Figure 4.3. Schematic representation of the coastal recession model used to calculate the distance of retreat of a particular beach feature. Ovals represent user inputs, boxes represent intermediate steps of automated

calculations, and text along the arrows details the formulae or methods used to get from one step of the model to the next step.

From Figure 4.4 below, we can determine the gradient of transect line L relative to north (as the m value in a straight line equation) by:

$$\frac{Hx - Sx}{Hy - Sy} \qquad \text{...Eqn. 4.6}$$

From calculations of retreat (as shown in the schematic model in Fig. 4.3) we can predict how far *R1* should be from the *SHWM*, along a back-extrapolation (dotted line) of transect line *L*. This is value *H*. Given *H* and the calculated gradient of *L*, it is possible to calculate θ by:

$$\tan\theta = \frac{O}{A} \qquad \text{...Eqn. 4.7}$$

Distance *O* can therefore be calculated as:

$$O = \sin\theta \times H \qquad \text{...Eqn. 4.8}$$

Distance *A* can be calculated as:

$$A = \cos\theta \times H \qquad \text{...Eqn. 4.9}$$

Note, although Figure 4.4 represents a geographic co-ordinate system, all calculations were preformed in meters. The values of *O* and *A* represent the respective distances that *Hx* and *Hy* need to shift by, in meters, in order to display point *R1* on *L*. These distances were converted into values in decimal degrees, which were added or subtracted to the original co-ordinates (depending on the orientation of the transect) to give the new co-ordinates of the feature.

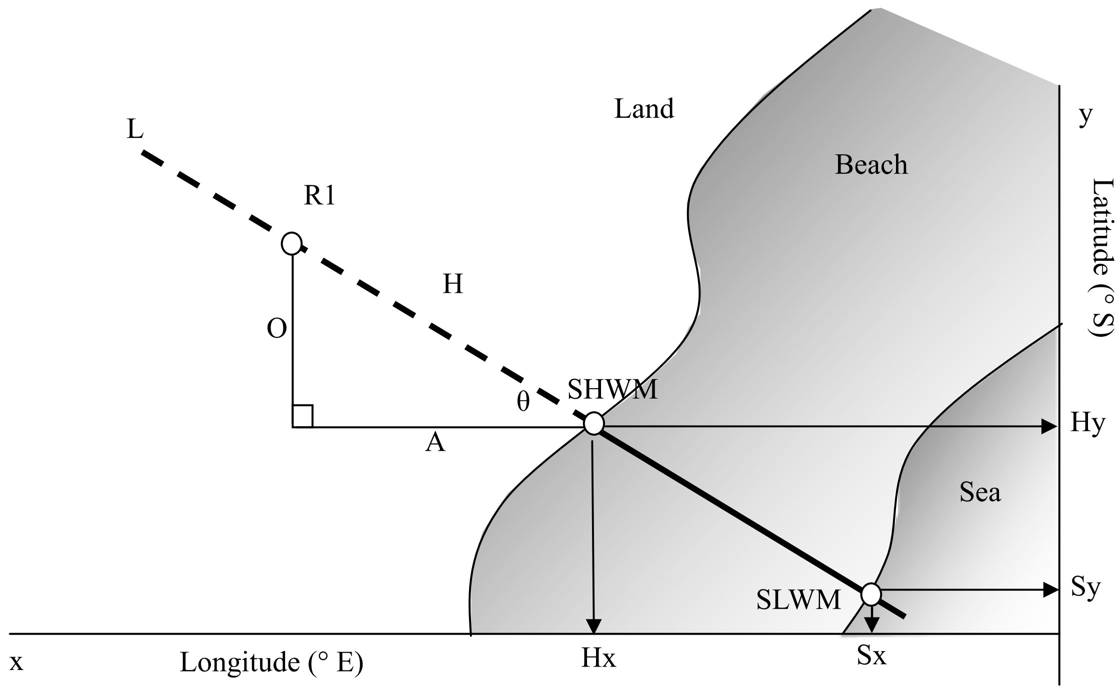

Figure 4.4. A diagram showing the calculation of the co-ordinates of a beach feature (the SHWM in this example) for a specified distance of retreat along a transect line. Where: *L* (thick, dark solid and dashed line) = transect line, perpendicular to the coastline; *R1* = predicted position of the SHWM after a rise in sea level; *O* = Opposite side of right-angled triangle; *A* = adjacent side of right-angled triangle; *H* = hypotenuse of right-angled triangle; θ = angle theta, representing the angle of orientation of the transect line *L* relative to north; *SHWM* = current spring high water mark; *SLWM* = current spring low water mark; *Hx* = longitude of the SHWM ; *Sx* = longitude of the SLWM; *Hy* = latitude of the SHWM; *Sy* = latitude of the SLWM; *x* = latitudinal axis in degrees; *y* = longitudinal axis in degrees.

Data analysis

Beach retreat without coastal defence

The data from the 508 transects were run through the coastal recession model using three different scenarios of sea-level rise by 2090-2100: a low scenario of 0.2 m, which is an approximate extrapolation of the current rate of sea-level rise ~2.7 mm per year (Mather, 2007), and similar to the 0.18 m rise predicted by the IPCC Fourth Assessment Report (IPCC, 2007); a middle scenario of 1.0 m, which is the upper value of the IPCC Third Assessment Report (Houghton *et al.*, 2001), but could also represent possible storm conditions with a low sea-level rise scenario (see below); and a high scenario of 1.8 m, which represents possible storm conditions with a high scenario of sea-level rise (see below). Further reasoning behind the selection of these particular scenarios is that it would provide us with a prediction of impact that we could test against an actual event (see Chapter 5) where sea level rose by ~0.2 m with, albeit temporarily, a storm wind and wave setup of 0.8 m (Mather & Vella, 2007; Smith *et al.*, 2007a; Smith *et al.*, 2007b; Mather, 2008). The new co-ordinates of each of the beach features (back beach, spring high water mark and spring low water mark) per scenario (low, medium and high) were plotted in ArcGIS 9.2 (ESRI) and projected into Universal Transverse Mercator (UTM) using the WGS84 projection.

These beach features point shapefiles were converted into polygons (Fig. 4.5a). The polygons of the predicted location of the back beach for each of the three sea-level rise scenarios were clipped based on a polygon of the current back beach position (Fig. 4.5b). The area of the clipped polygons (Fig. 4.5c) was calculated using the XTools extension (DataEast, 2007), which gave the total area that the beach would need to erode by in order to maintain its current equilibrium profile, assuming the coast was unconstrained. This, however, is largely a fictitious scenario because in reality, the coastline is heterogeneously developed, armoured and unconstrained. Note that where rock occurs, the profiles generally returned zero values for the intertidal slope and thus the new beach co-ordinates were the same as the current position – which is the predicted response. However, not all rocky sections were covered by profiles and so this equivalent of "coastal armouring" was not completely taken into account.

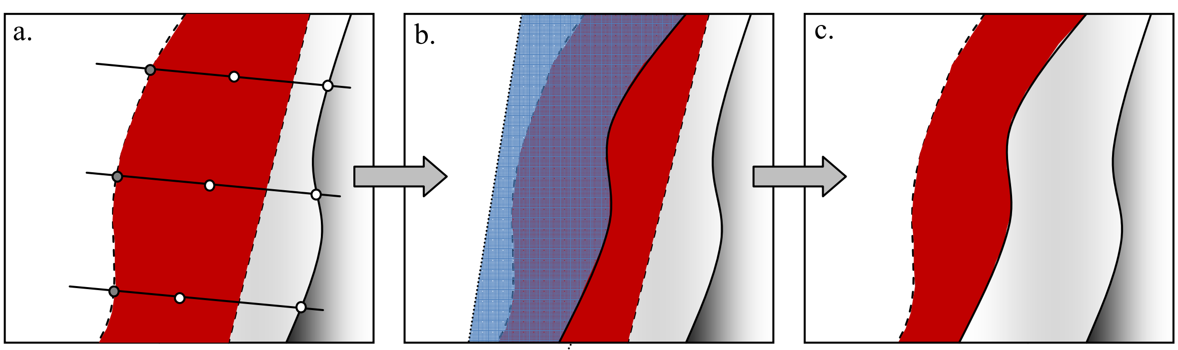

Figure 4.5. Schematic representation of the method followed to get a polygon shapefile of the amount of predicted retreat. In (a), three parallel lines represent three transects, with points at the spring low water mark (left border of the dark grey shape) and at the spring high water mark (left border of the light grey shape) with the grey point indicating the new location of the spring high water mark for a retreat scenario. The red shape is the original polygon of the retreat area. In (b), the original retreat polygon was clipped with the backbeach polygon (blue), to give (c) a clipped retreat area polygon (red).

Beach retreat with coastal defence

In order to generate more accurate values of predicted beach erosion for the province, the areas of the coast that are currently armoured need to be removed from the layers of beach retreat. This is assuming, of course, that these defences will be maintained in the future. All sections of the coastline that are currently defended in some way were used in the analysis. This included a back beach state, as calculated in Chapter 2, of: wall; loffelstein; dolosse/rubble; harbour mouth; tourism amenities; road; and rock (which effectively acts as a wall). Softer engineering interventions such as: geofabric sand bags; other sand bags; and dune reconstruction efforts were also included, with the premise that if the hinterland is worth defending now, it will be defended in the future. The back-beach state had previously been mapped in a polyline format, and polygons of each segment of "hard coastline" were created, extending perpendicularly from the beach area until it intersected the most landward boundary of the retreat polygons (Fig. 4.6a). Thus, when the retreat polygon was clipped by the immovable back beach polygon, all land behind the defended portion of the coastline was excluded (Fig. 4.6b). The area of each of these new beach retreat polygons were recalculated using the XTools extension (DataEast, 2007).

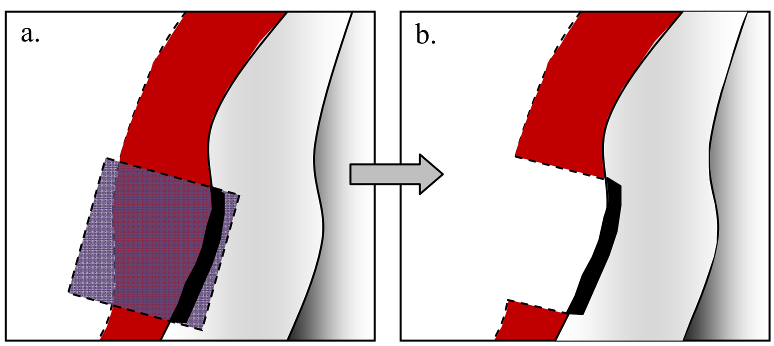

Figure 4.6. Schematic diagram of how coastal defences (thick black line) were converted into a polygon shapefile (purple square) perpendicularly to the coastline (a), and the area of retreat behind the defence was removed from the total area of retreat (b).

Note: it is difficult to predict what the exact coastal management strategies will be in the future and hence, what will happen to development in the zone of potential erosion represented by the retreat polygons. Properties could be expropriated, defended, demolished or inhabited with the risk until they collapse in a storm event. Thus, we cannot assume that the areas where the retreat polygon intersects development will reflect areas that are defended in the future. Development was therefore excluded from this analysis, and represented as "development at risk" in another analysis described below. There is currently a proposition to use the 10-m elevation contour as the setback line (Breetzke *et al.*, 2007), which would remove most of the potentially defendable development anyway.

In order to understand the spatial distribution of impacts, each of the six scenarios (three sea-level rise, with and without current defence) were clipped based on polygons of the three sections of coast that were identified in Chapter 2. These are: the northern region, just north of Richards Bay extending to the northern border of KZN; the central region, from Richards Bay to the Bluff/Durban Harbour southern breakwater, the southern region, including the land between the Bluff and the southern border of KZN. The areas of the retreat polygons were recalculated as above.

Development at risk

To determine how much development is at risk of impacts from erosion, coastal development layers were generated by digitizing all infrastructure within 20 m above mean sea level (Fig. 4.7a). Development in river valleys was considered only up to 500 m up the estuary (approximately the distance inland that the 20 m contour spanned), because the coastal, beach environment is the focus of this study. Thus, the elevation in these areas was only about 10-20 m. The development layer was created from SPOT 5 imagery in ArcGIS 9.2, digitized at a 1:5 000 resolution to ensure consistent accuracy. This layer has an error range of between 5 – 10 m. This was largely determined by the resolution of the SPOT 5 imagery. Three scenarios of development were used (Fig. 4.7a): (1) a low scenario showing only current development and assuming no further construction; (2) a middle scenario of a 500 m extension buffer created around the current development (*i.e.,* assuming no further coastal nodes will form); (3) a high scenario of a 1 km extension buffer around current development (same assumption). Given the high rates of contemporary land-use change in the coastal zone (Celliers, in prep), and the prediction of the east coast being a more favourable area to live in, in the next century (Naidu *et al.*, 2006), these might be conservative predictions. The polygons of beach retreat for the three sea-level rise (SLR) scenarios were clipped based on the three development scenarios to calculate the area of development at risk of impacts (Fig. 4.7b, c). This gave a total of nine possible states of the coast over the next century (Table 4.1).

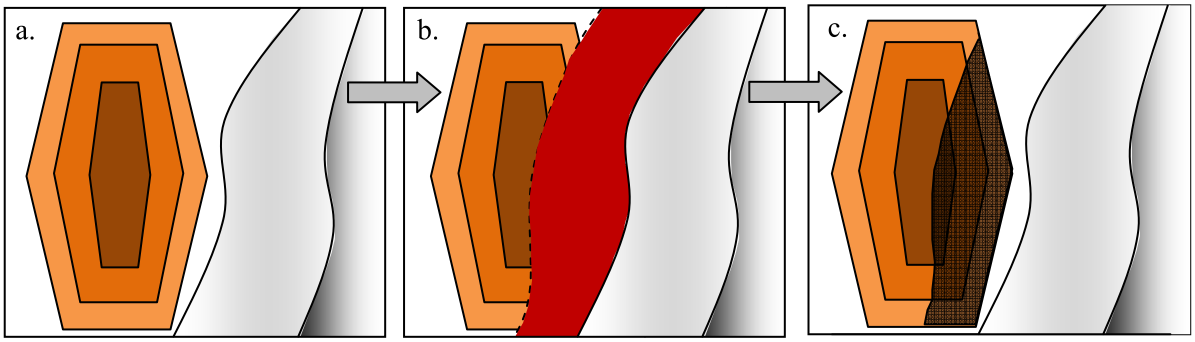

Figure 4.7. (a) The current development (brown shape), 500 m buffer (dark orange shape) and 1 km buffer (light orange shape) clipped (b) based on the retreat scenarios (red shape), to give (c) the area of development at risk of impacts (dark brown shaded area).

Table 4.1. The nine possible states of the coast by 2100 used in this study

	Current development	Current + 500 m buffer	Current + 1 km buffer
0.2 m SLR	1	2	3
1.0 m SLR	4	5	6
1.8 m SLR	7	8	9

The area of development at risk was calculated for each of these scenarios both with and without current defence, and per coastal region using the same techniques as for the determination of beach retreat detailed above. Each of these development-at-risk area values was also converted into a percentage of total development.

Beach loss due to coastal squeeze

While the implications of sea-level rise and storms for coastal development is the primary concern for coastal managers and engineers, the implications for beaches as ecological systems is equally important. The amount of coastal squeeze anticipated was calculated by considering area losses in both the backshore beach – here defined as the beach area between the spring high water mark and the back beach (Dahl's (1952) sub-terrestrial fringe and Salvat's (1964) drying zone); and the intertidal zone. This analysis was performed based on the immovable back beach polygon (described above) and the 508 transects (from above). The across-shore width of the intertidal (Fig. 4.8a: L to H) and the backshore beach (Fig. 4.8a: B to H) was calculated from the points of the transects, using the measure tool in ArcGIS 9.2. The distance by which each of the beach zones would be reduced was measured in the same way (Fig. 4.8b). These are the respective distances between the current back beach and the retreated position of the back beach (Fig. 4.8b: B to B_1) and the spring high water mark (Fig. 4.8b: B to H_1), in the cases where the retreated beach features lay landward of the defence structure. If the spring high water mark also retreated beyond the current back beach (as in Fig. 4.8b below), then the distance between the predicted spring high water mark and the current back beach was subtracted from the distance between the predicted to current back beach. The determination of beach loss was repeated for the three sea-level rise scenarios.

The across-shore (Fig. 4.8c: Ac S) values of beach loss calculated above were multiplied by the along-shore (Fig. 4.8c: Al S) length of the defence line segments on a site by site basis. In this way, the amount of beach area lost per segment, per beach zone (light blue and darker blue shapes) was calculated (Fig. 4.8b). These values were recalculated by region.

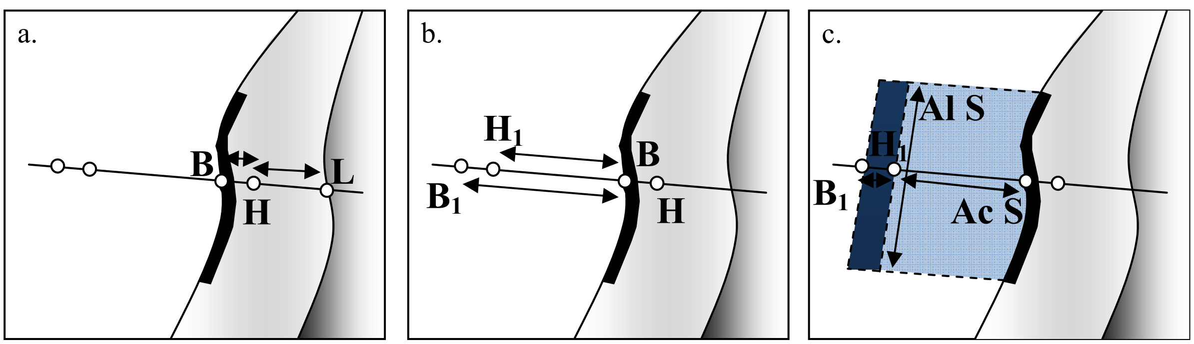

Figure 4.8. (a) Schematic representation of the method used to calculate: the across-shore distance of the intertidal (L to H) and the backshore beach (H to B); (b) the distance between the retreated position of the beach feature (spring high water mark: H_1, and back beach: B_1) and the current back beach, *i.e.,* how much beach is lost; and (c) the area of the beach lost for the intertidal (light blue shape) and the backshore beach (darker blue shape).

Efficacy of the 10-m elevation contour as a setback line

A shapefile of the 5-m elevation contours for KZN was obtained from the Surveyor General (Department of Land Affairs: Chief Directorate Surveys and Mapping, Cape Town). This coverage was incomplete, with a few quarter-degree blocks missing data. In these blocks, contour lines were interpolated from the 25 m x 25 m DEM using the XTools extension (DataEast, 2007). From these two data sets, a 10 m contour shapefile was created. This line was clipped based on the three retreat scenarios. The length of clipped line, *i.e.,* the areas where the 10-m elevation contour was overshot by beach retreat, and the length of the whole 10-m elevation contour were both calculated using the XTools extension (DataEast, 2007).

Results

Coastal retreat

The application of the coastal recession model is shown below (Fig. 4.9). It illustrates how the future location of any beach feature can be predicted to fall along a virtual transect line, depending on the sea-level rise input determined by the user, and Figure 4.10 shows how these transects can be converted into polygons.

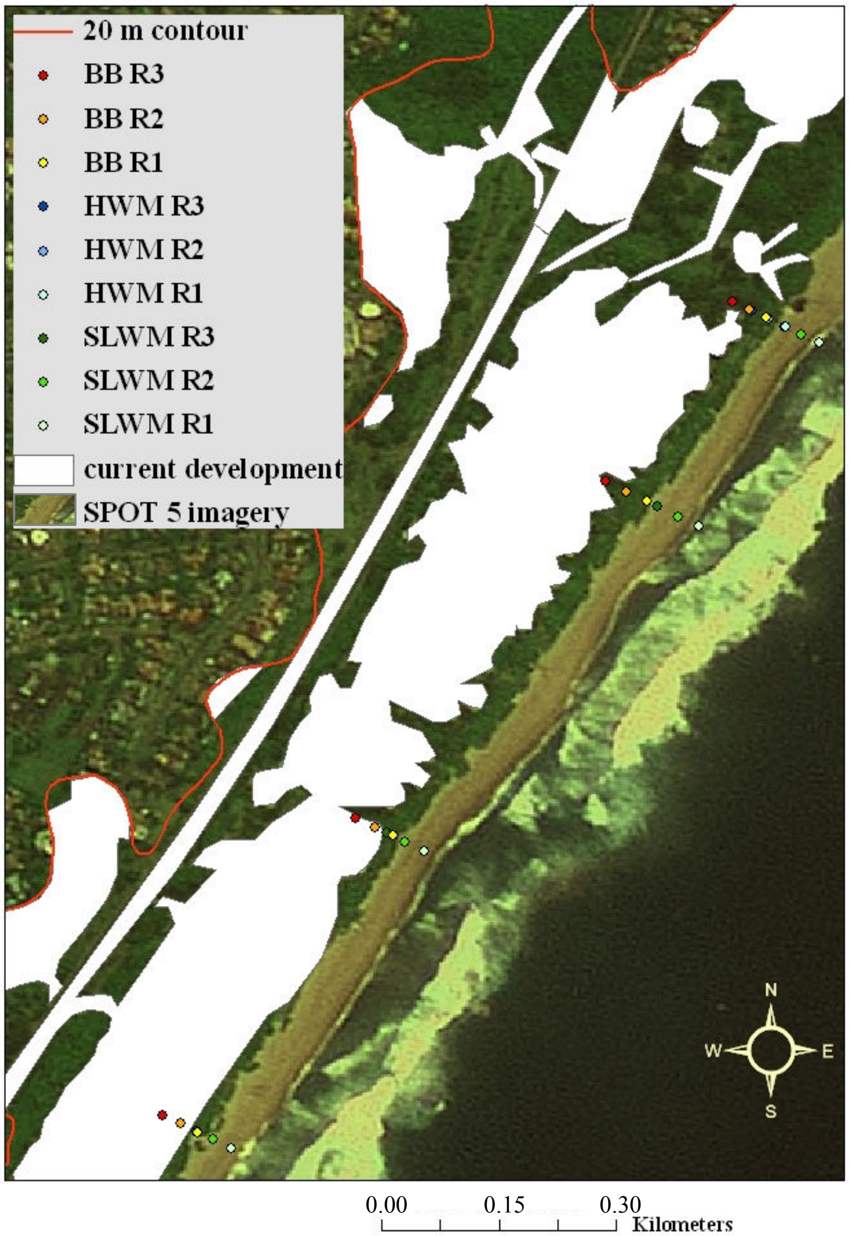

Figure 4.9. An example of the application of the coastal recession model in the KZN south coast, showing six transects (displayed by the points). The lightest coloured (R1) points represent the realigned position of the coast for retreat scenario 1 (0.2 m of sea-level rise); the medium-coloured (R2) represent the realigned position of the coast for retreat scenario 2 (1.0 m of sea-level rise); and the darkest coloured (R3) points represent the realigned position of the coast for retreat scenario 3 (1.8 m of sea-level rise). SLWM = spring low water mark; SHWM = spring high water mark; BB = back beach. All coastal development below the 20-m contour (red line) study area is shown in white. All GIS layers are overlain on SPOT 5 satellite imagery.

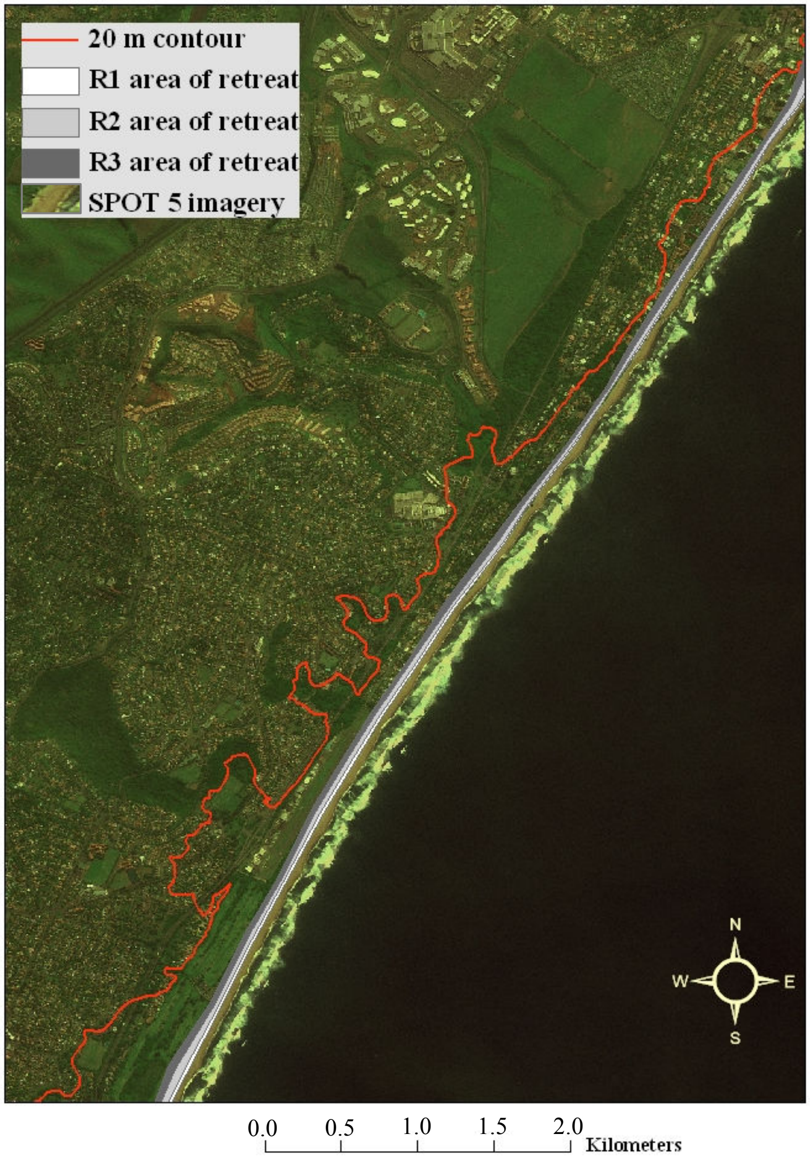

Figure 4.10. An example of the polygons used to calculate the area of retreat for the three scenarios of sea-level rise. Scenario R1 represents the retreat scenario for 0.2 m of sea-level rise; R2 for 1.0 m of sea-level rise; and R3 for 1.8 m of sea-level rise. The 20-m contour represents the study area.

The northern region is predicted to have the most retreat for all scenarios of sea-level rise – approximately double the retreat predicted for the rest of the province. There is a comparable amount of retreat in the central and southern regions, but it is anticipated that the south will retreat more than the central region. Coastal armouring decreases the amount of predicted retreat, with the effect being greatest in the south and the least (negligible) in the north (Table 4.2).

Table 4.2. The amount of predicted recession (km^2) by 2100 under three scenarios of sea-level rise for the KZN coastline, with and without current defence interventions. Data also presented as a percentage of the total beach area per region in brackets.

	No Defence			With Current Defence		
	Sea-level rise Scenario			Sea-level rise Scenario		
	0.2 m	1.0 m	1.8 m	0.2 m	1.0 m	1.8 m
Total	8.87	38.49	69.34	8.14	35.52	64.12
	(2.52)	(10.95)	(19.72)	(2.31)	(10.10)	(18.23)
North	4.15	19.91	36.05	4.15	19.89	36.02
	(2.97)	(14.25)	(25.81)	(2.97)	(14.23)	(25.78)
Central	2.24	8.6	15.4	1.92	7.34	13.22
	(2.03)	(7.8)	(13.97)	(1.74)	(6.66)	(11.99)
South	2.48	9.97	17.86	2.07	8.29	14.88
	(2.44)	(9.8)	(17.56)	(2.03)	(8.15)	(14.63)

Development at risk

The amount of development at risk, based on the retreat scenarios calculated above, shows that more development is at risk as either development expands or sea levels rise. However, the impacts of beach retreat on coastal development are ameliorated to some degree by the current defence measures. There are spatial differences in the amount of development at risk, which also mirrors the patterns of existing development. The northern region has the least development, followed by the central region, with the southern region having the greatest amount of development. Currently, there is no defence in the northern region and thus it makes no difference to the amount of development at risk of impacts from coastal retreat (Table 4.3). An example of the coastal recession model output showing the development that is at risk is given in Figure 4.11 below.

Table 4.3. The amount of development at risk of impacts from erosion (km^2) for three scenarios of sea-level rise, both with and without current defence. Data also presented as a percentage of the total amount of development in brackets.

			Development at risk – no defence			**Development at risk – with current defence**		
			Sea-Level Rise Scenario			**Sea-Level Rise Scenario**		
	Development Scenario	**Total area of development (km^2)**	**0.2 m**	**1.0 m**	**1.8 m**	**0.2 m**	**1.0 m**	**1.8 m**
Total	Current	90.80	1.69 (1.86)	3.92 (4.32)	6.43 (7.09)	1.13 (1.24)	2.83 (3.12)	4.83 (5.14)
	500 m buffer	459.57	4.85 (0.86)	16.48 (3.59)	29.31 (6.38)	3.73 (0.81)	13.10 (2.86)	23.65 (5.15)
	1 km buffer	642.29	5.49 (0.85)	19.15 (2.98)	33.68 (5.24)	4.37 (0.68)	15.69 (2.44)	28.01 (4.36)
North	Current	0.20	0.01 (5.00)	0.01 (5.00)	0.01 (5.00)	0.01 (5.00)	0.01 (5.00)	0.01 (5.00)
	500 m buffer	9.03	0.15 (1.66)	0.78 (8.64)	1.61 (17.83)	0.15 (1.66)	0.78 (8.64)	1.61 (17.83)
	1 km buffer	22.03	0.40 (1.82)	1.96 (8.90)	3.54 (16.07)	0.40 (1.82)	1.96 (8.90)	3.54 (16.07)
Central	Current	36.62	0.36 (0.98)	0.82 (2.24)	1.22 (3.33)	0.14 (0.38)	0.42 (1.15)	0.63 (1.72)
	500 m buffer	205.55	1.16 (0.56)	3.85 (1.87)	6.64 (3.23)	0.79 (0.38)	2.84 (1.38)	5.04 (2.45)
	1 km buffer	295.20	1.35 (0.48)	4.45 (1.51)	7.71 (2.61)	0.98 (0.33)	3.43 (1.16)	6.07 (2.06)
South	Current	53.87	1.31 (2.43)	3.09 (5.73)	5.2 (9.65)	0.98 (1.82)	2.40 (4.46)	4.19 (7.78)
	500 m buffer	244.99	3.52 (1.44)	11.85 (4.84)	21.06 (8.60)	2.79 (1.14)	9.48 (1.14)	17.07 (6.67)
	1 km buffer	325.06	3.72 (1.14)	12.72 (3.91)	22.43 (6.90)	2.99 (0.92)	10.35 (1.92)	18.44 (5.67)

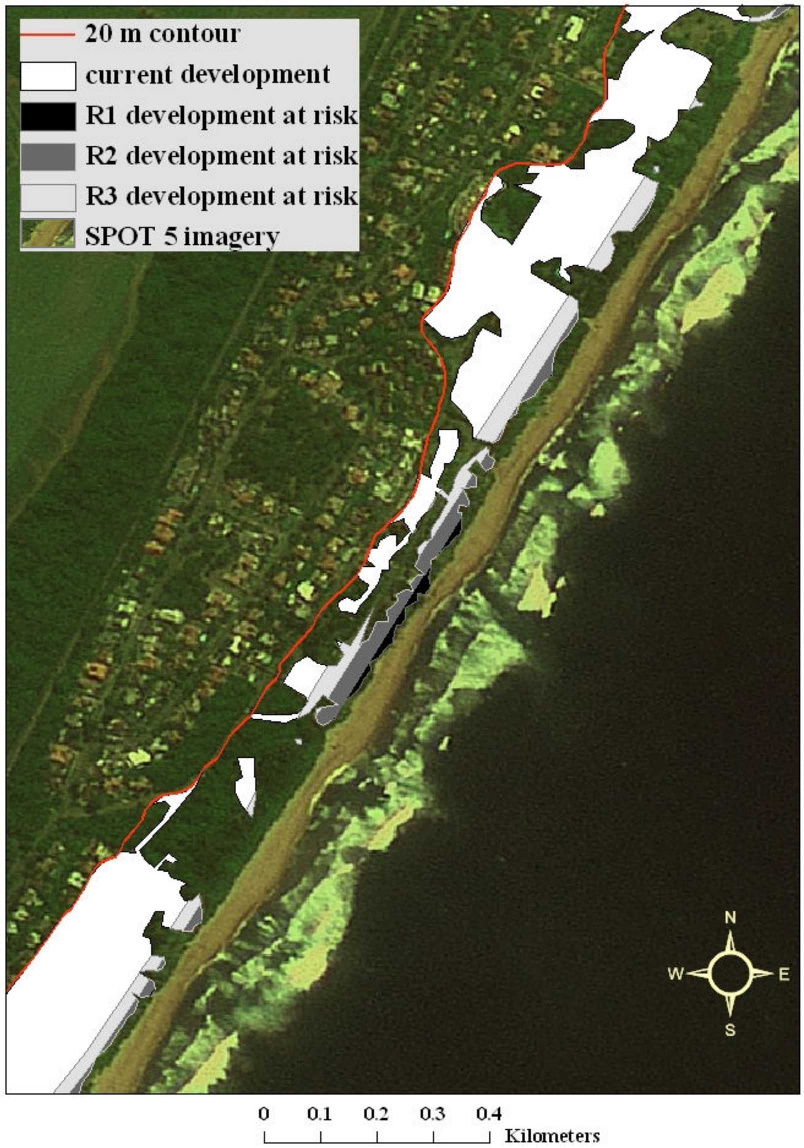

Figure 4.11. Map showing the development at risk based on the three different scenarios of sea-level rise. Scenario R1 represents the retreat scenario for 0.2 m of sea-level rise; R2 for 1.0 m of sea-level rise; and R3 for 1.8 m of sea-level rise. The 20-m contour represents the study area.

Coastal squeeze and beach loss

The area of beach loss anticipated in front of coastal defence shows that backshore beach is particularly at risk, with losses of up to 89 %. The intertidal also shows high losses of up to 69 % of the total area in front of defence structures. No beach loss is predicted for the northern region, while the greatest losses are anticipated to occur in the southern region (Table 4.4).

Table 4.4. The predicted beach area loss in front of hard defence structures due to inundation, for different scenarios of sea-level rise (SLR). Data are presented as a total and per region, given as a loss value in: km^2; % of total beach area in front of the defence in round brackets; and as a % of beach area loss of the whole focus area in square brackets.

	0.2 m SLR		**1.0 m SLR**		**1.8 m SLR**	
	Intertidal	**Backshore beach**	**Intertidal**	**Backshore beach**	**Intertidal**	**Backshore beach**
Total	0.45	0.36	1.67	0.78	2.20	0.85
	(14.27)	(37.33)	(52.71)	(81.23)	(69.30)	(88.68)
	[0.12]	[0.10]	[0.47]	[0.22]	[0.62]	[0.24]
North	0.00	0.00	0.00	0.00	0.00	0.00
Central	0.16	0.12	0.69	0.35	0.98	0.39
	(8.58)	(24.25)	(37.96)	(69.69)	(53.65)	(78.90)
	[0.14]	[0.10]	[0.62]	[0.31]	[0.88]	[0.35]
South	0.25	0.20	0.88	0.39	1.11	0.42
	(18.69)	(45.92)	(64.19)	(88.72)	(81.50)	(95.22)
	[0.24]	[0.19]	[0.86]	[0.38]	[1.09]	[0.41]

10-m contour setback line

In order to prevent the detrimental impacts of coastal squeeze and the associated consequences for coastal development, the 10-m elevation contour line has been proposed as the setback line in KZN (Breetzke *et al.*, 2007). Table 4.5 below shows that it might not be entirely effective, because 20 – 35 % of the 10-m elevation contour lines within 3 km of the coastline are overrun by a polygon of beach retreat.

Table 4.5. The efficacy of the 10-m elevation contour as a setback line by the percentage of the contour line that is overrun by a polygon of retreat for three scenarios of sea-level rise

Retreat Scenario	% of 10-m contour lines overrun by retreat
1 (0.2 m SLR)	20.09
2 (1.0 m SLR)	29.07
3 (1.8 m SLR)	34.64

Discussion

Retreat, development and coastal squeeze

North region

Owing to the spatial heterogeneity in the response of the KZN coastline to sea-level rise, it is sensible to consider the implications of the different scenarios per region. The model predicts that the northern region will have more coastal retreat than the other two regions. This can be explained by the morphodynamic type of the beaches. As was shown in Chapter 2, the north has many more dissipative beaches than the central and southern regions. Dissipative beaches characteristically have fine sand that is easily eroded (McArdle & McLachlan, 1992; Short, 1999; Defeo & McLachlan, 2005) and shallow slopes (Short, 1999; Brown & McLachlan, 2002; Benedet *et al.*, 2004). These two characteristics make them more vulnerable to erosion and inundation, respectively, and hence they display the greatest retreat. However, because there are no coastal defence structures in the northern region, and because very few beaches are backed by rock (which functions like a wall), this retreat is not coupled with a predicted loss in beach habitat. This is a very positive result from ecological perspective.

It is particularly fortunate that the northern region, with the most predicted coastal retreat, is the region with the greatest natural capacity to respond to sea-level rise. The unconstrained coast with natural sand reserves (in the form of dunes) will mean that the northern region can retreat and still support a functional beach system, and it will therefore continue to provide uncompromised ecosystem goods and services. The critical importance of preserving this inherent resilience and adaptive capacity cannot be emphasized enough. The ecological importance of this region is driven by its role as a nesting site for the endangered loggerhead (*Caretta caretta*) and leatherback (*Dermochelys coriacea*) turtles. Consequently, strict setback lines will be required to protect the future of the north coast for turtle conservation (Fish *et al.*, 2008). This is especially important because some studies have shown shoreline management practices, like sandy beach nourishment, can reduce turtle nesting frequency and success (Rumbold *et al.*, 2001). It could be expected that pressures from ecotourism will challenge these setback lines in the years to come. This will be driven by the deteriorating “beach experience” that will be afforded to tourists in the other two regions. However, all prospective development in the north will need to be appropriately located so as not to interfere with the natural dynamics of this local system.

Central and south regions

The central and southern beaches are far more complicated systems to manage because in both cases, natural resilience and adaptive capacity have been compromised by development investments of significant economic value. Thus, there is a myriad of factors to consider when designing conservation management plans for these regions: protecting high-priority development; placing future development; maintaining beaches for tourism and tourist-related activities; coastal squeeze, beach inundation and associated habitat losses; biodiversity conservation; metapopulation connectivity; creating sustainability to ensure provision of ecosystem goods and services; and maintaining inter-ecosystem linkages for nutrient and energy flows. To complicate matters further, there are often conflicts between the management strategies that would optimize each of the different objectives.

The south coast represents the worst case for future states of the KZN coast for different amounts of sea-level rise. There is a similar retreat distance predicted for the central and southern beaches, but the amount of development at risk is higher in the south. This is simply because there is more development along the south coast, compared to the nodes of development in the central region. The currently undeveloped areas in the central region therefore require strategic management (*e.g.,* setback lines) in order to avoid future risks and significant economic losses. Given the expected consequences of sea-level rise for the beaches in the south coast, which will be exacerbated by storm impacts, it is recommended that the railway line is relocated proactively, *i.e.*, before it gets damaged beyond repair from these climate-change impacts. This would be advantageous from an economic point of view because the railway line would need to be moved in the near future anyway because of sea-level rise and storm impacts. Moving it proactively would ensure continued use of this infrastructure, without a halt in business due to damages. It would also increase the resilience of the beach by having a more functional foredune.

Hardening coastlines with defence structures

Coastal defence structures were predicted to decrease the amount of development at risk but, they also reduce the amount of beach area, as also shown in previous studies (*e.g.,* Pilkey & Wright, 1988; Hall & Pilkey, 1991). In the south, there is a 19 – 82 % predicted loss of the intertidal and 46 – 95 % predicted loss of the backshore beach areas in front of the coastal defences for a sea-level rise between 0.2 – 1.8 m. The values for the central beaches are comparable, although not quite as high. These results are similar to those of Snoussi *et al.* (2008), who calculated a 9 – 70 % loss of beaches by 2100 for a 0.2 – 0.89 m rise in sea level because of coastal squeeze.

Ecological implications of sea-level rise

From an ecological perspective, the primary implication of sea-level rise for sandy beaches is the expected reduction in beach area due to coastal squeeze. This translates into a loss of the upper intertidal beach zones and a reduction in the mid-intertidal zones (Dugan *et al.*, 2008). Concomitantly, it is predicted that the fauna, ecosystem goods and ecosystem services that are associated with these upper zones will be compromised, and eventually lost. Initial implications as the backshore beach is lost include losing: species, such as shorebirds and wrack-associated invertebrates (Dugan *et al.*, 2008); ecosystem goods, such as subsistence harvesting of ocypodid crabs (Kyle *et al.*, 1997); and ecosystem services, such as turtle nesting grounds (Fish *et al.*, 2008). It is expected that there would also be a decline in the services associated with buffering storm effects, and sand storage; and breakdowns in the linkages with coastal systems, *e.g.*, sand dunes. However, it is assumed that if beaches are trapped in a coastal squeeze, these latter ecosystem services would have already been removed by the placement of development in the littoral active zone. While not an ecological implication *per se*, it is still important to note that recreational opportunities that beaches provide humans with would be compromised as beach area is reduced. This could have knock-on ecological implications, in that the intensity of tourism pressures for beach fauna would increase if the same number of people visited the beach, but their activities were concentrated over a smaller area.

Setback lines

There has been a strong move towards management practices that work with natural coastal processes (Ferreira *et al.*, 2006; Phillips & Jones, 2006; Breetzke *et al.*, 2007; Milligan *et al.*, 2008). These include strategies such as sandy beach nourishment and coastal realignment by implementation of setback lines. These, and cases for the implementation of each, will be examined in greater detail in Chapter 6. What will be considered here, however, is the efficacy of the currently proposed setback line for KZN (Breetzke *et al.*, 2007).

It has been suggested that the 10-m contour is used to guide the placement of future developments in KZN (Breetzke *et al.*, 2007). The output of the model in this chapter, admittedly coarse in scale, shows that 10 m above sea level is not enough of a coastal buffer because 20 – 35 % of the 10-m contour lines within approximately 3 km of the coast are overrun by a retreat polygon for 0.2 – 1.8 m of sea-level rise. The distribution of these vulnerable areas is not spatially concentrated in any location and they occur all along the KZN coastline.

From a coastal development perspective, whether 20 – 35 % is an acceptable amount of risk is a debatable point and depends on the objectives of the setback line: to reduce risk or prevent it. It has been suggested that the 10-m contour is a flexible setback line, where properties can be exempt from the restrictions based on an impact assessment by an expert[9]. An additional recommendation here is that there should be flexibility of the setback line in the opposite, landward direction as well, where properties landward of the 10-m contour and in highly vulnerable retreat zones should be included in the setback restrictions. Even once setback lines have been enforced, it is not always appropriate to develop immediately behind the line (Breetzke *et al.*, 2007).

Implementation of setback lines should not be solely to protect infrastructure, but, given the ecological implications described above, should also aim to protect the ecology of sandy beaches. (Although, again, this has human implications because of the economic benefits associated with the ecosystem goods and services of sandy beaches). Thus, from an ecological perspective, the 10-m elevation contour is likely not to be enough of a setback line to ensure sufficient conservation of biodiversity, ecosystem goods and ecosystem services. This is because approximately a third of the

[9] Discussions in the KZN Provincial Coastal Committee meetings, 2007.

coastline will be compromised if development is allowed up to the 10-m elevation contour, across the province. This estimate does not include areas that will be exempt from the setback owing to their tourism value, *e.g.*, the Durban Golden Mile, and thus it is likely to be higher than one third of the coastline that will be trapped in coastal squeeze. Consequently, it is suggested that determination of this setback line is revisited based on model studies such as were used in this chapter, but run with higher resolution GIS data to ensure more accuracy.

Climate change scenarios vs. development scenarios

It is also evident that the amount of development affects the impacts associated with a particular scenario of sea-level rise. If one considers Table 4.3, the amount of development at risk for the high development scenario (1 km buffer) is similar to the amount at risk under current levels of development with a 1.8 m rise in sea level. As argued by Nicholls (2004), the socio-economic scenarios can be responsible for driving the impacts of climate change more than the scenario of the climate change itself. Thus, it is important not only to manage the predicted impacts, but also to avoid exacerbating future impacts by sensible regulation of future development.

In summary, future development needs to be appropriately located to prevent unnecessary negative impacts from coastal erosion. The northern region will require greatest proactive management by strict implementation of setback lines, while the central and particularly the southern regions will require more site-by-site management. In this case, specific goals will need to be managed for so that the ecosystem as a whole is conserved sustainably, whilst still meeting user demands and goals from all stakeholders. This is the essence of integrated coastal zone management. Achieving this desired state will depend on predictions of the state of the coast given different climate change and development scenarios, and how best to improve the adaptive capacity of the beach in each case. The more accurate the predictions, the more confidence can be applied when implementing proactive management strategies.

Practical recommendations to improve the accuracy of the coastal recession model predictions

The important outcome of this chapter is the development of a tool to predict coastal erosion spatially in a GIS, which can be applied by management authorities to local beaches and thereby aid strategic coastal planning. Owing to the very coarse application of the tool in this chapter, the results represent a broad-scale prediction of the future state of the coastline. Here, trends and relative impacts are more important than the actual figures and it is recommended that finer-scale studies are undertaken to accurately assess impacts. The analyses are an example to show: the different parameters that can be predicted by the coastal recession model; how these are calculated; what the results could imply; and finally what is recommended for the different scenarios.

There are ways that the application of the tool can be modified compared to this chapter, in order to attain more accurate predictions. Most of the improvements come from field-based sampling, although there are also ways to improve the model if it is done as a desktop study. However, these two methods are not mutually exclusive and can, in part, be used in combination.

Improvements: desktop

1. The more transects there are in the study area, the more accurate the results will be. This does not necessitate creating 3D polyline transects as was done in this chapter. Pair-wise digitizing of the intertidal boundaries is sufficient. However, one would need to add height data to these points using the 3D analyst tool before exporting the data for modeling in a spreadsheet. If there was a specific beach feature that was of interest, *e.g.,* the back beach for calculating total retreat, this would have to be digitized in alignment with a respective pair of intertidal co-ordinates. In this case, a transect line might be a useful guide for the placement of the points.
2. Digitizing the development layers is limited by the resolution of the satellite imagery. If more accurate imagery is available, it would improve the confidence in predicting how much development is at risk from erosion impacts, and thus where to place setback lines. Where accurate imagery is not available, one alternative is to contact local authorities for potentially existing GIS files of development, which may have additional benefits. For

example, if there were social data attached to a property-parcels layer, one could get estimates of how many people would be directly affected by different sea-level rise scenarios. Additionally, if property prices were included in the attribute table of the property-parcels layer, the total economic value of the recession impacts could be calculated.

Improvements: field-based sampling

1. Depending on the size of the study area, resources and time available, the ideal application of the coastal recession model is to do across-shore transect profiling instead of using virtual transects. In this way, the accurate position of the beach features can be mapped with differential GPSs, and the profile elevations can be determined using land surveying equipment (*e.g.,* theodolite and a measuring staff). Owing to the dynamic nature of the beach, this would have to be repeated temporally (Appeaning Addo *et al.*, 2008), taking the different summer (calm) and winter (storm) profiles into account.
2. Mapping the back-beach state is limited by the resolution of the satellite imagery available. For example, a beach may be backed by rock, but this might not be obvious from the imagery – particularly if there is cloud cover over the study area. This could be improved by field mapping.
3. One could cut out the conversion from intertidal beach slope to sediment grain size step by collecting sediment samples, and replicating this over time. It would provide a more accurate estimation of sand grain size and thus the most accurate slope of retreat as predicted by the Bruun rule.

Advantages of coastal modeling

A major advantage of GIS models is that one can create virtual coastlines, allowing visualization on computers and in virtual reality theatres, as explored by Brown *et al.* (2006). This can be an emotive way to gain public support for coastal realignment, but it would necessitate accurate modeling. One critical component of developing such models is model validation with past or simulated data (Patt *et al.*, 2005). Whilst acknowledging this as a fundamental process in the development of accurate, useful models, it was not covered in this chapter. Chapter 5 is dedicated to testing the coastal recession model.

Conclusion

The use of predictive models to aid proactive management interventions is a topic of much debate. Some believe the beach is too dynamic and unpredictable to model accurately in the face of so much uncertain change (Pilkey & Thieler, 1992; Pilkey *et al.*, 1994; Cooper & Pilkey, 2004b; Pilkey & Cooper, 2004) and should rather be modeled qualitatively (Cooper & Pilkey, 2004a). Others believe it is essential to make predictions from an expert perspective rather than leaving it up to policy-makers and lawyers (Cowell & Thom, 2006). I endorse this debate on coastal erosion and recession modeling, because I believe both sides have the same ultimate end. That is to find a tool (if it even exists, mathematical or not) that will predict the behaviour of a local beach with sufficient accuracy to allow confident implementation of proactive adaptation strategies. Without such a tool, the efficacy of coastal management plans to improve the resilience of beach ecosystems to the predicted impacts from climate change (*e.g.*, phased retreat by enforcing setback lines) will be compromised. Not only will this put society at risk, but it could cause significant loss of sandy beaches: a high-value ecosystem with a unique biodiversity, and many under-appreciated associated ecosystem goods and services.

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CHAPTER 5

COASTAL RECESSION MODEL VALIDATION: A COMPARISON BETWEEN THE IMPACTS OF A PRESS (SEA-LEVEL RISE) AND PULSE (STORM) DISTURBANCE FOR SANDY BEACHES

Abstract

The applicability of mathematical models to dynamic environments, like sandy beaches, is a contentious topic. Many of the arguments surrounding these models stems from their inability to accurately predict beach behaviour. One of the primary issues in model development is appropriate validation. Owing to the predictive nature of coastal models, validating models with real data of future states of the environment, rather than with simulation techniques, is almost impossible. However, a freak storm event in KwaZulu-Natal (KZN) provided an opportunity to test a coastal recession model with data that approximated a 2100 scenario of sea-level rise. In March 2007, a cut-off low pressure storm coincided with the high astronomical tide (HAT) during the Saros spring equinox tides, causing a rise in sea level of approximately 0.2 m, with an additional temporary 0.8 m wind and wave set up. The total rise in sea level was thus approximately 1.0 m. Using a geographic information system (GIS), the high water mark (used as a proxy for coastal retreat) from this storm was compared with the high water mark predicted under Bruun's Rule for a 0.2 m (low) and 1.0 m (high) sea-level rise. The results were also compared by geographic region (north, central and south) and beach morphodynamic type (dissipative, intermediate, reflective and rock). Predictions from the low scenario more closely matched coastal recession than the high scenario did in all cases, with the latter tending to over-predict the amount of recession. This pattern was expected owing to the short duration of the storm, the spatial and temporal variability of the wind and wave setup, and the insufficient time during the storm for new equilibrium profiles to establish. A comparison between the predicted and observed retreat per beach morphodynamic type revealed that the calibration had not been completely successful because the correlation between beach intertidal slope and sand grain size needed to be based on a wider range of beach morphodynamic types, especially for dissipative beaches. This was confirmed in the regional results, where the central beaches – the beaches used in the model calibration – showed the most accurate retreat

predictions with the least variation. It was concluded that, given the available accuracy of the data, the model generally performed well.

Introduction

Developing ecological models that can provide accurate predictions suffers a major obstacle: validation (Gardner & Urban, 2003; Araújo *et al*., 2005a; Araújo *et al*., 2005b). Modelers are forced to use techniques, such as hindecasting (*e.g.,* List et al., 1997; Miller & Dean, 2004), bootstrapping or jack-knifing (Efron & Gong, 1983) of existing data in order to test their models. In light of the expected impacts from global climate change (IPCC, 2007), downscaling and assessing localized impacts is vital. This will empower authorities to reduce risk to human life by being prepared. In addition, proactive management of currently stressed systems will aid in maintaining ecosystem goods and services, and the socio-economic benefits associated with them, and also in conserving biodiversity and habitats. Proactive management can increase the resilience and adaptive capacity of ecosystems and ensure sustainability into the future. However, effective implementation of such management will rely heavily on accurate predictions.

Many questions have been raised regarding the applicability of mathematical models to highly dynamic systems like beaches (Lowenstein, 1985; Pilkey & Thieler, 1992; Pilkey *et al*., 1993; Pilkey *et al*., 1994; List *et al*., 1997; Cooper & Pilkey, 2004a, 2004b; Pilkey & Cooper, 2004; Davidson-Arnott, 2005; Pilkey & Cooper, 2006). Certainly, there are still several aspects of this ecosystem that we just do not understand yet, like beach connectivity for example (McLachlan & Dorvlo, 2007). Some scientists believe that the behaviour of a beach in response to different scenarios of sea-level rise or management interventions cannot be modeled mathematically, and a qualitative approach should be taken instead (Cooper & Pilkey, 2004a). The question of determining future beach behaviour is further challenged by the uncertainty associated with many of the climate-change predictions themselves (Reilly *et al*., 2001). The result is much debate and scepticism over the accuracy of predictions of shoreline retreat (Cowell & Thom, 2006; Cowell *et al.*, 2006; Pilkey & Cooper, 2006; Cooper & Pilkey, 2007). This is further fuelled by the limited validation and inability of the models to hindecast previous states of the coast (*e.g.,* List *et al*., 1997). In Chapter 4 of this dissertation, a GIS-based model was derived from the existing Bruun rule (Bruun, 1962) and was used to predict recession for the KwaZulu-Natal (KZN) coastline. In light of the debate above, how confident can coastal managers be that the predictions made using this model represent realistic future states of the coast?

It is rare that nature provides us with a glimpse of what environmental conditions might be like in the future. However, we were provided with a unique opportunity to test the accuracy of a coastal recession model against an event that approximated a “2100 scenario”, rather than having to validate it using artificial simulation techniques. In this way, site-specific validation of a model that was derived for KZN can provide valuable information for the predicted future of this coastline and the accuracy of extrapolated scenarios.

The late summer months of 2007 were prominent ones for the KZN coastline. Tropical cyclone Dora combined with a mid-latitude cyclone from the south, producing waves of 2 - 3 m that hit KZN on 11 – 13 February (Smith *et al*., 2007b). Cyclone Gamede moved towards Madagascar a fortnight later, where it turned south, degraded into an extra-tropical depression and remained off the east coast of KZN from 1 – 6 March (Mather, 2008). Waves of 2 - 4 m hit KZN from an easterly direction during this time. The impact of these waves was great enough to open the St Lucia estuary mouth, which had been closed for 7 years prior to this event (N. Carrasco, 2008, pers. comm,[10]). The combined result of these two cyclones, Dora and Gamede, was to reduce the amount of sediment on the beaches across KZN to the point where many of them were sand-starved (Smith *et al*., 2007b). This set the scene for greater destruction to come.

High tides had been predicted for 2007 as early as September 2006 (Mather, 2008). This is because the Saros equinox spring tide was predicted to occur in March 2007. Every 18.6 years, the sun, moon and earth are in perfect alignment, which causes the greatest gravitational pull on the earth’s oceans and hence the greatest tides (Smith *et al*., 2007a; Mather, 2008). This is known as the High Astronomical Tide (HAT). During this time, the sea level rose by approximately 0.2 m (Mather, 2008). However, this event also coincided with a cut-off low pressure storm off the east coast of KZN: a frontal low pressure came from the south and became blocked south-east of East London by two high pressure cells on 18 March (Mather, 2008). This cut-off low intensified and its central pressure dropped below 996 hPa (Mather, 2008). This created steep pressure gradients and thus, very strong south-westerly winds of between 40 – 45 knots (Smith *et al*., 2007b). Winds of this

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magnitude, combined with the 450 km fetch, caused waves of 8.5 m on average (14 m maximum) to pound the KZN coast, peaking in the early morning of 19 March (Smith *et al*., 2007a; Smith *et al*., 2007b). The orientation of the coastline (SSW-NNE) meant that the waves (coming from a SSE direction) hit the coastline perpendicularly, thus the wave energy struck with full force (Smith *et al*., 2007a; Smith *et al*., 2007b). By 20 March, conditions had subsided, and waves were reduced to approximately 3 m (Mather, 2008).

The effect of this "perfect storm" on the KZN coast was dramatic, with repair bills of up to R 1 billion (Smith *et al*., 2007b). Buildings suffered great damage, with some even collapsing; pathways, promenades and roads were washed away; the railway line on the south coast was broken in several places; and infrastructure, *e.g.,* sewerage pump stations, was damaged (Fig. 5.1 below). By comparison, undeveloped beaches showed little evidence of the storm impacts (Fig. 5.2 below). From an ecological perspective, a tremendous amount of sediment was eroded from the beach – the eThekwini coast alone lost 3.5×10^6 m^3 of sand (Smith *et al*., 2007b). Some of the sediment was washed too far offshore to permit its return during calm conditions. The high water mark retreated temporarily by 10 - 30 m in some places (Smith *et al*., 2007b).

The wind and wave set up from the storm was 0.8 m (Smith *et al*., 2007a). Thus, when combined with the HAT (0.2 m), the sea level was approximately 1.0 m higher than usual, at 2.79 m Chart Datum (CD) compared to the usual average at 1.8 m CD (Smith *et al*., 2007a). In Chapter 4, the coastal erosion model was run for three scenarios: 0.2 m; 1.0 m; and 1.8 m of sea-level rise. This equates to: a low scenario of sea-level rise, without a storm; either a low scenario of sea-level rise with a storm, or a high scenario of sea-level rise without a storm; and a high scenario of sea-level rise with a storm. The scenarios representing storm effects could even be considered to be conservative, because it is considered likely that storm frequency and intensity will increase in the future. If the coastal erosion model is correct, then the predictions made for the 1.0-m scenario should approximate the retreat experienced during the March storm.

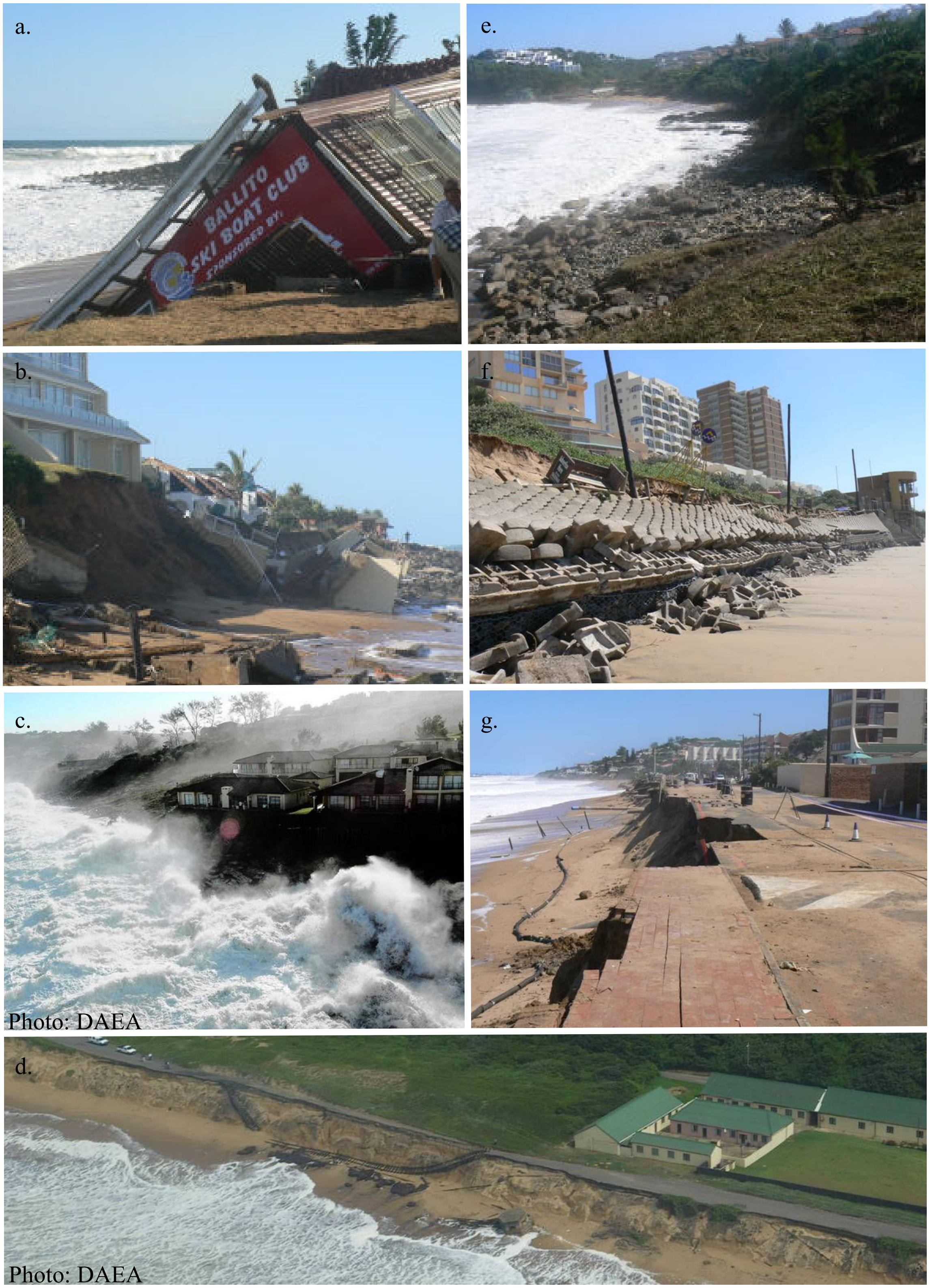

Figure 5.1. Photographs of the damaged cause by the March 2007 for the KZN coastline taken on 20 March 2007. (a) The Ballito Ski Boat Club clubhouse washed away as the bank in front of it eroded; (b) the

swimming pool in front of a block of luxury holiday flats in Ballito collapsed from erosion and wave impacts; (c) big waves at Tinley Manor pounding into the coastline (source: DAEA – Department of Agriculture and Environmental Affairs); (d) road at the Bluff crumbled (source: DAEA – Department of Agriculture and Environmental Affairs); (e) Thompson's Bay – a sandy beach eroded down to the bedrock; (f) loffelstein wall at the Umhlanga Rocks main beach fell to pieces; (g) road at Umdloti was badly damaged, which trapped some residents in their houses or apartments because it was the only vehicle access to this residential area.

Figure 5.2. A photograph of the Mtunzini Beach, just south of the launch site, showing significantly less damage from the March storm compared to Fig. 5.1 above. At this beach, the only evidence of the storm, was more than usual debris had washed up onto the beach, and there was some minor erosion at the dune base. Photograph taken: 21 March 2007.

The March storm conditions were experienced as a short pulse event, and thus the coast would not have reached an equilibrium point. Although beach profiles had been significantly altered, case studies like the Amanzimtoti and Kelso beaches showed that the aftermath of the storm event required further erosion and retreat in order to re-attain a new offshore equilibrium profile (Breetzke *et al.*, 2007; Mather & Vella, 2007). In these cases, the Amanzimtoti beach eroded landwards by approximately 90 m (Figure 5.3) and the Kelso beach, 78 m, which caused much concern and emergency management interventions (Breetzke *et al.*, 2007; Mather & Vella, 2007). This in itself highlights the need for accurate predictions of the future state of the coast so that management can be proactive and carefully planned, rather than reactive, which has the potential to cause further damage rather than resolve the problem.

Figure 5.3. Photographs of the Amanzimtoti beach, showing the same locality (a) before (February 2007) and after the storm and subsequent erosion (July 2007). Source: East Coast Radio News Watch website: http://blog.ecr.co.za/newswatch/?p=283.

The aim of this chapter is to test the coastal recession model developed in Chapter 4 with data from a real event that approximates a 2100 scenario of sea-level rise. In order to perform this test, the predicted high water mark, as estimated by the coastal erosion model for scenario R1 (0.2 m sea-level rise, hereafter, low scenario) and R2 (1.0 m sea-level rise, hereafter, high scenario) will be compared with the observed high water mark of the March 2007 storm. The high water mark was considered to be the most simple, measurable proxy for coastal recession, so the concepts of high-water mark advancement, retreat and recession are used synonymously in this chapter. Additional comparisons were made between the predicted and observed retreat per beach morphodynamic type and per region to test the calibration and overall performance of the coastal recession model.

Materials and methods

A polygon shapefile of the high water mark during the March storm was created in ArcGIS 9.2 (ESRI) by examining a series of oblique aerial photographs of the KZN coastline that were taken one month after the storm (by Roddy Ward, obtained from EKZNW). This was based on several features, namely: debris that had been washed up; erosion that had cut into dunes; and damage to coastal property. At least one of these features was applicable on a site-by-site basis. While recovery efforts on the part of municipalities were immediate, there was still evidence of where the high water mark had been during the storm. However, the high water mark as estimated by the process described above was lower at some sites than the actual high water mark during the event (personal observations). For example, the estimated high water mark along the Golden Mile in eThekwini was the wall backing the beach but the observed high water mark went well beyond that, with water flooding into restaurants and car parks behind the wall. This error was not corrected for because the precise location of the high water mark was not known for the entire coastline, and correcting some areas and not others would bias the results. Nevertheless, it should be noted that the high water mark for the storm as used in this chapter is a conservative estimate in some cases.

The coastal recession model shapefile for the low scenario was opened in ArcGIS 9.2 (ESRI) and overlaid with the March storm high water mark layer. The distances between the original high water mark and the model-predicted high water mark, and between the original high water mark and the March storm high water mark were measured for all the transect points. These values were used to determine the average percentage attainment of the model-predicted high water mark by the storm, *i.e.,* giving an indication of how accurate the predictions were for a 0.2 m rise in sea level. This was repeated with the high scenario.

A pair-wise Wilcoxon signed ranks test was performed in SPSS 15 to determine if there was a significant difference between the predicted high water mark advancement and the observed March storm high water mark advancement for both the low and high scenarios (Kolmogorov-Smirnov test, $p < 0.001$ for all datasets and residuals). A pair-wise Wilcoxon signed ranks test was performed to test if there was a significant difference between the low- and high-scenario predicted and observed recession per beach morphodynamic type (Kolmogorov-Smironov test: $p < 0.05$ in some cases when data were split per beach morphodynamic type, per recession scenario). This would give some indication of how accurate the beach morphodynamic type calibration was. Furthermore, because the storm hit from the south of the province, the impacts should be less in the north compared to the central and southern regions (see Chapter 2 for details on the regions). Coastal recession was thus compared per region using a pair-wise Wilcoxon signed ranks test (Kolmogorov-Smironov test: $p < 0.05$ in some cases when data were split per coastal region, per recession scenario).

Results

Overall model performance

There was no significant difference between the observed coastal recession from the March storm and the predicted low scenario (Fig. 5.4) of a 0.2 m rise in sea level (Wilcoxon signed ranks test: $Z = -1.222$, $p = 0.222$). However, there were cases where the observed March storm high-water mark was not even reaching the current average high water mark. For the high scenario of a 1.0 m rise in sea level, the observed advancement of the high water mark was significantly different from predicted (Wilcoxon signed ranks test: $Z = -14.056$, $p < 0.001$), with Figure 5.4 indicating that the predicted retreat was significantly higher than observed.

Coastal Regions

There was no significant difference between the predicted and observed coastal recession in the northern region for the low scenario (Wilcoxon signed ranks test: $Z = -1.115$, $p = 0.265$). The central beaches under-predicted retreat for the low scenario (Wilcoxon signed ranks test: $Z = -5.465$, $p < 0.001$), while the southern beaches significantly over-predicted retreat (Wilcoxon signed ranks test: $Z = -3.620$, $p < 0.001$). All regions in the high scenario significantly over-predicted coastal recession (Wilcoxon signed ranks test: $Z = -7.703$ (north); -5.870 (central); -9.832 (south), $p < 0.001$ in all cases) (Fig. 5.5).

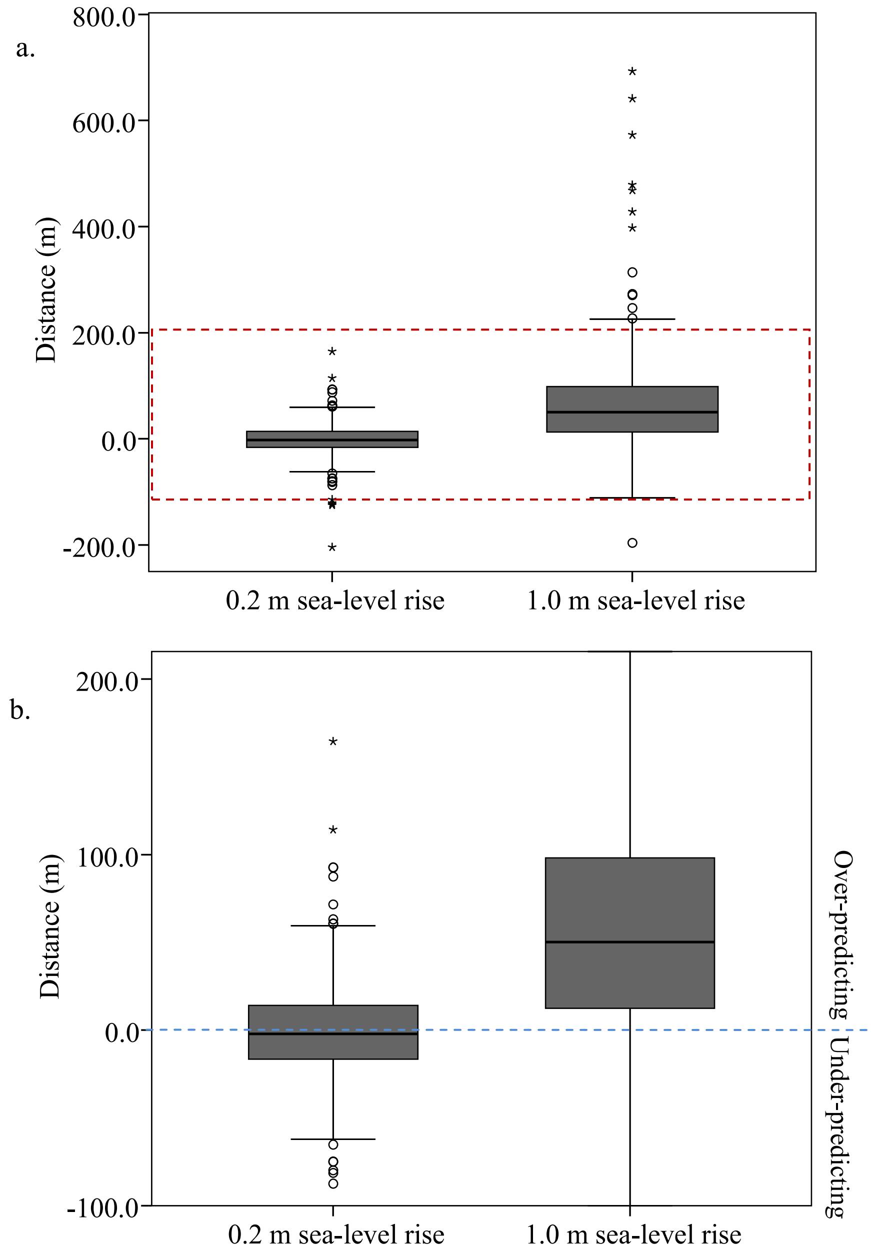

Figure 5.4. Normalised pairs of data showing the difference between the predicted (modeled) and observed (consequence of the March storm) distance of retreat (m) for a low (0.2 m) and high (1.0 m) scenario of sea-level rise (n = 360). The red dashed box in Fig. 5.4a is shown as enlarged area in Fig. 5.4b so that the differences between scenarios can be visually determined, whilst still having an appreciation for the amount of variation in the data. The box represents the 50 percentile, whiskers are the upper and lower 25 percentiles, and the black line in the box is the mean. Values above zero indicate the model is over-predicting retreat and values below zero indicate where the model is under-predicting retreat.

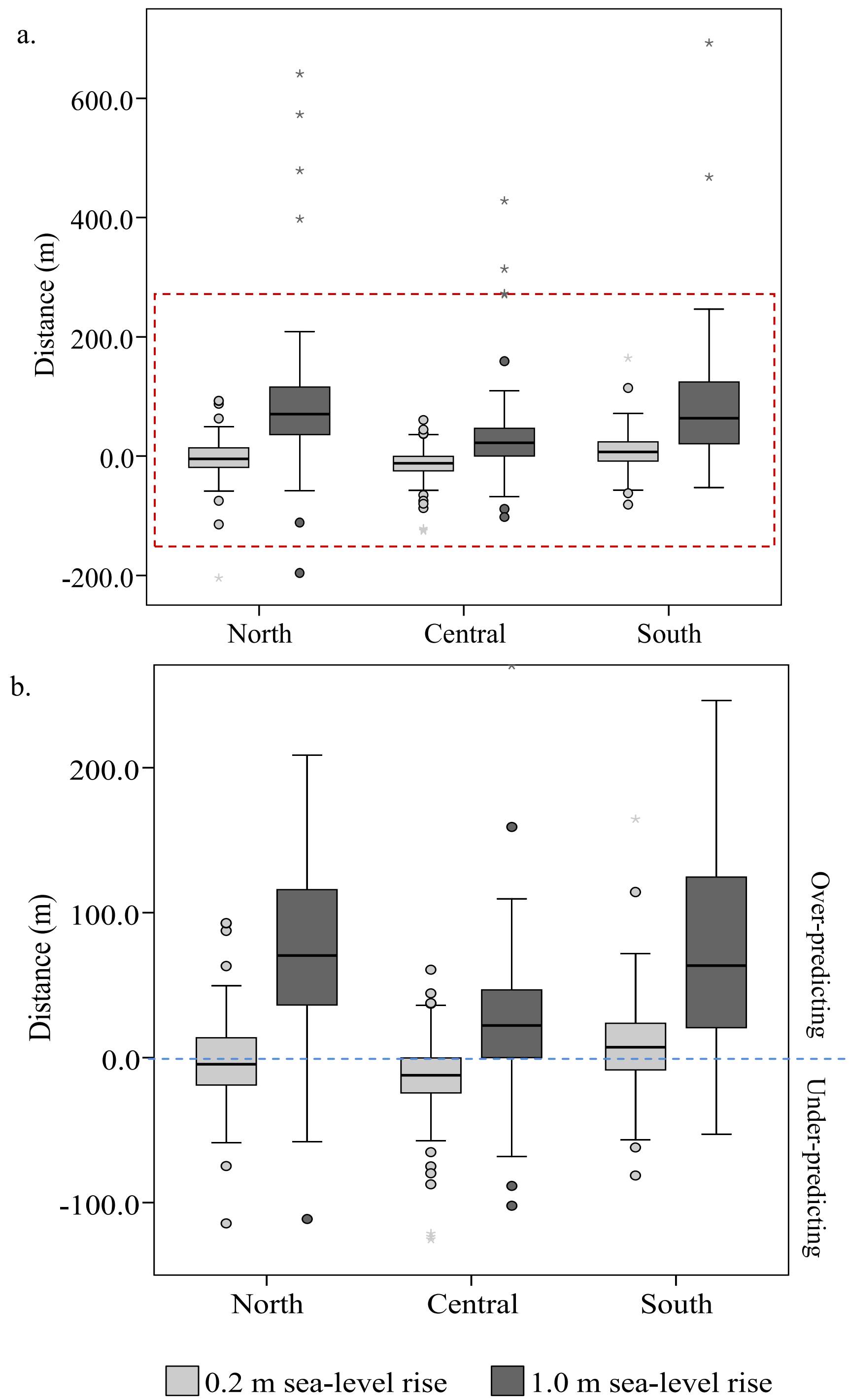

Figure 5.5. Normalised pairs of data showing the difference between the predicted (modeled) and observed (consequence of the March storm) distance of retreat (m) for a low (0.2 m) and high (1.0 m) scenario of sea-level rise, per coastal region (Northern beaches: n = 97; Central beaches: n = 111; Southern beaches: n = 152). The red dashed box in Fig. 5.5a is shown as enlarged area in Fig. 5.5b so that the differences among scenarios

and regions can be visually determined, whilst still having an appreciation for the amount of variation in the data. The box represents the 50 percentile, whiskers are the upper and lower 25 percentiles, and the black line in the box is the mean. Values above zero indicate the model is over-predicting retreat and values below zero indicate where the model is under-predicting retreat.

Beach morphodynamic type

The only beach morphodynamic type that had no significant difference between the predicted and observed coastal recession was the intermediate beaches for the low scenario (Wilcoxon signed ranks test: $Z = -0.990$, $p = 0.322$). All other beach types, in both the low and high scenarios, showed significant differences between the predicted and observed coastal recession. For the low scenario, coastal retreat was significantly under-predicted on dissipative beaches (Wilcoxon signed ranks test: $Z = -3.005$, $p = 0.03$) and reflective beaches (Wilcoxon signed ranks test: $Z = -2.148$, $p = 0.032$), and over-predicted on rocky beaches[11] (Wilcoxon signed ranks test: $Z = -3.013$, $p = 0.03$). For the high scenario, coastal recession was over-predicted in all cases (Wilcoxon signed ranks test: $Z = -3.422$ (dissipative); -9.697 (intermediate); -4.609 (reflective) and -8.005 (rock), $p < 0.001$ in all cases) (Fig. 5.6).

In terms of the predicted retreat distances, intermediate beaches have the most predicted retreat, followed by reflective beaches, dissipative beaches and the least retreat is predicted for rocky beaches, based on mean values. The observed retreat, however, showed most retreat for the dissipative beaches, and least retreat for reflective beaches (Fig. 5.7).

[11] Rocky beaches refer to beaches where there was more rock than sand on the beach, admittedly not strictly a beach morphodynamic type, but was included in the classification for the purposes of this analysis.

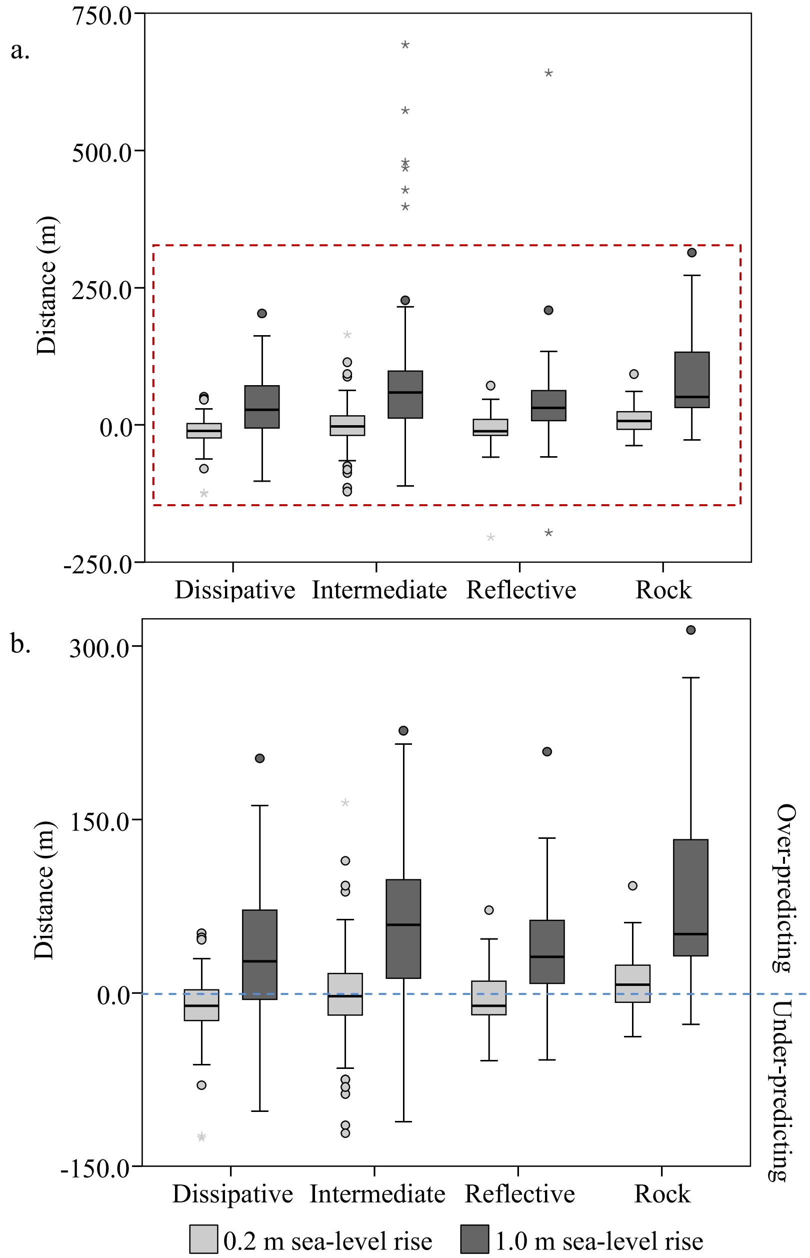

Figure 5.6. Normalised pairs of data showing the difference between the predicted (modeled) and observed (consequence of the March storm) distance of retreat (m) for a low (0.2 m) and high (1.0 m) scenario of sea-level rise, per beach morphodynamic type (Dissipative beaches: n = 53; Intermediate beaches: n = 161; Reflective beaches: n = 50; Rocky beaches: n = 88). The red dashed box in Fig. 5.6a is shown as enlarged area in Fig. 5.6b so that the differences among beach morphodynamic types and scenarios can be visually determined, whilst still having an appreciation for the amount of variation in the data. The box represents the 50 percentile, whiskers are the upper and lower 25 percentiles, and the black line in the box is the mean.

Values above zero indicate the model is over-predicting retreat; values below zero indicate where the model is under-predicting retreat.

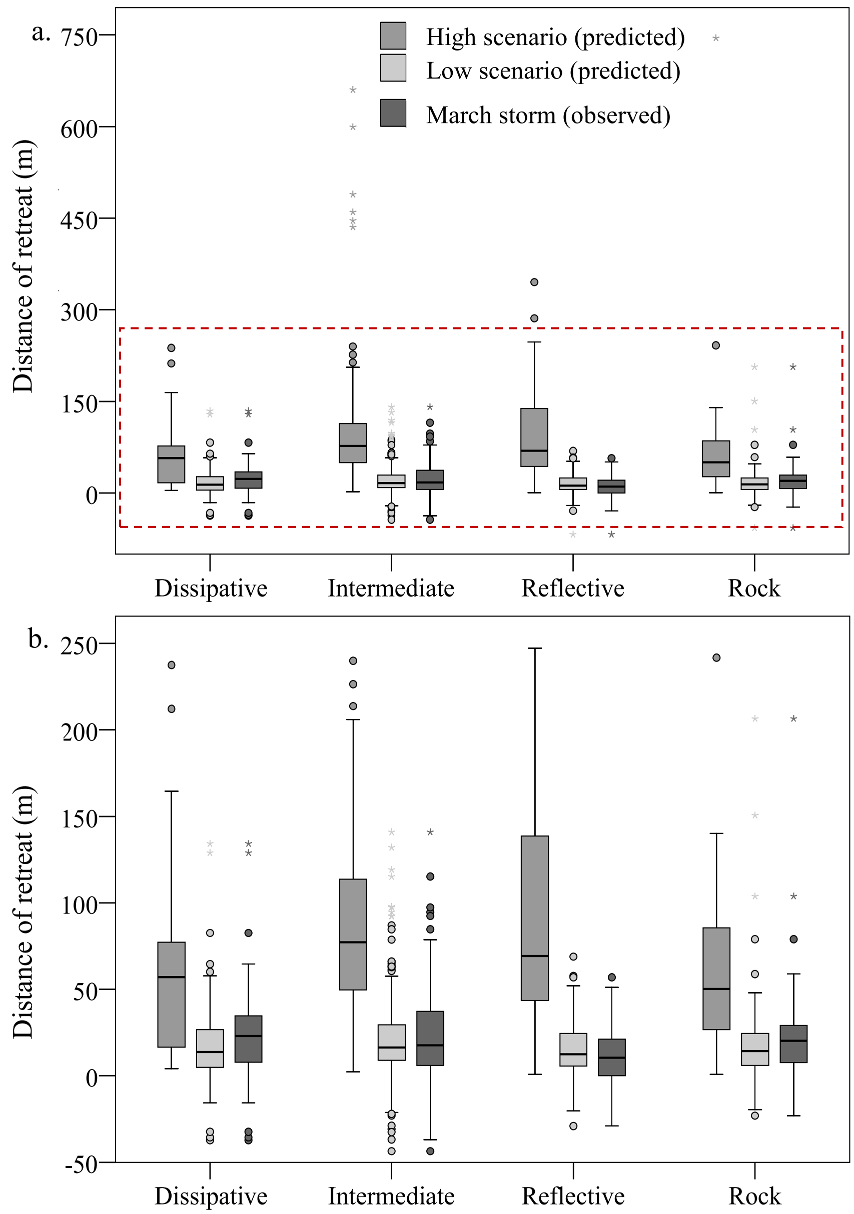

Figure 5.7. Comparison of the amount of retreat (m), per beach morphodynamic type, predicted by a coastal recession model for two scenarios (low scenario = 0.2 m sea-level rise; high scenario = 1.0 m sea-level rise) and observed retreat from a storm event that approximated a 1.0 m rise in sea level (Dissipative beaches: n = 53; Intermediate beaches: n = 161; Reflective beaches: n = 50; Rocky beaches: n = 88). The red dashed box in Fig. 5.7a is shown as enlarged area in Fig. 5.7b so that the differences among groups can be visually

determined, whilst still having an appreciation for the amount of variation in the data. The box represents the 50 percentile, whiskers are the upper and lower 25 percentiles, and the black line in the box is the mean.

Discussion

Overall model performance

It is difficult to assess the exact performance of the model because of the local conditions that would have affected the advancement of the high water mark as a result of the storm. Factors such as fine-scale offshore bathymetry (which might affect how close the waves break to the shore, and thus the swash length up the beach), orientation of the coastline with respect to the direction of the waves (which would affect wave energy), local patterns of wind and wave setup (affecting wave height and sea level), and coastal development (which would have reflected wave energy and not permitted the maximum high water mark to be attained) would all have influenced the location of the high water mark during the storm, and thus affected the perceived accuracy of the model predictions. The analysis, therefore, is based on broad patterns.

The March storm peaked in intensity for, at most, two tidal cycles. During this time it can be assumed that the wind and wave setup was not uniform, either spatially or temporally, and thus that the rise in sea level would have been between 0.2 m and 1.0 m; likely closer to 0.2 m overall. In addition, the model is based on Bruun's rule, which assumes beaches to maintain equilibrium profiles as they retreat (Bruun, 1962). Case studies like the Amanzimtoti beach (Fig. 5.3), and a similar scenario at the Happy Wanderers beach in Kelso, are examples of the fact that beaches had not necessarily achieved new equilibrium profiles during the March storm (Breetzke et al., 2007; Mather & Vella, 2007). Thus it is expected that the observed retreat from the immediate effect of the storm, i.e., not taking post-storm erosion into account, will be lower than the amount of predicted retreat for the high scenario.

With all of these factors in mind, it would be of exceptional concern if there was no significant difference between the observed retreat from the storm and the predicted retreat for the high sea-level rise scenario. This would mean that the model was under-predicting the amount of retreat. Rather, the observed retreat should be expected to fall between the low and high predicted retreat scenarios.

Based on the assumption that the observed retreat should be closer to the low predicted scenario than the high predicted scenario, we can conclude that the model performed well overall. For the low scenario, the mean difference between the predicted and observed retreat was almost at zero. In terms of the high scenario, the majority of the data (50 percentile) had a difference between the expected and observed retreat of approximately 10 – 95 m. The post-storm retreat at Amanzimtoti and Kelso (90 m and 78 m, respectively) fall within this limit, suggesting that the assumption that equilibrium profiles were not necessarily attained during the storm could hold true.

What is unacceptable, however, is the widespread inaccuracies in predicted retreat compared to the observed retreat (as much as 750 m in some cases), and in the negative values of the observed retreat. The former inaccuracies are likely to be a result of the limited accuracy of the method used to estimate intertidal beach slope. Clearly a 25 m x 25 m digital elevation model (DEM) is not sufficient for accurate coastal modeling, and finer scale mapping is required. However, data availability is a limiting factor and could not readily be overcome in this project. Regarding the values of negative observed retreat, this implies that the high water mark during the March storm was lower than the current average high water mark. It is very unlikely that this was true, especially for so many cases (~18 %). This is indicative of digitizing errors and inaccurate estimation of the high water mark because of the limited resolution of the SPOT 5 satellite imagery.

KZN coastal regions

The model over-predicted retreat in the southern region for both the low and the high scenarios. There are three contributing factors to this trend. Firstly, the southern beaches are predominantly reflective and rocky (Chapter 2), and, as discussed below, the model does not perform well for rocky beaches because it tends to over-predict retreat. Secondly, the south coast is the most developed and the most armoured (Chapter 2), and thus the advancement of the high water mark in this region would have been impeded by the coastal developments. Thirdly, the topography in the south region is fairly steep in sections, *e.g.*, at the Bluff, just south of the Durban harbour, and it would have been difficult to attain equilibrium profiles during the short period that the storm struck. This is evident in the examples of the Amanzimtoti and Kelso beaches described above – both south coast beaches.

It is likely that the central beaches are the ones that the model most accurately predict retreat for. This is because retreat for the low scenario was under-predicted and the high scenario was over-predicted, but the point at which there was no difference between the predicted and observed retreat crossed the 50 percentile of both scenarios. This was the only region that showed this trend. The model was calibrated based on data from the central beaches, and thus it is likely that this is why the model predicted retreat most accurately for this region. It appears that retreat in the northern region was predicted satisfactorily because retreat for the low scenario was under-predicted (by 4.09 %), and over-predicted (by 87.54 %) for the high scenario, based on means.

Beach morphodynamic type

The rocky beaches were the only beach morphodynamic type that over-predicted retreat for both the low and the high scenarios. This indicates that the model is not necessarily suitable for predicting retreat on hard coastlines (rock), as opposed to soft coastlines (sand). The coastal recession model should thus be recalibrated to include a term in the equation for rock, or alternatively, a separate model should be developed for predicting retreat on rocky beaches.

For all the sandy beach morphodynamic types, retreat was under-predicted in the low scenario and over-predicted in the high scenario, indicating satisfactory model performance. Based on the actual values of predicted retreat, however, it is evident that the calibration may not have been completely effective. Dissipative beaches are more susceptible to erosion and inundation than other beach morphodynamic types because the fine sand is more easily eroded, and the flat intertidal slopes equate to more inundation (Short, 1999; Defeo & McLachlan, 2005). Reflective beaches, with coarse sand and steep slopes, thus represent the other end of the scale because they are the beach morphodynamic type that is least eroded and inundated (Short, 1999; Defeo & McLachlan, 2005). The coastal recession model in Chapter 4 was calibrated by beach morphodynamic type by sequentially correlating intertidal slope, sediment grain size and the slope of Bruun's line of retreat. Theoretically, the beaches with flattest slopes would confer values for the finest sand and thus, the farthest retreat. While this trend is evident in the observed coastal recession per beach morphodynamic type, it does not hold for the predicted retreat. If one considers the trends across beach morphodynamic type for both the predicted low and high scenarios, the amount of retreat on intermediate beaches is greater than that on reflective beaches (based on mean values). Still greater recession should be predicted for dissipative beaches, but the model predicts less retreat. The normalized pair for dissipative beaches showed that, for the low scenario, retreat was being under-predicted. Based on beach ecology theory, it is evident that the dissipative beach retreat is being under-predicted, not because the observed retreat approximated a scenario between the low and high scenarios, but because the model does not predict enough retreat for dissipative beaches.

There are two plausible explanations for this short-coming in the model. Firstly, the DEM does not have sufficient resolution to accurately interpolate beach slope for dissipative beaches – the flattest beach morphodynamic type, thus inaccurate retreat predictions would have resulted. Secondly, when calculating the correlation between beach slope and sand grain size, the beaches that were used were predominantly intermediate and reflective beaches. There was concern at the time that the range of beaches would not confer an accurate enough correlation, but it was not considered to be concern enough to merit further field work. In retrospect, this might have been incorrect. However, this is not a challenging problem to overcome: it will merely mean changing a single parameter in the model once a more accurate correlation between beach intertidal slope and sand grain size has been established. The model should then be tested again to determine if this correction has resolved the disparity sufficiently. It is likely that a combination of these short-comings in the model is the reason for its inability to predict retreat on dissipative beaches with sufficient accuracy.

Conclusion

The coastal recession model performed satisfactorily, although there are two aspects of the model that require refining. Firstly, the limited resolution of the GIS data (DEM and satellite imagery) is likely to be the source of the high variation in the predictions. There were a number of very significant outliers in the data, which is not acceptable for coastal management purposes. These outliers were not attributed to any particularly features of the coast that could be considered more vulnerable to retreat; in almost all cases, the outliers lay between two transects that predicted retreat within an acceptable range for the respective scenarios. Secondly, the calibration of the model by beach morphodynamic type needs to be based on a correlation that spans a wider range of beach morphodynamic types. Once these corrections are made, the model would have to be tested again to determine if more accuracy has been conferred, and that it is suitable as a predictive management tool.

The results of this study showed that the landward advancement of the high water mark, a proxy for landward recession, from a single storm can approximate a mid-range scenario for 100 years of predicted sea-level rise. Given that the current rate of sea-level rise is tracking the high end of the IPCC predictions (Rahmstorf, 2007; Rahmstorf *et al.*, 2007) as opposed to a mid-range scenario, the everyday wave-climate in 2100 could be worse than was experienced during the March storm. Based on the observed response of the coastline to the March storm and the significant damage this pulse event caused, it is clear that the current state of the KZN coast will not be sustainable 100 years from now. This, particularly if conditions are worse than what they were during the March storm (which they likely will be, even if just temporarily during pulse events), and certainly the developed beaches are not prepared for climate change. What is of additional concern for coastal management is the superimposition of the two disturbances: intense storms coupled with sea-level rise. Their combined, synergistic erosive force for beaches that are currently sand-starved represents a potential coastal crisis that is arguably already manifesting itself in KZN. It is crucial that coastal management and proposed coastal developments both think beyond tomorrow. Saving the sandy beach ecosystem, concomitantly protecting human lives and reducing financial burdens from repair and defence bills, will require sensibly planned, proactive management.

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CHAPTER 6

THE ECOLOGICAL IMPLICATIONS OF SEA-LEVEL RISE AND STORMS FOR THE KWAZULU-NATAL BEACHES: A WAY FORWARD FOR MANAGEMENT

Introduction

Owing to the aesthetic beauty and economic incentives of coastlines, sandy beaches are a site of many diverse activities, ranging from recreation to military and defence (McLachlan & Brown, 2006); subsistence harvesting (Kyle *et al.*, 1997) to conservation (Defeo *et al.*, 2008). Subsequently, beaches have a number of stakeholders, each with their own needs for coastal management plans. This proves to be problematic because many of these user group requirements can be in conflict with one another: clearly beach driving and boat-launch site requirements are in strong opposition to the requirements for turtle conservation, for example. Conflicts also arise between individuals of user groups, *e.g.,* between fishermen and surfers, particularly around piers. These conflicts are even more evident when development and permanent hard engineering structures compromise ecosystem integrity by changing sand budgets, and also compromise a tourist's experience of nature by diminishing the sense-of-place associated with pristine beaches. Thus, there needs to be some way to reconcile these differences such that the needs of all user groups are satisfied, whilst still preserving the integrity of sandy beaches as ecosystems.

The contemporary threats to beaches are additional issues for coastal management. These threats include coastal development pressures, beach driving, erosion and pollution, among others (Brown & McLachlan, 2002; Schlacher *et al.*, 2006; Schlacher *et al.*, 2007; Defeo *et al.*, 2008). Furthermore, the near- future predicted impacts of anthropogenically accelerated climate change (*e.g.,* IPCC, 2007), essentially just one of the myriad of stressors, urgently need to be included in management plans. This is important to ensure the persistence of sandy beaches and their concomitant processes, goods and services, and to ensure the protection of high-value coastal developments and their inhabitants.

With so many widely varying considerations, coastal management that can sustainably cater for all stakeholder demands, whilst meeting ecosystem conservation targets in a world of climate change, appears to be a daunting, virtually impossible task. Further, proactive management actions that can pre-empt disasters have the additional benefits of reducing total financial costs (Gibbs, 1984), and minimizing impact within the environment. Studies in the literature suggest that the most effective way of managing coastal ecosystems is through integrated coastal-zone management (ICZM) (Chemane *et al.*, 1997; Clark, 1997; Huang, 1997; Anker *et al.*, 2003; Cicin-Sain & Belfiore, 2005). This is defined as, "…*a governance system of managing multiple uses in an integrated way through the cooperation of government agencies at different levels of authority, with nongovernmental organizations and among different economic sectors*" (Cicin-Sain & Belfiore, 2005). This chapter examines practical and conceptual tools that, if coupled with ICZM, will (theoretically) ensure the conservation of sandy beaches into the future, in the context of the KwaZulu-Natal coastline.

The KwaZulu-Natal Beaches

Physical context

The KZN coastline is spatially heterogeneous, ranging from nearly untouched, pristine beaches with well-developed sand dunes, to compromised beaches that are intensively developed and visited by hundreds of thousands of tourists. Most of the coastline (91 %) has some form of natural habitat immediately behind the backshore beach. Of this natural land, nearly two-thirds is undeveloped, and a quarter is not over-developed (*i.e.,* has sparse or low development). Only 9 % of the coastline is highly to intensively developed; but more than half of this development (56 %) is armoured by either hard (*e.g.,* sea walls) or softer (*e.g.,* sand bags) coastal defences. Almost 80 % of all coastal development has its seaward boundary on the primary dune, which translates into a third of the primary dune extent along the KZN coastline being developed – this is essentially in the southern region, and in sporadic nodes in the central region. One must bear in mind, however, that 25 % of the coast is currently protected by the St Lucia and Maputaland Marine Reserves in the north region, and this area comprises the majority of the pristine, natural and undeveloped beaches in KZN.

The predominant beach morphodynamic type in KZN is intermediate (45 % of the coast), with approximately equal proportions of dissipative and reflective types (~10 % each) that are mostly found in the north and south of the province, respectively. Rock comprises a third of the coastline, with the majority of the rocky areas located in the south. On the basis of the distributions of these physical features of the coastline – development and beach morphodynamic type – it can be broadly divided into three regions: north central and south.

Biological context

The KZN beaches were shown to conform to the paradigm in sandy beach ecology that species richness increases from reflective to dissipative beaches (McLachlan *et al.*, 1995; McLachlan *et al.*, 1996; Defeo & McLachlan, 2005; Lercari & Defeo, 2006; McLachlan & Dorvlo, 2007), as is predicted by the swash exclusion hypothesis (McLachlan *et al.*, 1993). This means that for conservation planning purposes, beach morphodynamic state can be used as a proxy for biodiversity. However, there is a biogeographic break at Cape Vidal in the northern region. While we might claim to have 25 % of the KZN coastline protected by marine protected areas (MPAs: the St Lucia and Maputaland Marine Reserves), these reserves are protecting beaches only in the Delagoa bioregion. There are 28 macrofauna species in the Natal bioregion that are not formally protected, apart from in the comparatively small Trafalgar/Mpenjati MPA, which barely comprises 1 % of the KZN coastline. The northern region is also where the majority of the KZN dissipative beaches are located. Theoretically, dissipative beaches seed reflective beaches and thus it could be argued that the protected beaches in the north region will seed the more reflective beaches in the rest of the province. However, this is not true because of the south-north direction of the currents and longshore drift, which means the beaches in the north will have very little influence on the southern beaches. Thus, there is a need for the proclamation of MPAs in the central and southern regions, based on systematic conservation planning guidelines, discussed below.

While this dissertation did not focus on ecosystem goods and services, it is still recognized that this is an essential component of coasts. Martínez *et al.* (2007) highlights the important ecosystem goods as:

1. Food for humans and animals
2. Salt, mineral and oil resources
3. Construction materials

4. Biodiversity, including a genetic stock that could have applications in medicine and bioprospecting

Defeo *et al.* (2008) and Schlacher *et al.* (2008) give a comprehensive list of the ecosystem services provided by sandy beaches:

1. Sediment storage and transport
2. Wave dissipation and associated buffering against extreme weather events
3. Dynamic response to sea-level rise (within limits)
4. Breakdown of organic materials and pollutants
5. Water filtration and purification
6. Nutrient mineralization and recycling
7. Water storage in dune aquifers and groundwater discharge through beaches
8. Maintenance of biodiversity and genetic resources
9. Nursery areas for juvenile fishes
10. Nesting sites for turtles and shorebirds, and rookeries for pinnipeds
11. Prey resources for birds and terrestrial wildlife
12. Provision of scenic vistas and recreational opportunities
13. Supply of bait and food organisms
14. Functional links between terrestrial and marine environments

By implication, a loss in beach habitat (including the dunes in some cases) compromises these ecosystem goods and services, as well as the economic benefits associated with them. Coastal and marine ecosystem goods and services are valued at approximately US$21 trillion per annum, which is 70 % above the terrestrial system (Krelling *et al.*, 2008). The importance of conserving coastal habitats speaks for itself.

Threats to beaches

There are a number of threats to sandy beaches and coastal ecosystems worldwide. These threats include: storms; disruption of sand transport; beach nourishment and bulldozing; erosion; global climate change; population pressures; pollution; beach driving; biological invasions; mining; exploitation (Brown & McLachlan, 2002; Schlacher *et al.*, 2006; Schlacher *et al.*, 2007; Defeo *et al.*, 2008). For a recent, comprehensive review on the threats to sandy beaches, the reader is referred to Defeo *et al.* (2008). This dissertation, however, focused on the threat of climate change to sandy beaches, particularly the implications of sea-level rise and storms.

Sea-level rise

Data from the last few decades have shown that the sea level off the Durban coast (and by inference, the KZN coast) is rising by 2.7 mm every year (Mather, 2007). Global trends suggest that the rate of sea-level rise is accelerating (Church, 2001; Church & White, 2006; Rahmstorf, 2007; Rahmstorf *et al.*, 2007) and thus it could be expected that the rate of sea-level rise for KZN will also increase. The IPCC (2007) predict global sea-level rise to be between 18 cm and 59 cm by 2100, however, evidence from observational data suggests that these predictions are too low, and that a 1 m rise in sea level could be expected (Rahmstorf, 2007). This is not unlikely seeing that the current rise in sea level is following the upper limits of the IPCC Third Assessment Report (Houghton *et al.*, 2001; Church & White, 2006; Rahmstorf, 2007; Rahmstorf *et al.*, 2007).

The amount of predicted retreat for KZN in response to sea-level rise is greatest for the northern region, and comparable for the central and southern regions, with slightly more retreat predicted for the latter than for the former. From a conservation perspective, particularly turtle conservation, it is most fortunate that this northern region is undeveloped and thus, able to respond naturally to sea-level rise without compromising the sandy beach ecosystem. However, the coastal recession model used to calculate areas of retreat may have been under-estimating recession on dissipative beaches, and over-estimating it on reflective beaches because the calibration of the model might not have spanned a wide enough range of beach morphodynamic types.

The development scenario for the future of the coast is as important as the sea-level scenario, if not more important. Results in this study show that as the extent of development in the coastal zone increases, and its proximity to the beach decreases, the extent of development at risk of erosion impacts (and inundation in some cases) for any given sea-level rise scenario increases. By implication, the key to coastal management for sustainable coastlines will be to prohibit all future developments close to the beach, *i.e.,* behind suitable setback lines. Using the proposed 10-m elevation contour as that setback line will not protect all areas of the coast by 2100, even if the sea level rises by less than the currently observed rate. It is recommended that erosion-prone areas should consider a wider setback zone. Apart from the economic cost and potential social hazards, further justification for having setback lines rather than developing at will and subsequently defending with sea walls, is the fact that hard defences greatly reduce the area of the beach, both the backshore beach and the intertidal zone. Based on the literature, this will confer a loss of beach biodiversity (Dugan *et al.*, 2008).

Storms

Loss in beach habitat can also result from intense storms that erode certain beaches (without dunes) down to their bedrock. This was observed in part during the Sardinia Bay sampling in Port Elizabeth, and also as a consequence of the March 2007 storm in KZN, *e.g.,* at Thompson's Bay in Ballito. In this latter case, the previously sandy beach became completely devoid of sand and was a rocky outcrop for quite some time after the storm until the sand returned. It is likely that, in the short-term, all the macrofauna died at this beach. While we observed no outstanding changes in the macrofauna communities at Sardinia Bay following the large storm, the beaches there have a high perceived resilience. The beach is backed mostly by large sand dunes and there is nearshore reef that dissipates much of the wave energy before the waves reach the intertidal beach. The beach at the edge of the bay showed greater erosion from the storm because there was no reef to buffer the wave energy, and because the back beach has been modified from dunes into a car park. However, apart from reductions in overall abundance of macrofauna after the storm at this site, the community was still largely intact.

Storms are temporary disturbances, but the fauna are very well adapted to coping with changes in their dynamic habitat (McLachlan & Brown, 2006) and can generally survive through these events. However, storms will have their greatest impact where they are spatially superimposed over areas of high development, particularly beaches that are armoured with hard defence structures like sea walls. Observations of the March storm showed that erosion and perceived impact on the beach was far higher in the intensively developed areas compared to undeveloped areas. Perhaps of greatest concern will be the increased frequency at which intense storm events impact the coast. Already two thirds of the coastal disasters recorded annually are because of extreme weather events (Adger *et al.*, 2005), and this is predicted to increase (IPCC, 2007). Many of the beaches in KZN are at risk of being sand-starved because of river-catchment practices that reduce sediment movement through the system, *e.g.,* damming rivers, and mining sand (*e.g.*, Garland & Moleko, 2000). By removing the sand, possibly changing its grading at local sites, and changing offshore profiles, which in turn may influence the beach morphodynamic type, the combined action of sea-level rise and storms has the potential to cause shifts in sandy beach communities.

Coastal squeeze in KwaZulu-Natal

Although current trends show 9 % of the coastline is extremely developed and only about half of this is defended, a third of the province has development on the foredune, more than half of which is on the front half of the dune. Thus, it can be expected that a greater extent of the coastline will require defending in the near future as erosion threatens to compromise the integrity of the development, particularly in the south where most development is located. This then infers an increase in the proportion of the coast at risk of coastal squeeze and inundation. Additionally, this does not take future development into account. The more construction that occurs in the near-beach hinterland, the more beach area and associated biodiversity, ecosystem goods and ecosystem services are at risk of disappearing as sea-levels rise.

Motivation for conserving the KwaZulu-Natal beaches

Beaches contribute significantly to local (and national) economies through tourism (Kohler, 2005). In South Africa, tourism contributes more to the national gross domestic product (GDP) than gold (Kohler, 2007). Tourism has further been identified as a tool that can promote economic upliftment and reduce poverty in developing countries (Binns & Nel, 2002). This has particularly emerged in the literature regarding South African local economic development (Binns & Nel, 2002). In order to encourage tourism, it is important to meet the needs of the tourists. A study that examined the factors influencing human beach choice showed that a balance of developed and undeveloped beaches were required in order to satisfy people's diverse recreational-experience requirements (De Ruyck *et al.*, 1995). With its spatial heterogeneity, the KZN coast has scope for this – for now, at least.

The ecosystem goods and services relating to the coast in South Africa contribute 35 % to the GDP[12] (White Paper on Sustainable Coastal Development, 2000), and KZN is one of the country's four coastal provinces. There are also a number of under-appreciated services that do not contribute

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[12] South Africa's GDP in 2007 was US$ 283.071 billion (International Money Fund: www.imf.org)

directly to national economies, *e.g.,* shoreline protection from extreme weather events, mineralization of nutrients and water filtration. Furthermore, South Africa is a signatory state to the Convention on Biological Diversity in Rio de Janiro in 1992, and is thus obliged to fulfil its commitments to biodiversity conservation. Additionally, KZN is an important turtle nesting ground. Thus there is both economic and conservation motivation for maintaining as much of the KZN coast as possible.

A way forward

Sandy beach conservation encompasses more than just "saving the beach worms". Rather, it requires a holistic view that considers the three pillars of sustainable development: social, economic and environmental systems (Krelling *et al.*, 2008). Scale is also a fundamental aspect of coastal management, because the threats to and impacts on sandy beaches range in both temporal and spatial scales (Defeo *et al.*, 2008). Therefore, co-ordinated, local-scale management needs to be seated in a broader management strategy so that all coastal issues can be taken into account. It is thus suggested that the broad-scale objectives are met through systematic conservation planning (SCP) (Margules & Pressey, 2000); and local-scale objectives are met by making decisions within a conceptual framework that promotes resilience and adaptive capacity of social, economic and ecological systems, to attain sustainability.

Integrated coastal-zone management and systematic conservation planning: a solution for beaches

Manage functional units: maintain processes, maintain biodiversity

The only way all coastal goals can be met is if there is still a beach in the future. For this to occur, the first objectives for any coastal management plan must be maintaining beach processes that mainly relate to the sand, such as sediment supplies, erosion-accretion cycles and longshore drift. Essentially this means managing the littoral active zone as a single functional unit (McLachlan & Brown, 2006; Schlacher *et al.*, 2008). By implication, coastal management extends beyond the beach itself, and includes adjacent ecosystems, such as sand dunes and, although not strictly a component of the littoral active zone, estuaries because of their role in beach sediment budgets.

River catchment management strongly influences how much sediment arrives on the beach: damming and sand mining both reduce sand input from estuaries to beaches. Regulating development in the littoral active zone, particularly on the primary dune immediately behind the beach, is important because the traditional function of sand dunes is to act as a buffer to storm damage and as a store of sand that can replenish beaches during erosion events. Development in the littoral active zone blocks the dynamic movement of sand between the dune and beach, enhancing erosion impacts during storms. ICZM thus should not only include integrating the diverse stakeholder requirements for sandy beaches, but also coastal ecosystems themselves in order to maintain beach area, and thus its biota.

Systematic conservation plans for beaches

The second objective will be to design and implement a network of marine protected areas (MPAs) specifically for beaches, which could include features in adjacent systems that contribute to beach resilience to impacts, as seen in Chapter 3. Reserve determination is best performed by doing a systematic conservation assessment (SCA) (Knight *et al.*, 2006), that runs a specific objective function through simulated annealing software, such as Zonae Cogito, in combination with Marxan or C-Plan. The user can modify various parameters in the objective function, such as biodiversity targets, site connectivity rules, clustering of sites and multiple uses of the area, to achieve optimal results. The output is a recommended reserve network of conservation priority areas based on site irreplaceability, which achieves the conservation targets. If the targets are not sufficiently met, the input parameters can be modified until the output reserve network does meet the targets. Designing these MPAs should involve stakeholders from the outset (Roberts *et al.*, 2003; Wheeler *et al.*, 2008) to incorporate all their interests, because this has shown to improve community support and compliance in the MPA (Klein *et al.*, 2008). The key considerations of a SCA for sandy beach ecosystems are as follows:

1. Set planning units

For effective sandy beach conservation prioritization, the planning units of the SCA should be 2 km in length, because anything less than that is considered a pocket beach, and it has been shown that macrofauna diversity decreases as beaches get shorter than 2 km (Brazeiro, 1999). The across-shore extent of the planning units should be at least the width of the littoral active zone, possibly wider if salient features that would contribute to the MPA lie slightly removed from the littoral active zone, *e.g.,* shallow-lying rock or reef that would buffer wave energy and storm impacts that occurs further seaward than the littoral zone. If such features were rare or it was not feasible to have a broader study area, the salient features could be cross-tabulated into the littoral active zone planning units to boost habitat heterogeneity for example. Owing to the close linkages among the adjacent coastal ecosystems (surf, beach and dunes), a reserve that could couple a terrestrial and marine protected area would be ideal.

2. *Identify areas of exclusion*

There should be as much natural adaptive capacity as possible in the sites selected for conservation priority. This means that the planning units should be cross-tabulated with GIS layers of coastal development intensity and proximity to the coast, so that part of the objective function can be to exclude highly developed areas from site selection. Concomitant benefits of this will be to reduce financial implications, and conflict with stakeholders. For example, a motion to set aside coastal urban areas, such as Durban, Umhlanga Rocks or Ballito as MPAs for beaches, would be met with substantial resistance. This would be particularly problematic because equally suitable sites outside these urban areas are available, which have virtually no development and are not constrained by sea walls. These two features of the adjacent sites would: avoid the cost of dune reconstruction for the MPA; significantly reduce the inconvenience to the people that would be displaced from the immediate hinterland; and would reduce shifts in stakeholder use of developed beaches. For example, it would be impossible to run high-profile beach events like the Durban Beach Africa Festival if the Golden Mile was transformed to a pristine ecosystem without tourist amenities and the infrastructure to support the festival.

3. *Identify areas of ecological importance (adapted from the criteria in Roberts* **et al.,** *2003)*

a. Important ecological processes

Owing to the strong influence of the physical drivers on beach fauna communities (refer to Fig. 1.2 in Chapter 1), it is important to include ecological processes in objective function. If one site is particularly exposed and susceptible to storm damage for example, an equivalent site of lesser susceptibility should be chosen in preference for inclusion in a MPA. This does not mean compromising the conservation targets of beach morphodynamic types, and excluding dissipative beaches, which are generally more exposed than reflective beaches. Choosing the less susceptible site in this context refers to, for example, an option of including a beach of a certain morphodynamic type with either shallow lying bedrock or deeper lying bedrock. In this case, the beach with deeper lying bedrock should be given preference for conservation. This is because a beach with shallow-lying bedrock will not contribute to conservation if all the sand on the beach is removed with every storm, thereby causing mass-mortalities of the local fauna.

b. Biodiversity and biogeography

Established beach ecology theory states that groups of organisms can only live certain beach types as suggested by the swash exclusion hypothesis (McLachlan *et al.*, 1993). Additionally, owing to the temporal changes in beach morphology, it can be assumed that not all species are necessarily accounted for in once-off, “snapshot sampling”. Thus, for the purposes of a SCA, site-specific biodiversity can be inferred by beach morphodynamic type, where groups of animals, *e.g.,* isopods, molluscs, amphipods or polychaetes are assigned to the beach morphodynamic type that they are traditionally associated with. KZN has a marine biogeographic break at Cape Vidal, although the intertidal break was based only on rocky shore invertebrate and seaweed communities and did not consider beach fauna (Lombard *et al.*, 2004). Regardless of the specific locality of the break for sandy beach communities, the biodiversity mapping in Chapter 2 revealed a number of species that, based on our samples at least, occur only in the south of the province, or only in the north. Thus, the biodiversity layer cannot rely solely on the beach morphodynamic type proxy, and some sampling of the beaches across the province is required to determine which species are only found in a single biogeographic province. These patterns would need to be taken into account when cross-tabulating the planning units with a biodiversity layer.

c. Habitat representation and heterogeneity, including linkages among systems

Certain habitat features of the coast can contribute to resilience to disturbances, as was seen in Chapter 3, with the nearshore reef and sand dunes. Further, as was pointed out in Chapter 1 (see Fig. 1.1), there are dialectical linkages among the dune, beach and surf zone regions. The bidirectional, unimpeded movement of sediment through these regions is the most ideal state for a beach to be in if the aim is natural resilience and maximum adaptive capacity. A site that has these characteristics should be chosen in preference to other sites. In these cases, the MPA can be extended beyond the beach, synergistically achieving conservation targets in adjacent systems within a single area that will be logistically easier to manage than each MPA in isolation. However, not all beaches in protected areas should include reefs because their presence has implications for sand movement within the surf zone, possibly preventing the formation of rip-circulation cells. Reef-protected beaches could thus form a percentage of the conservation target, for example.

d. Species and/or populations of importance and vulnerable life stages

In KZN, the nesting sites of loggerhead (*Caretta caretta*) and leatherback (*Dermochelys coriacea*) turtles in the northern region is of utmost conservation importance. All these nesting sites are currently protected by the St Lucia and Maputaland Marine Reserves, but would still be included in the SCA objective function (no planning units would be selected specifically for turtle conservation though, because the conservation target for turtle nesting sites has been met by the existing reserves). The only beach-related shorebirds that nest in KZN are the white-fronted plovers (*Charadrius marginatus*). Their nesting sites would need to be cross tabulated into the planning units. The persistence of supratidal, backshore beach fauna, *e.g.,* ocypodid ghost crabs are threatened, particularly in the southern region, because of coastal squeeze and the fact that their habitat zone on the beach will be the first to disappear as sea levels rise. The presence of sand dunes in a site, or an unconstrained back beach at least, will be required for the conservation of this fauna group.

e. Ecosystem goods and services

The important ecosystem goods and services would need to be mapped so they can be included in the SCA. Some could be inferred based on beach morphodynamic type, *e.g.,* rates of water filtration are far greater on reflective beaches than on dissipative beaches (McLachlan, 1989), although dissipative beaches filter out more particulate organic matter (Jones, 2008). Other ecosystem goods and services would need to be mapped – this includes tourism, which is a non-consumptive good. Ideally, beaches that are very popular among tourists, e.g. Durban Golden Mile, would preferably need to be excluded from the reserve network. Most of these beaches are generally associated with urban areas, and would more than likely be excluded in criteria two above. For the other ecosystem goods and services, conservation targets would need to be set.

4. Size, clustering and connectivity

Studies have shown that the greater the area of the beach (McLachlan & Dorvlo, 2007), and the longer the beach (Brazeiro, 1999; Deidun & Schembri, 2008), the greater the species diversity.

While 2 km might be set as the absolute minimum beach MPA length, the greater the area of a single MPA, which can be adjusted by setting the requirement for clustering of selected sites to be high, the better for beach conservation. Reserves that are spatially compact, *i.e.,* a few larger reserves as opposed to many fragmented ones, are more likely to enforce compliance (Klein *et al.*, 2008). A part of the clustering factor could include economic costs. By considering financial costs along with biological benefits, cost efficiency can be maximized (Perhans *et al.*, 2008). The connectivity parameter of the objective function is currently difficult to set because we simply do not know what the minimum connectivity distance between beaches is, or if beach populations even function as metapopulations in the first place. Assuming beaches are connected by local hydrographic currents (Caddy & Defeo, 2003), it is likely that, for most of the province, connectivity is asymmetrical, with source beaches (dissipative beaches according to the theory (Caddy & Defeo, 2003; Defeo & McLachlan, 2005)) seeding beaches northwards of them because of the south-north direction of longshore transport off the KZN coast (Schoonees, 2000). Furthermore, beach area will not solely exist in the MPAs, and species would still be able to use the beaches between MPAs as connectivity corridors.

5. Zonation

Zonation involves allowing, restricting or preventing certain activities in particular areas of a MPA. For example, beach walking at night may be prohibited in areas where turtles nest; subsistence harvesting and permit-regulated shoreline fishing might be allowed in some areas, while other areas are set aside as sanctuaries. How MPAs are zoned depends on the purpose of the MPA and the specific species and processes that are found in the sites. A site that is particularly included in a reserve specifically because of its sand dunes, for example, might be zoned such that access through the dunes is prohibited.

Implementation and action

Once the SCA has been performed and a viable reserve network has been determined, the implementation strategy component of the systematic conservation planning process, and ultimately conservation management, must take place. Knight *et al.* (2006) identify these two respective steps as the assessment-planning gap and planning-action gap, because too often, peer-reviewed literature focuses on innovative reserve selection techniques rather than the implementation and action of the

SCAs. In the KZN context, the leading management authority, Ezemvelo KwaZulu-Natal Wildlife (EKZNW), are gathering data for a provincial SCP for all ecosystems, including sandy beaches. Thus, the institutional will for the implementation of sandy beach MPAs is already there. With the recent tabulation of the Integrated Coastal Management Bill (2007), there is legal justification for implementation of beach reserves and general management of the coast, both inside and outside these protected areas. It is therefore likely that, should an official SCP be drafted for KZN, it could be employed according to the implementation strategy in the plan.

Management objectives within the MPAs

Management within these MPAs would take on the strictest enforcement of ecologically selfish strategies, where preserving beach ecology is the uncompromised goal. This could be in the form of setback lines that are more conservative than for the rest of the province, for example. In some cases, this may mean gradual expropriation of coastal development – although this would be minimized through the SCA process. Sites of ecological pristineness in many instances become associated with ecotourism. This would need to be regulated with the utmost care so as not to compromise the very ecosystem underpinning this initiative. Further, community involvement in the MPA, and possible ecotourism opportunities, would fit in with the goal of jointly combating poverty, and promoting sustainability and resilience to climate change (Smit & Pilifosova, 2001).

Areas outside MPAs: meeting remaining stakeholder goals

Once MPAs have been identified, the third objective is to manage the remainder of the coastline, because sea-level rise and storms are issues for all sections of the coastline. MPAs ensure primarily that the ecological requirements are met; there are still of myriad of other stakeholder conflicts in the rest of the coastal zone that need to be resolved. Included in the conflict resolution is improving the adaptive capacity and resilience of all beaches to the impacts of climate change. This would involve planning at a local scale. Thus, systematic conservation planning is a tool that is nested within a greater conceptual framework for coastal management. In order to appreciate the value of MPAs from more than an ecological perspective, it is important to understand the "bigger picture" of coastal zone management.

Conceptual framework for local-scale decision making to combat coastal squeeze: meeting all stakeholder requirements

Conserving for resilient ecosystems

The overarching goal for conservation into the next century, and beyond, should be to manage ecosystems in such a way that they can persist through disturbances, whether pulse or press, with equivalent levels of ecosystem integrity. This integrity relates to the biodiversity and processes that comprise the ecosystem, and to the concomitant goods and services these provide. In essence, this means managing ecosystems to be resilient (Klein *et al.*, 2003), and to maximize the adaptive capacity inherent in the system such that artificial management interventions can be minimized. This will not only reduce damage to the ecosystem proper, but will also reduce the financial implications associated with the damage. In order to achieve this idealistic state, management for resilience needs to be proactive. By jointly pursuing economic, social and ecological resilience (Fig 6.1 below), it is theoretically possible to attain a level of existence where humans can live sustainably in a world of climate change, and ecosystems have sufficient adaptive capacity to buffer the impacts of climate change.

Social resilience

Social resilience is the ability of groups of people to cope with external stresses resulting from environmental, political or economic change (Adger, 2000), such that important structures, processes and feedbacks are maintained through the stress (Adger *et al.*, 2005). A society's resilience is shown by the extent to which it can organize itself, and build the capacity for learning and adaptation (Adger *et al.*, 2005). There are two primary sources of social resilience: social capital and social memory (Folke *et al.*, 2005) that are linked through their dialectical dependence for jointly building capacity for resilience. Social capital refers to social networks, and focuses on bridging gaps between the different members, agencies and organizations within the network (Folke *et al.*, 2005). Social memory refers to past experience of dealing with change, knowledge, values and worldviews that can be drawn on to find innovative responses to stress and guide policy formation (Adger *et al.*, 2005; Folke *et al.*, 2005). The relationship between social capital and social memory is that social capital facilitates the mobilization of social memory, either pre-emptively by using information, or reactively in the face of a crisis (Folke *et al.*, 2005). Strong social capital in the form of improved communication and awareness, and linking organizations such as national and international nongovernmental organizations (NGOs), can strengthen resilience and improve capacity for dealing with stress, particularly during crises (Adger *et al.*, 2005).

Economic resilience

Economic resilience is defined as "…*the policy- induced ability of an economy to recover from or adjust to the negative impacts of adverse exogenous shocks and to benefit from positive shocks*" (Briguglio *et al.*, 2006). The definition extends to include two aspects: inherent resilience – the ability of a system to withstand shocks under normal circumstances; and adaptive resilience – the ability of the system to recover quickly from shocks (Rose, 2004; Briguglio *et al.*, 2006). The effect of these external shocks can be to cause loss through direct impacts, *e.g.,* property damage, or indirect impacts, *e.g.,* interrupted flow of business (Rose, 2004). Economic resilience occurs at all scales, from microeconomic – households and businesses – to macroeconomic – world markets (Rose, 2004), and it is evaluated based on the sufficiency of the policy covering four areas: macroeconomic stability; macroeconomic market efficiency; good governance; and social development (Briguglio *et al.*, 2006). In the context of climate change, Faber (1995) argues that the impacts of the extreme weather events will be high for poor people with low economic resilience and adaptability, and this will contribute to a weaker economy.

Ecological resilience

Ecological resilience has a similar definition to economic and social resilience, in that it concerns "…*the persistence of relationships within a system and is a measure of the ability of these systems to absorb changes of state variables, driving variables, and parameters, and still persist*" (Holling, 1973). Holling (1973) went on to differentiate between resilience and stability, suggesting that highly resilient ecosystems may still fluctuate in their state, *i.e.,* have a low stability. Biodiversity has been shown to increase the resilience of ecosystems to disturbances (Chapin III *et al.*, 1997; Walker *et al.*, 1999; Chapin III *et al.*, 2000) and arguments have been made that functional redundancy, *i.e.,* species that perform similar roles in the ecosystem, operating across scales can promote ecological resilience (Peterson *et al.*, 1998). In a sandy beach context, it would appear that ecological resilience stems firstly from the maintenance of the sand component of the ecosystem. This, in turn, ensures the continued existence of the beach biodiversity, and delivery of ecosystem goods and services.

A conceptual model linking resilience to integrated coastal zone management for sandy beach decision-making

It is impossible to build sustainable development from any of these three spheres – sociology, economics or ecology – in isolation because of their intimate dependence on one another. Social and ecological resilience are linked through communities' reliance on the resources or other benefits provided by the environment (Adger, 2000, Kyle *et al*., 1997); ecological and economic resilience are linked through the financial implications of environmental hazards, and the economic benefits from ecosystem goods and services; economic and social resilience are linked through human dependence on money to meet basic, primary needs. Building adaptive capacity into each sphere promotes resilience in each, driving the unit as a whole into an ideal state of sustainability (Fig. 6.1), where no action in one sphere compromises the integrity of the other spheres.

This conceptual model can be contextualized for sandy beaches. Knowing the measurable functional units, drivers of those units, and goals of each sphere, provides a decision space in which decisions on how to manage sandy beaches can be made. The following figure (Fig. 6.1) depicting these principles is based on a similar conceptual figure by Townend (2002), who proposed the same social-ecological-economic interactions but for sustainability, rather than resilience here, within a total environment and indicated what the feedback loops are for each sphere.

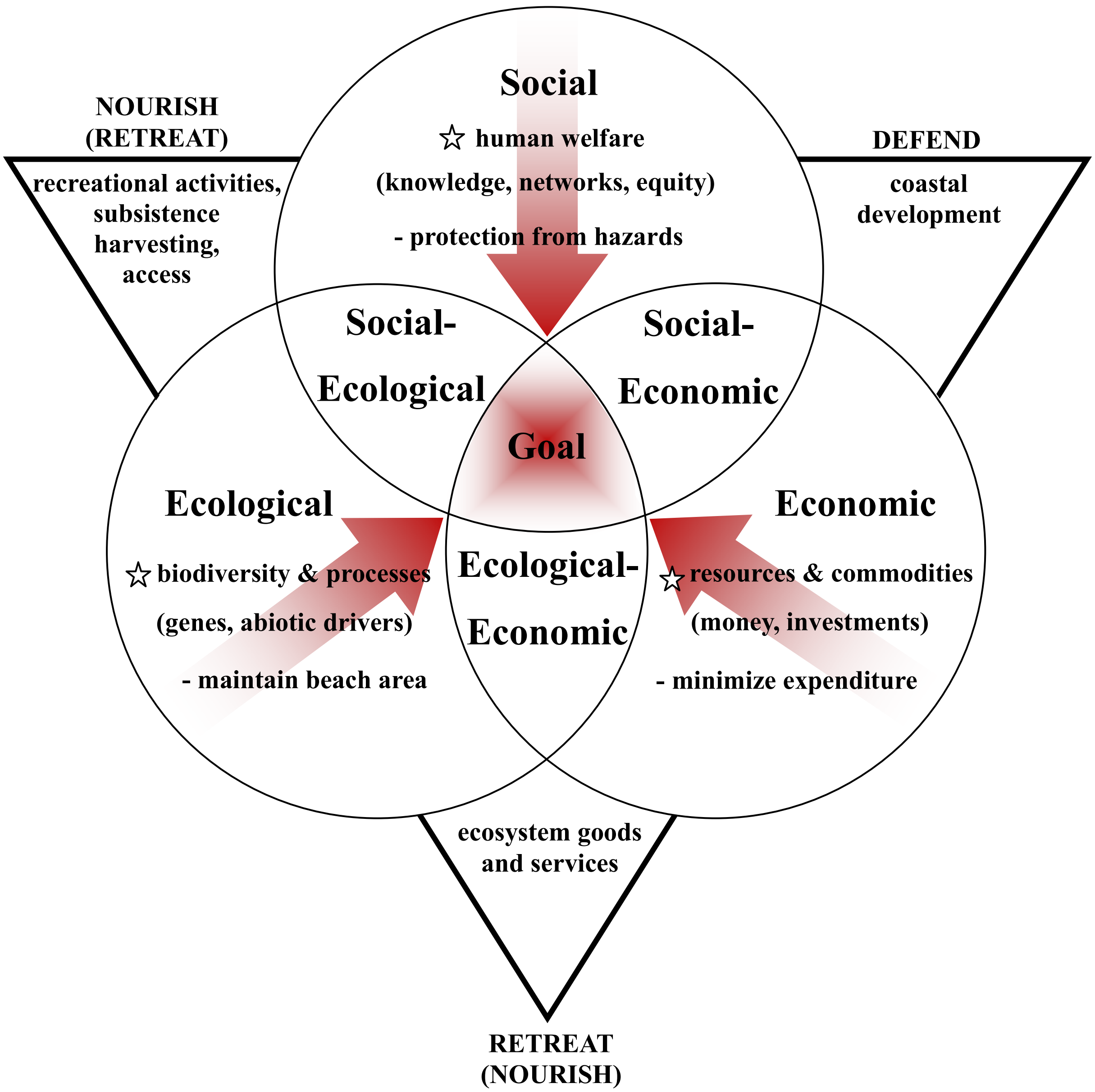

Figure 6.1. A conceptual model that superimposes the relationships among the social, ecological and economic needs of a coastal region onto a decision-making space (black triangle) in the face of climate-change and development impacts on sandy beaches. The increasing resilience (red arrows) in each sphere contributes to attaining an idealistic state (central red goal area) of sustainability and maximized resilience. Stars indicate the functional unit of the sphere, followed by the drivers of the units in brackets, with the primary goal of the sphere bulleted below the drivers.

In the figure (Fig. 6.1), social resilience for beaches sits on an axis of nourishment (although retreating would also meet the needs) to hard defence, based on the requirements that societies have of beaches that range from recreational, subsistence harvesting and beach access to protecting their coastal development. Economic resilience is on an axis of hard defence to retreat (although nourishment may also meet the needs in this sphere). The requirements of this sphere are to protect valuable coastal development and reap benefits from ecosystem goods and services, including tourism. The ecological axis is between retreat and nourishment to attain the requirements of maintaining beach area in either a natural or artificial form.

This figure is designed to be applied at a local beach scale, depending on the local stakeholders and physical context of the beach because of the identified spatial heterogeneity of coastlines. If a beach has high-value infrastructure and it has a low tourism (*i.e.,* social) value, then the management decision is pulled towards the "defend" end of the social axis. However, if the beach has high-value infrastructure and it is a highly valued beach for tourism, the management decision could sit half way along the social axis, defending the development and nourishing the beach so that both needs are met. If a beach has low-value infrastructure, but the beach has important ecological value, the decision would slide down the economic axis to allow the beach to retreat. And so on. The closer the system achieves the central goal state, the fewer management decisions need to be made because there is greater resilience and sustainability in the system.

The value of MPAs: the goal state

The value of MPAs is that they represent the idealistic goal state. When storms pound coastlines and beaches retreat in respond to sea-level rise, none of primary goals, drivers or functional units of any of the spheres is compromised (and least, not more than temporarily): ecological systems are still intact and biodiversity is not reduced (Chapter 3); economic costs are minimized because there is no (or very little) infrastructural damage to repair, and ecosystem services are maintained; and from a social perspective, recreational activities can continue to occur because there is still a beach area, and society is not at risk of impacts because the natural barriers (dunes) function to buffer the effects of the storms.

Working with nature so ecology is not compromised

From both studies in the literature and the arguments presented throughout this dissertation, sandy beaches are dynamic systems, and should be managed as such, particularly in light of the uncertainty of the future associated with global climate change. Thus, the concept of building hard structures in this constantly shifting environment is completely illogical and has shown not only to cause more problems than they necessarily solve (Jolicoeur & O'Carroll, 2007), but also to be detrimental to the ecosystem and its fauna (Dugan *et al.*, 2008; Fish *et al.*, 2008). For truly sustainable, long-term management of sandy beaches, we need to work with the principles in nature (Jennings, 2004), and beaches should be allowed to retreat (Daniel, 2001; Ferreira *et al.*, 2006). Where this is not possible because of already-established coastal development, practices used to defend the coast should take the dynamisms of the ecosystem into account. These are practices such as beach nourishment (Greene, 2002; Nordstrom, 2005; Speybroeck *et al.*, 2006) and dune reconstruction (Nichols, 1996; Nordstrom *et al.*, 2000): recognizing, of course, that these really are only temporary solutions to a long-term problem that will only get worse and a phased retreat is the most ideal option.

The problem with retreat is that humans have significantly altered the coastline with high-value investments in coastal property and residential developments. These have a strong economic inertia against relocation (Klein *et al.*, 2003), meaning that expropriation of these developments for dune reconstruction and coastline rehabilitation is very unlikely, and strong cases will be built for their defence with sea walls. And so, admittedly, there will be trade-offs in the decision-making process and sadly, most of these decisions will more than likely be economically driven, in spite of the costs to the natural environment (Knogge *et al.*, 2004). However, as argued by Paterson *et al.*(2008), "*Until we recognize that conserving biodiversity is in the interest of global communities, the very schemes put in place to prolong our welfare and prosperity may, perversely, constrict them.*"

In his speech to present the Integrated Coastal Management Bill (2007) to the South African National Assembly, Marthinus van Schalkwyk[13] (2008) noted that, "*…our coastline is currently not being managed and developed in a way that optimizes its resources and opportunities. Economic and social opportunities for wealth creation and equity are being missed while coastal ecosystems*

[13] Minister of the Department of Environmental Affairs and Tourism, South Africa

are being systematically degraded." This can change, but only once the anthropocentric paradigm that nature is infinite is shifted; and once we realize that, having accelerated climate change and significantly placed a number of species and ecosystems at risk of annihilation, we have a responsibility to nature and to future generations to reduce that risk. Townend (2002) makes the following analogy regarding our responsibility to future generations, "…*it is a case of passing the baton in a relay race, always mindful of the fact that if you drop the baton you are disqualified from the race!*"

Lessons learnt

Answers to questions

The question posed at the outset of this dissertation was: what are the ecological implications of sea-level rise and storms for KZN? The answer can be summarized in the following:

1. The combined erosion from sea-level rise and storms will cause beaches to retreat landwards, mostly in the northern region of the province, but this region is most able to respond because the beaches are undeveloped and landward retreat is unconstrained.
2. Coastal squeeze as a result of sea-level rise most threatens the beaches in the southern region and in front of urban nodes in the central region where development is in the littoral active zone. It is predicted that this will cause significant amounts of beach area loss, including intertidal and backshore beach, which will reduce beach faunal biodiversity (*e.g.,* backshore beach species like ocypodid crabs) and loss of certain ecosystem goods and services (*e.g.,* recreation, water filtration and nutrient remineralization).
3. An increase in storm frequency and intensity will exacerbate existing erosion problems, and thus contribute to coastal squeeze.

These facts present a strong case for managing the coastline sustainably, such that these consequences can be avoided as much as possible.

Recommendations

General

Based on the results in this dissertation and principles in the literature, the recommendations for managing sandy beach ecosystems are to incorporate the following framework for management into the overarching strategy of integrated coastal zone management:

1. Create links with management of adjacent coastal systems to conserve whole ecosystem processes.
2. Establish a scientifically determined reserve network of MPAs that will ensure the conservation of the sandy beach ecosystem and its associated biodiversity, goods and services.
3. Perform local-scale assessments of beaches in order to determine an appropriate response strategy to climate change for the beach to build adaptive capacity for resilience, and ensure the persistence of the user needs on the beach, including maintaining tourism opportunities.

Recommendations specific to KZN

There are three main recommendations for the KZN sandy beaches, which are seated in the three general recommendations described above. These include:

1. Establish MPAs in the south and central regions

Based on current protection of the KZN sandy beaches, the Natal bioregion is particularly under-represented in MPAs, and it is recommended that protected areas are proclaimed in the central and south regions of the KZN province based on the systematic conservation planning principles outlined in this chapter.

2. Create high-resolution spatial data for modeling coastal recession to aid determination of suitable setback lines

Possibly the greatest limiting factor for the coastal recession modeling done in this study was the unavailability of high-resolution satellite imagery and digital elevation models (DEMs), as far as I am aware of. A DEM with pixels of 25 m^2 was the most accurate one that was available, but this resolution is not good enough when predicted recession can be much less than 25 m, and even less accurate when interpolating intertidal slope which can be less than a 1 m change in elevation. Furthermore, plotting coastal development where there is a 5 – 10 m digitizing error is not accurate enough, particularly from a home-owner perspective where this error margin is enough to place their houses and properties either in or out of the "at risk" category. High resolution imagery of the KZN coast has been made available in the last few months (Dr. P. Goodman, 2007, pers. comm.[14]). To complement this, I recommend that management authorities invest part of their coastal budget in developing a high-resolution DEM of the coastline, so that accurate modeling can be performed. This would aid conservation plans for sandy beaches by significantly improving predictions of coastal retreat and determining suitable setback lines. The spatial distribution of beach types that have different erosion-accretion characteristics is far from uniform, and this heterogeneity needs to be reflected in the setback line. It is also recommended that this is an adaptive strategy, and DEMs are created every few (perhaps five) years so that predicted recession can be revised and management plans altered accordingly, where necessary. This would also allow for evaluation of the coastal recession modeling methods, and give scope for modeling improvements.

3. Consider proactive relocation of the south coast railway line

The south coast is particularly at risk of impacts from sea-level rise and storms because of the close proximity of the development to the beach. The railway line runs half way up the primary dune for almost the whole length of this region and is thus at an imminent risk of damage from storms in the shorter-term, and from the combination of sea-level rise and storms in the longer-term. It would be sensible to relocate the railway line proactively. This would ensure continued use of this infrastructure without having to halt business due to repairs or construction after a high-impact event. There would be a double-benefit of this action: economic benefits for railway line companies, and increased resilience for beaches.

The value of geographic information systems for sandy beach management

This dissertation has highlighted the value of geographic information systems in performing spatial analyses of coastlines. As a side recommendation, user-friendly programs that are based on erosion or recession models (*e.g.,* Chapters 4 and 5) should be developed, where managers can enter sea-level rise scenarios (and possibly development or armouring scenarios) and the program

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automatically runs to give a three-dimensional model of the coastal area, and possibly dynamic visualizations of the erosion or recession process (Brown *et al.*, 2006). This would be a very powerful tool in motivating their decisions, and gaining public support.

Conclusion

With the formulation of the Integrated Coastal Management Bill (2007), South Africa has shown a continued commitment to coastal conservation. This document "…*promotes a holistic way of thinking by promoting coordinated and integrated coastal management, which views the coast as a system and emphasizes the importance of managing it such*." (Van Schalkwyk, 2008). Further, the Bill, in conjunction with supplementary legislation, *e.g.,* the White Paper for Sustainable Coastal Development (2000), provides the legal support for coastal management decisions. In the current state the KZN coastline is in, certain sections are vulnerable to the impacts of sea-level rise and storms, simply because development in the littoral active zone has broken the coastal buffer and increased the exposure of the hinterland to these impacts. The last five to ten years have shown substantial transformation of the coastal zone in the central and southern regions (Celliers, in prep.; Kohler, 2005). However, if proactive management plans can promote a phased retreat and coastal realignment, and further research is conducted in the areas highlighted in this dissertation, a number of the implications of climate change for the KZN coast could be avoided.

The tides have a way of washing away the evidence of our daily beach activities. A set of footprints can be smoothed over by a single wave, and mighty sand castles are reduced to just small bumps on the beach. As sea levels rise, the tides now threaten to wash away the evidence of our activities beyond the beach, collapsing houses like sand castles. In the long term, the sea will always win. It is up to us how big we want to make the fight.

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