Department of Environmental Affairs
and Development Planning

Sea Level Rise and Flood Risk Assessment for a Select Disaster Prone Area Along the Western Cape Coast

Phase 2 Report: Eden District Municipality Sea Level Rise and Flood Risk Modelling

Final

May 2010

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UMVOTO

EXECUTIVE SUMMARY

INTRODUCTION

Umvoto Africa (Pty) Ltd was appointed by the Western Cape Department of Environmental Affairs and Development Planning (DEA&DP): Strategic Environmental Management division to undertake a sea level rise and flood risk assessment for a select disaster prone area along the Western Cape coast, namely the portion of coastline covered by the Eden District (DM) Municipality, from Witsand to Nature's Valley. The Western Cape DEA&DP required that a literature assessment of current global and local understanding and knowledge with regards to climate change and sea level rise be undertaken, in association with the development of a sea level rise and flood inundation Geographic Information System model. Umvoto Africa proposed a three-phase work approach, namely: Phase 1 – Inception and Data Acquisition, Phase 2 – GIS Model Development and Phase 3 – Risk Assessment. This report describes the sea level and flood inundation modelling undertaken during Phase 2.

MODEL METHODOLOGY

South Africa, despite having over 3000 km of coastline along which the majority of the country's large cities are situated, does not have basic coastal baseline data. This makes coastal modelling and shoreline prediction at anything other than a coarse regional scale difficult. Due to data, time and budget constraints, the modelling undertaken here provides a first, regional large-scale attempt at identifying areas along the Eden DM coastline that are vulnerable to migrating shorelines and tidal reaches, and storm associated extreme sea levels and estuary/river flooding.

The present worst case extreme sea level scenario for the southern Cape coastline would be a 1:500 year event, such as that experienced in March 2007 along the KwaZulu-Natal (KZN) coastline, where a 1:40 to 1:50 year storm with an associated local sea level rise of between 50-60 cm would occur simultaneously on the Highest Astronomical Tide (~ 140-150 cm above mean sea level for the southern Cape). The end result would be a storm surge related extreme sea level of over 2 m. This may in turn become a 1:30 year event by the end of the next decade, or a one in every two-week event by the end of the century as a result of a higher base sea level due to rising seas. Using information from and erosion lines observed along the KZN coastline after the March 2007 event, the City of Cape Town sea level rise model (Brundrit, 2008 and Fairhurst, 2008) developed three swash run-up contour lines, namely 2.5 mamsl (for sheltered or rocky coastlines), 4.5 mamsl swash (for exposed or sandy coastlines) and 6.5 mamsl (for headland and pocket bay beaches and sandy inlets) swash contour lines. These three City of Cape Town swash contour lines were in turn used for modelling the possible effects of storm induced extreme sea levels along the Eden DM coastline, due to similar coastal conditions in both areas, as well as allowing for correlation between regional studies. Associated storm surges often prevent flood waters from exiting into the ocean at estuary mouths, resulting in extensive back flooding of the low relief estuary areas and lower course river floodplains. Estuary flood waters along the southern Cape coast have reached levels of between 2-4 mamsl in the past during storm events, and hence the swash contour lines can also be converted into estuary and river flood lines.

Long-term shoreline evolution, whether eroding, accreting or dynamically stable, can be determined by the measurement of the shoreline position over time. The initial objective of the project with regards to shoreline evolution modelling was to use the coastal setback line methodology developed by Ferreira et al. (2006). Resolution and georeferencing issues made the calculation of shoreline evolution rates difficult however, with the rates of change calculated likely to be highly unreliable. A more simplified approach was therefore undertaken, with future sandy shoreline and tidal reach lines being modelled for both a 0.75

m and 2 m rise by 2050 and 2100 respectively. However the lateral evolution of both the shoreline and tidal reach lines were limited and within error for a 0.75 m rise, hence only the vulnerable areas for a 2 m rise were identified. It must be noted that the vertical resolution of the DEM (~ 3-4 m) and 10 m pixel resolution of the 2008 SPOT imagery does not allow for highly accurate and detailed predictions to be made, and the modelling results should be used in a more regional planning approach, where the swash/flood and shoreline/tidal reach evolution lines are used to identify possible vulnerable areas.

MODEL RESULTS

Table A Areas most vulnerable to coastal, estuarine and fluvial erosion and inundation along the Eden DM coastline.

Area	Coastline, Estuarine and Fluvial Erosion and Inundation
Witsand	Cape Infante may focus large storm swell energy, resulting in possible swash run-ups in the range of 4.5-6.5 mamsl in the vicinity of Witsand. This would result in erosion of the Breede Estuary sand bar, as well as the thin covering of sediment overlying the rock outcrops in front of Witsand. Coastal property and roads ~ 50-70 m from the shoreline will be damaged. Flooding and back flooding of the estuary may inundate marinas, jetties and oyster beds at Port Beaufort, and cause flood damage to farmhouses and roads along the Breede River and its associated tributary floodplains.
Skurwebaai to Stilbaai	A 2.5 mamsl swash run-up can be expected due to the predominantly rocky nature of the shoreline. Jongensfontein would be unaffected in the event of a 2.5 mamsl swash run-up, although bigger storm events and run-ups would damage the first line of coastal properties and infrastructure ~ 50-70 m from the shoreline. Increasing large storm run-ups in the future may damage the archaeologically important, Middle Stone Aged (~ 70 000 years before present (BP)) Blombos Cave.
Stilbaai	Morris Point may focus large storm swell energy, resulting in possible swash run-ups in the range of 4.5-6.5 mamsl in the vicinity of Stilbaai. This would result in the erosion of the Goukou Estuary sand bars, as well as causing damage to the first block of houses along western Stilbaai and Preekstoel, and a large portion of Lappiesbaai if the foredune is breached by swash run-up. The Goukou River floodplain and large portions of Stilbaai adjacent to the estuary and river are also vulnerable to flooding and back flooding. Damage to the R323 road due to flooding may occur.
Gouritsmond	A 2.5-4.5 mamsl swash run-up can be expected at Gouritsmond due to the relatively rocky nature of the coastline, with a small portion of coastal property along Voelklip possibly being affected by higher run-ups. Extensive Goukou River floodplain inundation along the lower reaches of the river may occur as a result of flooding and back flooding.
Mossel Bay	Cape St. Blaize may focus large storm swell energy, resulting in possible swash run-ups in the range of 4.5-6.5 mamsl along Mossel Bay. These run-ups would cause damage to coastal developments towards Cape St. Blaize, as well damaging Mossel Bay Harbour. Large swell may inundate the N2 road and railway line, as well as damage them through cliff undercutting. A small portion of undeveloped foredune (~ 10-15 m high and 10-70 m wide) currently protects the Diasstrand, Bayview and Voorbaai coastal and residential areas, and would prevent a swash run-up of 6.5 mamsl causing damage.
Hartenbos, Klein-Brakrivier and Groot-Brakrivier	The Hartenbos, Klein Brak and Groot Brak River estuaries and floodplains are highly vulnerable to flooding, with a large portion likely to be inundated if estuary flood waters reach 2.5 mamsl. Klipheuwel would be flooded by a 2.5 mamsl flood, while the developed eastern bar of the Klein Brak Estuary could be damaged by a 4.5-6.5 mamsl swash run-up. Larger swash run-ups would damage coastal property along northern Hartenbosstrand due to development removing the protective foredune barrier. The western Groot Brak Estuary sand bar and suburb of Suiderkruis are also vulnerable to erosion and damage by a 4.5-6.5 mamsl swash run-up. Klein-Brakrivierstrand, Reebokstrand, Tergniet, Groot-Brakrivierstrand, Outeniquastrand and Glentana Beach are currently protected by a thin undeveloped shoreward section of foredune (~ 10-20 m and 20-70 m wide), except in parts where it has been removed through development and is vulnerable to higher run-ups.

Glentana Beach to Wilderness	A 2.5 mamsl swash run-up can be expected due to the predominantly rocky nature of the shoreline, with sand bar erosion occurring at the Maalgate, Gwaing and Kaaimans Estuaries. Herolds Bay and Victoria Bay are both highly vulnerable to large swell events due to their pocket beach structure, and are likely to receive 6.5 mamsl swash run-ups during extreme events. This would cause extensive beach erosion and damage to coastal property and amenity infrastructure at both beaches.
Wilderness	West Wilderness is susceptible to beach erosion and coastal property damage by 4.5 mamsl swash run-ups. A large portion of western Wilderness is also vulnerable to flooding of the Touws River estuary. Wilderness East and Kleinkrantz is currently protected by a small undeveloped shoreward portion of vegetated foredune (~ 5-30 m high and 10-40 m wide), with the entire dune acting as a barrier between the ocean and very low relief Wilderness-Swartvlei Estuarine System.
Kleinkrantz to Sedgefield	Eastern Sedgefield adjacent to the Swartvlei Estuary, developments surrounding Swartvlei Lake, the lower reaches of the Karatara River floodplain, Groenvlei and the N2 and railway line where it crosses Swartvlei Estuary are all vulnerable to flooding and inundation. Sedgefield shoreline developments are currently protected by a thin portion of undeveloped foredune (~ 5-10 m high and ~ 50-70 m wide) and aeolianite cliffs (~ 20-30 m high and wide). Erosion and undercutting from successive storm events may put these developments at risk however, especially those situated on steeper cliffs more vulnerable to collapse.
Buffelsbaai	Buffelsbaai town is situated on a protruding headland, and will therefore likely experience the full energy of an extreme storm and swell event in the form of a 6.5 mamsl swash run-up. Coastal developments within 20 m of the shoreline, and 150 m from the tip of Walker Point, will be damaged by an extreme swell event. The bay itself will likely experience 4.5 mamsl swash run-ups, which will cause beach erosion, as well as dune and aeolianite cliff undercutting and collapse.
Knysna	The town of Knysna is protected from storm surges by the narrow width and rocky nature of The Heads, although the risk of flooding and back flooding of the estuary is high and a large portion of the town is vulnerable to inundation. Thesen's Island, Leisure Island, Brenton, Hunter's Home golf course, the portion of Knysna town centre south of the N2, the sewerage treatment works, the edge of Belvidere and the Knysna River floodplain up to the head of the estuary all fall below the 2.5 mamsl floodline (see **Figure 3-3**), which has been breached in the past.
Plettenberg Bay	Despite a 6.5 mamsl swash run-up being likely due to the Robberg Peninsula focusing wave energy, Plettenberg Bay southwards of Beacon Island remains unaffected due to the current protection offered by a thin portion of undeveloped foredune (~ 10-20 m high, ~ 40-60 m wide) (see **Figure 3-4**). In contrast, the beach area between Beacon Island and Lookout Rocks will be highly eroded during a large storm event, with coastal developments also being vulnerable to damage due to development on and the removal of the foredune. The Piesang River estuary and floodplain are vulnerable to flooding and inundation, especially the caravan park, adjacent farmlands and part of the golf course along the river.
Keurbooms-Bitou Estuary	The Tides, Gansevlei, Bitou, Keurbooms and Diep River floodplains, suburbs of Anath and Matjiesfontein, and Stanley Island are all vulnerable to flooding and inundation below 2.5 mamsl (which has been breached in the past). Large swells and an associated 4.5-6.5 mamsl swash run-up may erode the entire estuary mouth bar and Lookout Beach, which has occurred in the past. A relatively undeveloped 10-20 m high foredune northeastwards of the estuary is present, although coastal development at Keurboomsstrand has resulted in some areas been vulnerable to large swash run-ups and dune erosion and undercutting.
Nature's Valley	The coastal development front of Nature's Valley is currently protected by a thin portion of undeveloped foredune (~ 5-10 m high and ~ 70 m wide), although a ~ 150 m wide section of the town adjacent to the Groot Estuary is vulnerable to inundation from estuary flooding. A higher pocket beach enhanced swash run-up of 6.5 mamsl will erode the estuary mouth sand bars and beaches in the area.

Table B Vulnerable sandy coastlines within the Eden DM based on shoreline evolution caused by a 2 m rise by 2100.

Sandy Coastline Section	Shoreline Evolution (for 2 m rise by 2100)
Witsand and Westfield	The shoreline is expected to move ~ 50-100 m inland in the vicinity of the Breede Estuary mouth eastern bar, with little movement landwards (~ 10 m) near Westfield due to the backing high gradient foredune.
Gouritsmond, Visbaai and Vleesbaai	Minor landward shoreline migration (~ 5-20 m) due to the backing high gradient foredune likely. Despite this, possible dune undercutting and collapse over time at Vleesbaai and Danabaai may occur, causing damage to coastal property.
Mossel Bay and Hartenbos to Glentana	A ~ 30-40 m landward shoreline movement along low gradient coastal areas may occur. Dune degradation would result due to a buffer area, which would allow for natural dune migration, being absent along most of the developed section of this coastline.
Wilderness, Sedgefield to Goukamma and Buffelsbaai	Minor landward shoreline migration (~ 5 m) along high gradient dune and aeolianite cliff areas is possible, increasing to ~ 10-30 m along lower gradient dune fields. Parts of Sedgefield are at risk to possible long-term dune migration.
Plettenberg Bay, Beacon Island, Lookout Rocks, Keurbooms and Bloubankies	Landward migration of the shoreline by ~ 5-20 m is possible, dependant on the dune gradient. This may affect coastal developments where the foredune has already been removed or degraded e.g. between Beacon Island and Lookout Rocks.
Nature’s Valley	Landward migration of the shoreline by ~ 20-30 m likely, causing dune migration and the possible movement of dunes into the first line of coastal developments at Nature’s Valley.

Table C Tidal reach evolution for vulnerable Eden DM estuaries, for a 2 m rise by 2100.

Estuary	Tidal Reach (for 2 m rise by 2100)
Breede	Tidal reach may laterally extend only 30 m inland due to relatively steep river bank slopes. Port Beaufort marinas, jetties and oysterbeds may be inundated however.
Duiwenhoks, Goukou and Gouritz	The tidal reach may laterally extend by ~ 50-100 m along low gradient flood plains, resulting in flooding risk to farmlands at Mazepa along the Duiwenhoks.
Hartenbos, Klein Brak and Groot Brak	Tidal reach may increase laterally inland by ~ 20-30 m within the Hartenbos Estuary, affecting some development along the estuary banks. This increases to ~ 100 m along the Klein Brak and Groot Brak Rivers and estuaries, affecting Klipheuwel in Klein Brak and Groot-Brakrivier town centre, Bergsig and The Island within the Groot Brak Estuary.
Swartvlei and Goukamma	Tidal reach may extend laterally inland by ~ 50-100 m along the upper low gradient sections of the Swartvlei and Goukamma Estuarys, affecting the estuary fronting developments of upper Sedgefield.
Knysna	An increase in lateral tidal reach of ~100 m may occur within the estuary south of Knysna town centre, affecting Thesen’s and Leisure Island, decreasing to ~ 20 m towards Brenton and the estuary head.
Piesang, Keurbooms-Bitou, and Groot.	Lateral tidal reach at the Piesang Estuary may increase by ~ 50 m in 2100, affecting the caravan park and golf course. Future lateral tidal reach at the Keurbooms-Bitou Estuary varies between ~ 30-100 m, with similar areas identified by the swash run-up modelling being affected. Lateral tidal reach may extend by ~ 30-90 m along the western banks of the Groot Estuary, affecting the adjacent estuary developments of Nature’s Valley.

RECOMMENDATIONS

- Western Cape level:
  - Develop large-scale sea level rise flooding models for the remainder of the Western Cape coastline, namely from Gordon's Bay to Witsand (Overberg DM coastline) and from Silverstroom Strand to Hoekbaai (West Coast DM coastline).
  - Conduct modelling updates of these models at least every 5 years. The current modelling undertaken in this project is at a broad scale and coarse, and new global and local climate change data and scenarios, local coastal geomorphic data and methodologies will help improve shoreline evolution prediction.
  - With regards to the Eden DM coastline, future modelling updates should focus on the vulnerable areas identified, in order to improve the resolution of the modelling i.e. each specific stretch of sandy coastline and estuary should have its own future coastal evolution model developed.
- Basic coastal baseline data upgrade:
  - Develop onshore and offshore 1 m x 1m DEMs (with an approximately 0.5 m vertical resolution) for the Eden, Overberg and West Coast DM coastlines.
  - Conduct beach profiling at selected beaches along the coastline, as well as detailed geophysical offshore bathymetry surveys, in order to determine various local variables and parameters that can be used in future detailed numerical modelling (see Eskom Holdings Ltd 2009a, 2009b and 2009c for detailed modelling examples).
  - Collection of all available photographic and remote sensing imagery, ensuring it is correctly georeferenced and stored in a central database for simple access for future coastal modelling.
- Eden District Municipality level:
  - Enforce the coastal buffer zone as defined in the National Environmental Management: Integrated Coastal Management Act (Act 24 of 2008) immediately, and prevent any further development within 100 m of the high water mark.
  - Strictly monitor (and preferably prevent) future development below the 6.5 mamsl swash contour and 4.5 m estuary/river flood contour, as well as on any undeveloped portions of foredune that are currently backed by development.
  - Ensure development along the coastal foredune takes into account future landward dune migration, and a further dune migration buffer zone should be put in place behind the coastal buffer zone.
  - Undertake a coastal education drive to make coastal residents aware of the importance of maintaining indigenous vegetated foredunes, as well as the possible hazards and risks faced if these natural barriers are removed.

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%	-	percent
~	-	approximately
°C	-	degrees Celsius
AR4	-	Fourth Assessment Report
BP	-	years before present
cm	-	centimetre
CCRC	-	Climate Change Research Centre
CZMU	-	Coastal Zone Management Unit
DM	-	District Municipality
DEM	-	digital elevation model
DEA&DP	-	Department of Environmental Affairs and Development Planning
e.g.	-	for example
etc.	-	etcetera
et al.	-	as well as
GIS	-	Geographic Information System
HAT	-	Highest Astronomical Tide
i.e.	-	that is
IPCC	-	Intergovernmental Panel on Climate Change
km	-	kilometre
KZN	-	KwaZulu-Natal
m	-	metre
mm	-	millimeter
mamsl	-	metres above mean sea level
R	-	Rand
SPOT	-	Satellite Pour l'Observation de la Terre
TAR	-	Third Assessment Report
UNSW	-	University of New South Wales

1. INTRODUCTION

1.1 SCOPE OF WORK

Umvoto Africa (Pty) Ltd was appointed by the Western Cape Department of Environmental Affairs and Development Planning (DEA&DP): Strategic Environmental Management division to undertake a sea level rise and flood risk assessment for a select disaster prone area along the Western Cape coast. The assessment area was defined as the southern Cape coastline within the Eden District Municipality (DM), from the Breede River mouth at Witsand to Nature's Valley east of Plettenberg Bay. The Western Cape DEA&DP required that a literature assessment of current global and local understanding and knowledge with regards to climate change and sea level rise be undertaken, in association with the development of a sea level rise and flood inundation Geographic Information System (GIS) model. Umvoto Africa proposed a three-phase work approach, namely:

Phase 1 – Inception and Data Acquisition: Collection of GIS data to be used in the development of the sea level rise and flood inundation model; collection and review of literature on both the global and local aspects of climate and sea-level change, as well as all national, provincial and local coastal legislation; and finalisation of the GIS and risk assessment model methodologies to be used.

Phase 2 – GIS Model Development: Development of a sea level rise and flood inundation model, based on specific sea level rise scenarios that were determined from literature.

Phase 3 – Risk Assessment: Undertaking of a coastal zone hazard risk assessment for identified Coastal Zone Management Units (CZMUs) within the Eden DM, based on a refined rapid assessment methodology described by Blake and Hartnady (2009).

This report describes the sea level and flood inundation modelling undertaken during Phase 2. **Chapter 1** provides a brief overview of the literature review conducted in the Phase 1 report. **Chapter 2** describes the model methodology that was used for both the shoreline evolution, and extreme sea level and estuary flooding modelling. The results from both models are described in **Chapter 3**, while **Chapter 4** concludes this report and provides recommendations.

The Phase 1 report details the literature and current understanding with regards to sea level rise both globally and regionally along the South African coastline, as well as the different sets of national, regional and local South African policies that have been developed to deal with future climate change induced coastal hazards. The Phase 3 report describes the coastal risk assessment methodologies and results respectively, as well as detailing the possible mitigation and adaptation measures for sea level rise.

1.2 GLOBAL AND REGIONAL SEA LEVEL RISE

The coastal zone can be defined as the interface and transition between the sea and land, and in South Africa approximately 30% of the country's population live within this zone (Theron and Rossouw, 2008). Twenty of the world's thirty megacities are situated within the coastal zone, with lower density peri-urban coastal areas between cities also rapidly growing (Small and Nicholls, 2003) e.g. the Garden Route along the southern Cape coastline between Cape Town and Port Elizabeth. A large variety of important economic and social activities take place within the coastal zone, including agriculture, tourism, recreation, manufacturing and transportation to name a few generalised examples. Due to the dynamic interaction of biophysical factors from both the Earth's land surface and ocean, and the high populations present, coastal areas are often at risk to natural and human-induced hazards. One such hazard, which is focused on in this study, is climate change induced sea level rise. Sea level rise causes shoreline retreat through coastal erosion and dune migration, and coastal inundation and flooding through the enhanced frequency of storm surges (whose intensity may also increase as a result of climate change). Rising sea levels can also cause groundwater and fresh coastal surface water contamination (with associated impacts on agriculture and aquaculture due to the decrease in soil and water quality), the loss of cultural and archaeological resources, and the possible destruction of important coastal habitats such wetlands, mangroves, estuaries etc.

Long term projections from coupled climate models are still uncertain with respects to global mean sea level rise and regional variations, due to the relatively unknown dynamic response of ice sheets to climate change, and the affects of regional climate circulation models (Cazenave et al., 2009). Eleven of the last twelve warmest years in the instrumental record occurred from 1995 to 2006, and the linear warming trend over the last 50 years is nearly twice that of the last 100 years (Intergovernmental Panel on Climate Change (IPCC), 2007). Temperature rise predictions range from 1.8-4 °C by 2100, with a 0.1-0.2 °C rise over the next two decades at least (IPCC, 2007). With regards to sea level rise, statistical analysis has correlated the rate of sea level rise with the rise in mean global temperature, and has indicated that the warmer it gets, the faster sea level rises (Rahmstorf, 2007 and Vermeer and Rahmstorf, 2009). Tidal gauge and (since 1993) satellite altimetry measurements have shown that sea level has risen 20 cm since 1870, with the rise during the 20th century being approximately 17 cm (University of New South Wales (UNSW) Climate Change Research Centre (CCRC), 2009). This rise of ~ 1.7 mm/year is an order of magnitude greater than sea level rise during the last 2000 years (Church et al., 2008). Satellite altimetry measurements since 1993 have shown that sea level has risen by 3.4 mm/year since 1993, which is 80% faster than the IPCC Third Assessment Report (TAR) (2001) prediction of 1.9 mm/year. Global sea level rise is non-uniform however, with wide variability present in the different ocean basins as recorded by satellite altimetry (Cazenave, 2009). Current future predictions taking into account new ice sheet understanding are twice the range of the IPCC Fourth Assessment Report (AR4) projections, with an upper limit of sea level rise of 2 m expected by 2100 (Rahmstorf, 2007, Vermeer and Rahmstorf, 2009 and the UNSW CCRC, 2009).

Brundrit (1984) conducted the first sea level studies in South Africa, along the west coast of the country. Little recent research into sea level rise and its effects has been undertaken however, with the majority of detailed studies occurring during the 1990s. The African sea level data set in general is limited in size and quality, and is smaller in comparison to most parts of the world (Woodworth et al., 2007). Mather et al. (2009) recently conducted the first detailed analysis of all tide gauge sites along the southern African coastline. The analysis shows that over the past 50 years, sea level rise along the southern African coastline has not been constant, varying between 0.42 mm/year (West Coast) to 3.55 mm/year (East Coast) (with a rise of 1.57 mm/year along the southwestern and southern Cape coastline) (Mather et al., 2009).

Sea level rise is often felt most not via the gradual advance of mean sea level, but by the increased frequency of storms and associated storm surge with the higher tidal regime. An analysis of sea level records over recent decades has shown evidence for an increase in extreme sea levels (i.e. those caused by storm surges) worldwide since 1975 (IPCC, 2007). Higher sea levels cause an increase in the frequency of storm surge events due to the higher sea base level, even if storm intensities themselves do not increase due to warming oceans (Church et al., 2008) i.e. a storm surge event with a 1:100 year return period may start to have a return period of 1:25 years due to smaller storms having the same effect on higher sea levels. The combination of cut off low generated storm surge systems during spring highs in February, March and September are responsible for the present highest sea levels along the southern and southwestern Cape coastline. A 30-year storm of +39 cm on a Highest Astronomical Tide (HAT) for Simons Town of 1.24 metres above mean sea level (mamsl), which would be a 1:500 year event at present, could turn into a 1:30 year event by the end of the next decade with an additional 15 cm of sea level rise (Brundrit, 2008). The 19th and 20th March 2007 storm along the KwaZulu-Natal (KZN) coastline provides a modern analogue for what damage such an event can cause. A 1:35 year wave height of 8.5 m and 1:100 year storm surge of +55 cm occurred on a tide of 1.33 mamsl, which was very close to HAT for Durban (HAT in turn occurred on the 21st March 2007) (Brundrit, 2008 and Smith et al., 2007). This combination represented a 1:500 year extreme sea level event and caused R1 billion damage (Mather, 2008 and Theron and Rossouw, 2008). 1:100 year flood lines from the sea caused by possible extreme events of 4-10 mamsl have been modelled for the proposed Thyspunt (near Cape Saint Francis in the Eastern Cape) and Bantamsklip (near Gansbaai) Eskom Nuclear 1 sites (Eskom Holdings Ltd, 2009a). By 2100, extreme sea level events of this nature may occur every 2 weeks on spring highs with the combination of a small to moderate storm (Theron and Rossouw, 2008).

2. MODEL METHODOLOGY

The majority of the world's coastlines have not been properly mapped or modelled, especially in developing countries where past shoreline evolution data can be rare to non-existent (Appeaning Addo et al., 2008). South Africa, despite having over 3000 km of coastline along which the majority of the country's large cities are situated, does not have basic coastal baseline data. This includes beach profiles, numerical wave refraction models, local bathymetry and detailed digital elevation models (DEM), whose non-existence across majority of the country make coastal modelling and shoreline prediction at anything other than a coarse regional scale difficult. In an ideal world the entire coastline would be modelled to the detail undertaken for the three proposed Eskom Nuclear-1 nuclear sites, namely Bantamsklip, Duynefontein and Thyspunt (see the coastal engineering and numerical modelling reports for Thyspunt (Eskom Holdings Ltd, 2009b and 2009c) as an example. Due to data, time and budget constraints, the modelling undertaken here provides a first, regional large-scale attempt at identifying areas along the Eden DM coastline from Witsand to Nature's Valley that are vulnerable to migrating shorelines and tidal reaches, and storm associated extreme sea levels and estuary/river flooding.

2.1 EXTREME SEA LEVEL AND ESTUARY FLOODING MODELLING

As has been stated prior, sea level rise will not be felt the most by coastal residents through relatively slow shoreline migration, but by the increased frequency of storms and associated storm surge with higher tidal regimes and increased wind speeds. The present worst case scenario for the southern Cape coastline would be a 1:500 year event, such as that experienced in March 2007 along the KZN coastline, where a 1:40 to 1:50 year storm with an associated local sea level rise of between 50-60 cm would occur simultaneously on the HAT (~ 140-150 cm above mean sea level for the southern Cape). The end result would be a storm surge related extreme sea level of over 2 m. This may in turn become a 1:30 year event by the end of the next decade, or a one in every two-week event by the end of the century as a result of a higher base sea level due to rising seas. The March 2007 KZN storm resulted in an erosion line approximately 4-5 mamsl (Smith et al., 2007). Rocky and sandy coastlines generally withheld against the swell and surge onslaught (Smith et al., 2007). However, mixed rock and sand beaches in the form of headland beaches and pocket bay beaches focused wave energy towards the shoreline due to their unique bathymetry, resulting in extensive erosion (Smith et al., 2007). Using this information and erosion lines observed along the KZN coastline, the City of Cape Town sea level rise model (Brundrit, 2008 and Fairhurst, 2008) developed three swash run-up (run-up is the rush of water up the beach slope within the swash zone, above the still or mean sea level) contour lines, namely:

- 2.5 mamsl swash contour line for sheltered or rocky coastlines;
- 4.5 mamsl swash contour line for exposed or sandy coastlines; and
- 6.5 mamsl swash contour line for headland and pocket bay beaches and sandy inlets.

These three City of Cape Town swash contour lines were in turn used for modelling the possible effects of storm induced extreme sea levels along the Eden DM coastline, due to similar coastal conditions in both areas, as well as allowing for correlation between regional studies. The three Eden DM swash contour lines were generated from a 10 m x 10 m DEM (with a 3-4 m vertical resolution) (see **Figure 2-1**), and then overlain on 2008 SPOT satellite imagery in order to identify possible vulnerable areas (see **Section 3.1**).

Figure 2-1 Eden DM 10 m x 10 m DEM and 2.5 mamsl, 4.5 mamsl and 6.5 mamsl swash and flood contour lines.

Large ocean swells and storm surges in the southern Cape are generated by strong frontal or cut off low weather systems during winter and spring/autumn respectively. These weather systems also generally cause extensive rainfall inland, which often results in flooding of the southern Cape river systems. Associated storm surges often prevent flood waters from exiting into the ocean at estuary mouths, resulting in extensive back flooding of the low relief estuary areas and lower course river floodplains. Estuary flood waters along the southern Cape coast have reached levels of between 2-4 mamsl in the past, and hence the swash contour lines can also be converted into estuary and river flood lines further inland. Areas vulnerable to estuary and river flooding and back flooding were hence also identified along the Eden DM.

2.2 SHORELINE AND TIDAL REACH EVOLUTION MODELLING

The coastline responds to sea level rise in three ways, namely: 1) the Bruun Rule or erosional model (Bruun, 1962); 2) the rollover model; and 3) the overstepping or drowning model (Pethick, 1984). The Bruun Rule is based upon the premise that sea level rise results in sediments along sandy coastlines being removed and deposited offshore due to increased wave action closer to shore, resulting in the lateral erosion of the coastline (Bruun, 1962). The rollover model describes how sediment barriers (e.g. barriers across river mouths) migrate landwards due to overwash and accumulation of sediment on the landward side of the barrier (Pethick, 1984). The drowning model (which applies to rocky coastlines) is based on sea level rise and coastal gradient, and describes how coastal features are flooded via inundation (Pethick, 1984). It must be noted that all three responses can occur along the same coastal strip, provided there is a variable coastal geomorphic structure present.

The Eden DM coastline was initially subdivided and delineated into sandy and rocky sections visually, using 2008 SPOT imagery and Google Earth. Twenty-seven sandy beaches or coastal sections were identified (see **Table 2-1** and **Figure 2-3**).

Table 2-1 Eden DM sandy beaches/coastal sections.

1	Witsand	15	Hartenbos-Glentana
2	Westfield	16	Wilderness
3	Duiwenhoks	17	Sedgefield-Goukamma
4	Maalhoek	18	Walker’s Bay
5	Morris Point	19	Buffelsbaai
6	Stilbaai	20	Plettenberg Bay
7	Preekstoel	21	Beacon Island
8	Ystervarkfontein	22	Lookout Rocks
9	Le Grange Bay	23	Keurbooms
10	Vinbekbaai	24	Bloubankies
11	Gouritsmond	25	Arch Rock
12	Visbaai	26	Tsitsikamma
13	Vleesbaai	27	Nature’s Valley
14	Mossel Bay		

Long-term horeline evolution, whether eroding, accreting or dynamically stable, can be determined by the measurement of the shoreline position over time. This can be done using a large variety of techniques, dependent on available data sources, accepted error ranges, time and budget (as described in Moore, 2000). The initial objective of the project with regards to shoreline evolution modelling was to use the coastal setback line methodology developed by Ferreira et al. (2006) in order to calculate the rates of shoreline evolution for sandy beaches along the Eden DM coastline, while using a simple inundation drowning model for the rocky sections of coastline. The shoreward extent of vegetation on the coastal foredune was used as the indicator for the shoreline, due to the unreliability inherent in using the wet sand-dry sand high water mark line (tidal, seasonal and storm variability) (Moore, 2000). The shoreward foredune vegetation line also provides the best indication of the transition between beach and marine processes and aeolian processes. Three sets of imagery were acquired to delineate the shoreline, namely 2008 SPOT satellite imagery (10 m pixel resolution), 2006 1:10 000 scale colour orthophotos, and 1985 1:150 000 scale black and white aerial photos. Although the shoreline was easily detected on the higher resolution colour orthophotos, it was difficult to delineate in areas on the SPOT and aerial photo imagery due to the lower resolution. Also, it was difficult to distinguish between darkly coloured vegetation and rock outcrops, and lightly coloured beaches and breaker zones on the aerial photos. Georeferencing was also difficult between the aerial photos and SPOT/orthophoto imagery (see **Figure 2-2**), with similar features hundreds of metres apart in most cases. The resolution and georeferencing issues therefore made the calculation of shoreline evolution rates difficult, with the rates of change calculated likely to be highly unreliable.

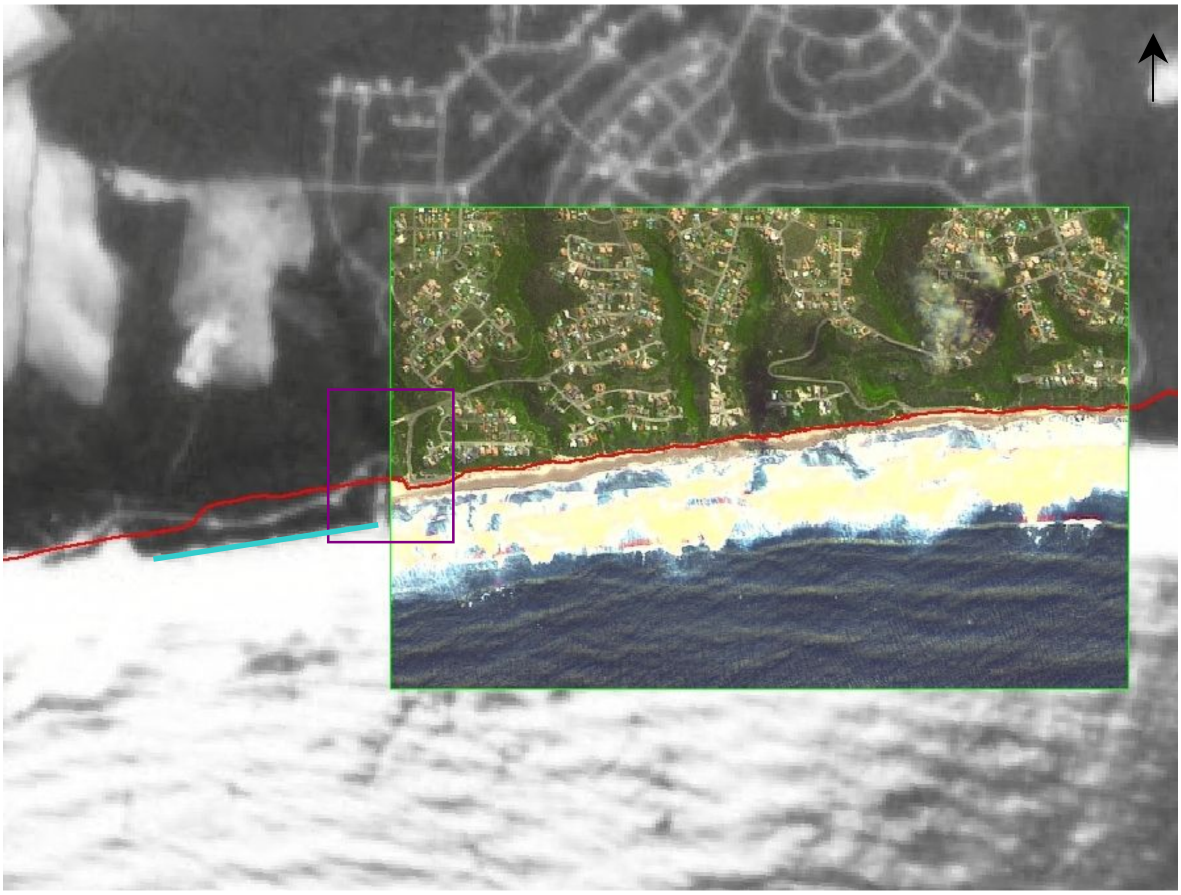

Figure 2-2 1985 1:150 000 aerial photo with 2008 SPOT imagery inset. Georeferencing discrepancy in the form of a shifted road split highlighted in the purple box. This shift may lead to an incorrect distance between the two shorelines (2008 shoreline in red, portion of 1985 shoreline in blue), and hence the shoreline evolution rates being miscalculated.

A more simplified approach was therefore undertaken. Due to the DEM not extending outwards entirely along the coastline, only the sandy beach areas as digitised from the 2008 SPOT imagery (due to the SPOT imagery having the greatest shoreline coverage) were used in modelling the extent of shoreline migration (see **Figure 2-3**).

The simplified equation: $X_2 = X_1 + (SLR/sin_a)$

(where X_1 – old shoreline position, X_2 – new shoreline position, SLR – future sea level rise +0.75 m at 2050, +2 m at 2100), a = slope angel from the DEM at X_1)

was used to calculate the shoreward migration of the shoreline. The same equation was applied to the position of the river/estuary banks (also delineated from 2008 SPOT imagery) in order to determine the possible change in the lateral (i.e. perpendicular to the longitudinal axis of the river) extent of the tidal reach.

It must be noted that the vertical resolution of the DEM (~ 3-4 m) and 10 m pixel resolution of the 2008 SPOT imagery does not allow for highly accurate and detailed predictions to be made. The modelling results should be used in a more regional approach, where the swash/flood and shoreline/tidal reach evolution lines are used to identify possible vulnerable areas. Future detailed studies at these specific areas can accurately determine the amount of land that can be expected to be eroded or inundated through sea level rise and storm surges or flooding.

Figure 2-3 2008 SPOT imagery with delineated sandy coastlines and estuary/river banks.

3. MODEL RESULTS

3.1 EXTREME SEA LEVEL AND ESTUARY FLOODING MODELLING

2.5 mamsl, 4.5 mamsl and 6.5 mamsl swash run-up contour lines, which could be produced during an extreme storm swell and sea level event as described above, were generated from the 10 m x 10 m resolution DEM for the whole Eden DM coastline. Areas vulnerable to erosion and inundation from extreme sea levels related to large swells/storm surges, and estuarine flooding and back flooding were identified, and described below in **Table 3-1** to **Table 3-4**.

Table 3-1 Areas vulnerable to coastal, estuarine and fluvial erosion and inundation along the Eden DM coastline, from Witsand to Gouritsmond.

Area	Coastline, Estuarine and Fluvial Erosion and Inundation
Witsand	Cape Infante may focus large storm swell energy, resulting in possible swash run-ups in the range of 4.5-6.5 mamsl in the vicinity of Witsand. This would result in erosion of the Breede Estuary sand bar, as well as the thin covering of sediment overlying the rock outcrops in front of Witsand. Coastal property and roads ~ 50-70 m from the shoreline will be damaged (see **Figure 3-1**). Flooding and back flooding of the estuary may inundate marinas, jetties and oyster beds at Port Beaufort, and cause flood damage to farmhouses and roads along the Breede River and its associated tributary floodplains.
Witsand to Duiwenhoks estuary	A swash run-up of 4.5 mamsl for this area is possible during a large storm event, although offshore rock outcrops may reduce wave energy and run-up. Beach erosion, with dune and aeolianite cliff undercutting and collapse is possible with increased storm frequency.
Duiwenhoks estuary	A 4.5 mamsl swash run-up would cause erosion of the Duiwenhoks Estuary sand bar. Flooding and back flooding would cause extensive inundation of the Duiwenhoks floodplain, including the settlement of Mazepa and numerous farmhouses. Aeolianite cliffs on the eastern head of the Duiwenhoks estuary protect Puntjie.
Duiwenhoks estuary to Skurwebaai	A swash run-up of 4.5 mamsl for this area is possible during a large storm event, although offshore rock outcrops may reduce wave energy and run-up in parts. Beach erosion, with dune/aeolianite cliff undercutting and collapse is possible with increased storm frequency.
Skurwebaai to Stilbaai	A 2.5 mamsl swash run-up can be expected due to the predominantly rocky nature of the shoreline. Jongensfontein would be unaffected in the event of a 2.5 mamsl swash run-up, although bigger storm events and run-ups would damage the first line of coastal properties and infrastructure ~ 50-70 m from the shoreline. Increasing large storm run-ups in the future may damage the archaeologically important, Middle Stone Aged (~ 70 000 years before present (BP)) Blombos Cave.
Stilbaai	Morris Point may focus large storm swell energy, resulting in possible swash run-ups in the range of 4.5-6.5 mamsl in the vicinity of Stilbaai. This would result in the erosion of the Goukou Estuary sand bars, as well as causing damage to the first block of houses along western Stilbaai and Preekstoel, and a large portion of Lappiesbaai if the foredune is breached by swash run-up (see **Figure 3-1**). The Goukou River floodplain and large portions of Stilbaai adjacent to the estuary and river are also vulnerable to flooding and back flooding. Damage to the R323 road due to flooding may occur.
Stilbaai to Gouritsmond	A swash run-up of 4.5 mamsl for the sandy coastline between Stilbaai and Vinbekbaai is possible during a large storm event, although offshore rock outcrops may reduce wave energy and run-up in parts. Swash run-up would be reduced to 2.5 mamsl between Vinbekbaai and Gouritsmond due to the rocky nature of the shoreline. Beach erosion, with dune and aeolianite cliff undercutting and collapse is possible with increased storm intensity and frequency. The coastal road between Ystervarkpunt and Gouritsmond may be damaged in parts due to future undercutting.

Figure 3-1 2.5 mamsl (red), 4.5 mamsl (orange) and 6.5 mamsl (blue) swash and flood contour lines for Witsand (a) and Stilbaai (b). Note the erosion of the respective estuary sand bars even with a 2.5 mamsl swash run-up, and the inundation of the Goukou River floodplain.

Table 3-2 Areas vulnerable to coastal, estuarine and fluvial erosion and inundation along the Eden DM coastline, from Gouritsmond to Groot-Brakrivier.

Area	Coastline, Estuarine and Fluvial Erosion and Inundation
Gouritsmond	A 2.5-4.5 mamsl swash run-up can be expected at Gouritsmond due to the relatively rocky nature of the coastline, with a small portion of coastal property along Voelklip possibly being affected by higher run-ups. Extensive Goukou River floodplain inundation along the lower reaches of the river may occur as a result of flooding and back flooding.
Cape Vacca to Vleesbaai	Cape Vacca and Vleespunt may focus large storm swell energy, resulting in possible swash run-ups in the range of 4.5-6.5 mamsl in the vicinity of Visbaai and Vleesbaai town. Visbaai is unpopulated, and swash run-ups will cause possible beach erosion, dune undercutting and collapse, and damage to the road along Cape Vacca. The majority of Vleesbaai town is currently protected by a rocky coastline, with only the northernmost sandy coastline section of Vleesbaai (first line of coastal developments) being possibly damaged during a 6.5 mamsl swash run-up.
Vleesbaai to Danabaai	A 2.5-4.5 mamsl swash run-up is likely in this area during an extreme event, causing beach erosion, dune undercutting and collapse, and erosion of the Blinde Estuary sand bars. Dune undercutting and collapse at Danabaai may cause damage to coastal property and infrastructure, with only ~ 30 m of the shoreward section of the vegetated foredune remaining undeveloped.
Pinnacle Point to Cape St. Blaize	The area is currently protected by rocky coastline and a swash run-up of even 6.5 mamsl (although 2.5 mamsl would be expected in the case of an extreme storm) would have no affect other than possible cliff undercutting. Pinnacle Point Cave 13B, which is a very important Middle Stone Age (~ 40 000-165 000 BP) archaeological site, may be damaged over time however.
Mossel Bay	Cape St. Blaize may focus large storm swell energy, resulting in possible swash run-ups in the range of 4.5-6.5 mamsl along Mossel Bay. These run-ups would cause damage to coastal developments towards Cape St. Blaize, as well damaging Mossel Bay Harbour. Large swell may inundate the N2 road and railway line, as well as damage them through cliff undercutting.
Diasstrand, Bayview and Voorbaai	A small portion of undeveloped foredune (~ 10-15 m high and 10-70 m wide) currently protects coastal and residential areas, and would prevent a swash run-up of 6.5 mamsl causing damage.
Hartenbos	The Hartenbos River estuary and floodplain are highly vulnerable to flooding, with a large portion likely to be inundated if estuary flood waters reach 2.5 mamsl (see **Figure 3-2**). Larger swash run-ups would also damage coastal property along northern Hartenbosstrand due to development removing the protective foredune barrier. Beach erosion and dune collapse might occur along the undeveloped foredune section towards Klein-Brakrivier.
Klein-Brakrivier	The Klein Brak River Estuary and floodplain are highly vulnerable to flooding, and as with Hartenbos Estuary a large portion is likely to be inundated if estuary flood waters reach 2.5 mamsl (see **Figure 3-2**). Klipheuwel would be flooded by a 2.5 mamsl flood, while the developed eastern bar of the Klein Brak Estuary could be damaged by a 4.5-6.5 mamsl swash run-up. Klein-Brakrivierstrand, Reebokstrand and Tergniet are currently protected by a thin undeveloped shoreward section of foredune (~ 10-20 m and 20-70 m wide).
Groot-Brakrivier	The Groot Brak River estuary and floodplain are also highly vulnerable to flooding, with central Groot-Brakrivier, Bergsig, The Island and N2 road all below the 2.5 mamsl flood line (see **Figure 3-2**). The western Groot Brak Estuary sand bar and suburb of Suiderkruis are also vulnerable to erosion and damage by a 4.5-6.5 mamsl swash run-up. Groot-Brakrivierstrand, Outeniquastrand and Glentana Beach are currently protected by a thin undeveloped shoreward portion of vegetated foredune (~ 10-20 m high and 20-50 m wide), except in parts where it has been removed through development and is vulnerable to erosion by 4.5-6.5 mamsl swash run-ups.

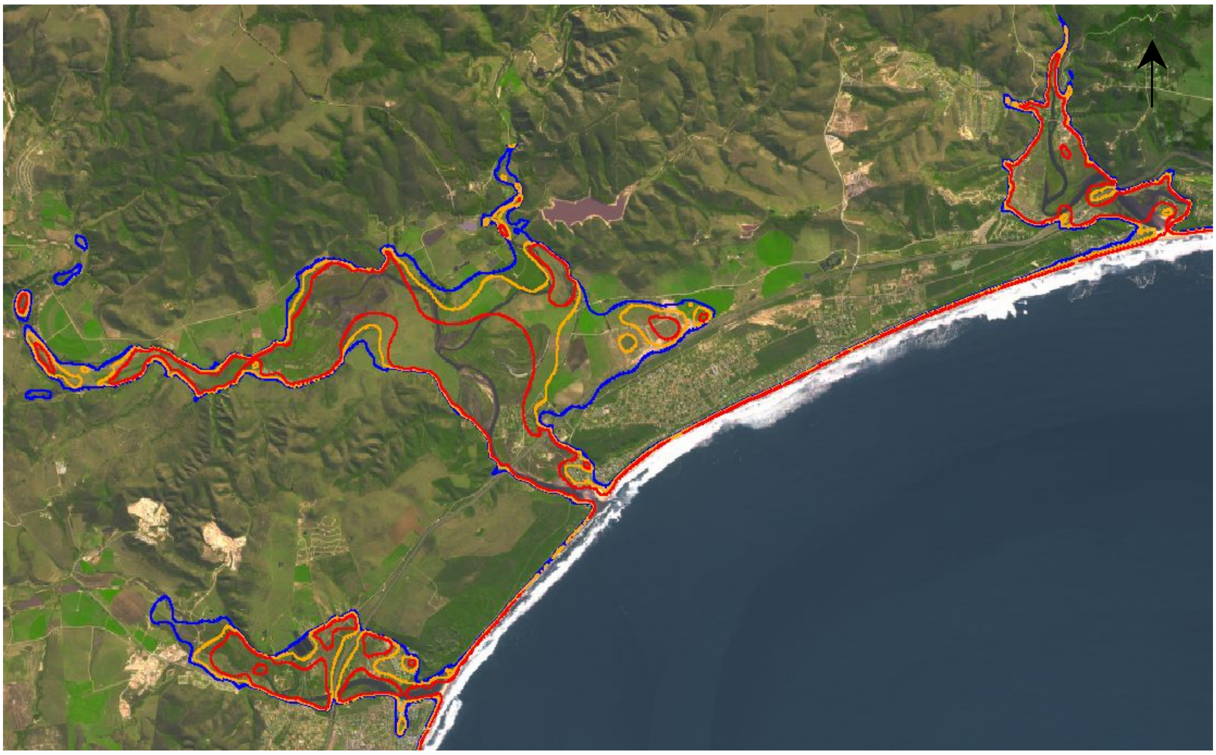

Figure 3-2 2.5 mamsl (red), 4.5 mamsl (orange) and 6.5 mamsl (blue) swash and flood contour lines for the Hartenbos, Klein Brak and Groot Brak Estuaries (from SW to NE). Note the large developed areas susceptible to possible estuarine flooding and back flooding.

Table 3-3 Areas vulnerable to coastal, estuarine and fluvial erosion and inundation along the Eden DM coastline, from Glentana Beach to the Robberg Peninsula.

Area	Coastline, Estuarine and Fluvial Erosion and Inundation
Glentana Beach to Wilderness	A 2.5 mamsl swash run-up can be expected due to the predominantly rocky nature of the shoreline, with sand bar erosion occurring at the Maalgate, Gwaing and Kaaimans Estuaries. Herolds Bay and Victoria Bay are both highly vulnerable to large swell events due to their pocket beach structure, and are likely to receive 6.5 mamsl swash run-ups during extreme events. This would cause extensive beach erosion and damage to coastal property and amenity infrastructure at both beaches.
Wilderness	West Wilderness is susceptible to beach erosion and coastal property damage by 4.5 mamsl swash run-ups. A large portion of western Wilderness is also vulnerable to flooding of the Touws River estuary. Wilderness East and Kleinkrantz is currently protected by a small undeveloped shoreward portion of vegetated foredune (~ 5-30 m high and 10-40 m wide), with the entire dune acting as a barrier between the ocean and very low relief Wilderness-Swartvlei Estuarine System.
Kleinkrantz to Sedgefield	Eastern Sedgefield adjacent to the Swartvlei Estuary, developments surrounding Swartvlei Lake, the lower reaches of the Karatara River floodplain, Groenvlei and the N2 and railway line where it crosses Swartvlei Estuary are all vulnerable to flooding and inundation. Sedgefield shoreline developments are currently protected by a thin portion of undeveloped foredune (~ 5-10 m high and ~ 50-70 m wide) and aeolianite cliffs (~ 20-30 m high and wide). Erosion and undercutting from successive storm events may put these developments at risk however, especially those situated on steeper cliffs more vulnerable to collapse.
Sedgefield to Goukamma Estuary	The coastline is likely to experience 2.5-4.5 mamsl swash run-ups, which may cause beach erosion, as well as dune and cliff undercutting and collapse. The Goukamma Estuary mouth bars may experience erosion. Some road damage via undercutting may occur between the Goukamma Estuary and Buffelsbaai.

Buffelsbaai	Buffelsbaai town is situated on a protruding headland, and will therefore likely experience the full energy of an extreme storm and swell event in the form of a 6.5 mamsl swash run-up. Coastal developments within 20 m of the shoreline, and 150 m from the tip of Walker Point, will be damaged by an extreme swell event. The bay itself will likely experience 4.5 mamsl swash run-ups, which will cause beach erosion, as well as dune and aeolianite cliff undercutting and collapse.
Knysna	The town of Knysna is protected from storm surges by the narrow width and rocky nature of The Heads, although the risk of flooding and back flooding of the estuary is high and a large portion of the town is vulnerable to inundation. Thesen's Island, Leisure Island, Brenton, Hunter's Home golf course, the portion of Knysna town centre south of the N2, the sewerage treatment works, the edge of Belvidere and the Knysna River floodplain up to the head of the estuary all fall below the 2.5 mamsl floodline (see **Figure 3-3**), which has been breached in the past.
Knysna to the Robberg Peninsula	Steep rocky cliffs dominate the coastline, therefore there is little risk to swash run-up damage and inundation. Noetsie Estuary is the exception, with erosion of the estuary mouth sand bar likely to occur due to it being a pocket bay beach. Sandbaai on the Robberg Peninsula may also be eroded during an extreme storm event.

Figure 3-3 2.5 mamsl (red), 4.5 mamsl (orange) and 6.5 mamsl (blue) swash and flood contour lines for the Knysna Estuary. Note the large developed areas susceptible to possible estuarine flooding and back flooding.

Table 3-4 Areas vulnerable to coastal, estuarine and fluvial erosion and inundation along the Eden DM coastline, from Plettenberg Bay to Nature's Valley.

Area	Coastline, Estuarine and Fluvial Erosion and Inundation
Plettenberg Bay	Despite a 6.5 mamsl swash run-up being likely due to the Robberg Peninsula focusing wave energy, Plettenberg Bay southwards of Beacon Island remains unaffected due to the current protection offered by a thin portion of undeveloped foredune (~ 10-20 m high, ~ 40-60 m wide) (see **Figure 3-4**). In contrast, the beach area between Beacon Island and Lookout Rocks will be highly eroded during a large storm event, with coastal developments also being vulnerable to damage due to development on and the removal of the foredune. The Piesang River estuary and floodplain are vulnerable to flooding and inundation, especially the caravan park, adjacent farmlands and part of the golf course along the river.
Keurbooms-Bitou Estuary	The Tides, Gansevlei, Bitou, Keurbooms and Diep River floodplains, suburbs of Anath and Matjiesfontein, and Stanley Island are all vulnerable to flooding and inundation below 2.5 mamsl (which has been breached in the past). Large swells and an associated 4.5-6.5 mamsl swash run-up may erode the entire estuary mouth bar and Lookout Beach, which has occurred in the past. A relatively undeveloped 10-20 m high foredune northeastwards of the estuary is present, although coastal development at Keurboomsstrand has resulted in some areas been vulnerable to large swash run-ups and dune erosion and undercutting.
Keurboomsstrand to Nature's Valley	A 2.5 mamsl swash run-up is expected, due to the shoreline being dominated by steep rocky outcrops. Estuary mouth sand bar erosion may occur at the Matjies and Sout Estuaries due to pocket beach related higher swash run-ups.
Nature's Valley	The coastal development front of Nature's Valley is currently protected by a thin portion of undeveloped foredune (~ 5-10 m high and ~ 70 m wide), although a ~ 150 m wide section of the town adjacent to the Groot Estuary is vulnerable to inundation from estuary flooding. A higher pocket beach enhanced swash run-up of 6.5 mamsl will erode the estuary mouth sand bars and beaches in the area.

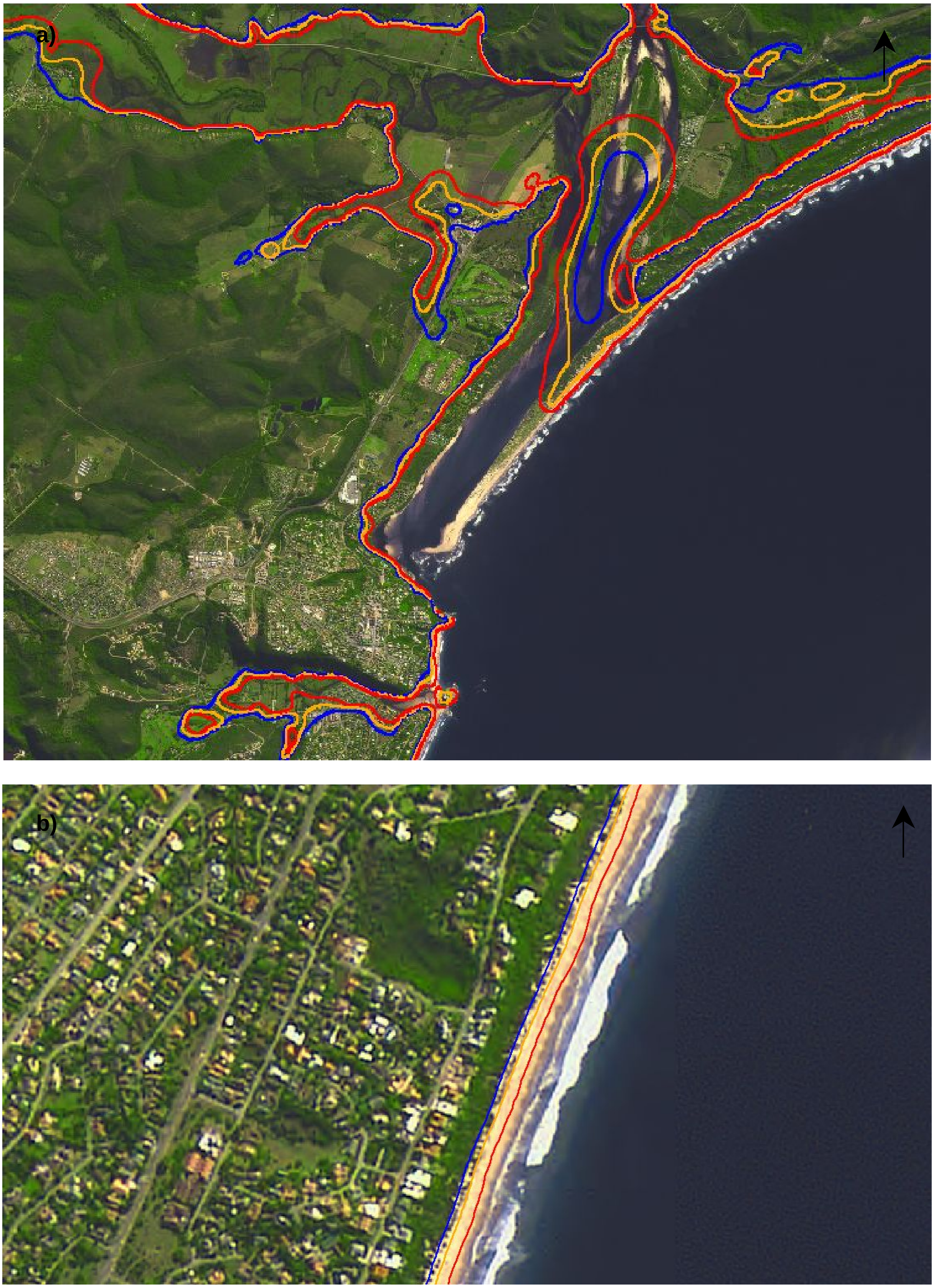

Figure 3-4 2.5 mamsl (red), 4.5 mamsl (orange) and 6.5 mamsl (blue) swash and flood contour lines for Piesang and Keurbooms-Bitou Estuaries (from SW to NE in a)). b) shows the current protective effect of undeveloped portions of the vegetated foredune at Plettenberg Bay.

3.2 SHORELINE AND TIDAL REACH EVOLUTION MODELLING

Future shoreline and tidal reach lines were modelled for both a 0.75 m and 2 m rise by 2050 and 2100 respectively. However the lateral evolution of both the shoreline and tidal reach lines were limited and within error for a 0.75 m rise, hence only the vulnerable areas for a 2 m rise were identified. There were also a number of data and methodological limitations as described in Section 2.2, which have reduced confidence limits in the results. A range of lateral evolution values have therefore been provided in **Table 3-5** and **Table 3-6**.

Table 3-5 Shoreline evolution along sandy coastlines within the Eden DM for a 2 m rise by 2100.

Sandy Coastline Section	Shoreline Evolution (for 2 m rise by 2100)
Witsand and Westfield	The shoreline is expected to move ~ 50-100 m inland in the vicinity of the Breede Estuary mouth eastern bar, with little movement landwards (~ 10 m) near Westfield due to the backing high gradient foredune.
Duiwenhoks	Shoreline may migrate landwards between 10-30 m, which will cause dune migration.
Maalhoek	Minor landward shoreline migration (~ 5-10 m) due to the backing high gradient foredune likely.
Morris Point, Stilbaai and Preekstoel	Possible landward shoreline migration of ~ 10-20 m. Shoreline evolution will cause the erosion and migration of the foredune, and hence damage to the first line of coastal property along the eastern section of Stilbaai.
Ystervarkfontein, Le Grange Bay and Vinbek Bay	Minor landward shoreline migration (~ 5-20 m) due to the backing high gradient foredune likely.
Gouritsmond, Visbaai and Vleesbaai	Minor landward shoreline migration (~ 5-20 m) due to the backing high gradient foredune likely. Despite this, possible dune undercutting and collapse over time at Vleesbaai and Danabaai may occur, causing damage to coastal property.
Mossel Bay and Hartenbos to Glentana	A ~ 30-40 m landward shoreline movement along low gradient coastal areas may occur. Dune degradation would result due to a buffer area, which would allow for natural dune migration, being absent along most of the developed section of this coastline.
Wilderness	Minor landward shoreline migration (~ 5 m) due to the backing high gradient foredune likely.
Sedgefield to Goukamma and Buffelsbaai	Minor landward shoreline migration (~ 5 m) along high gradient dune and aeolianite cliff areas is possible, increasing to ~ 10-30 m along lower gradient dune fields. Parts of Sedgefield are at risk to possible long-term dune migration.
Plettenberg Bay, Beacon Island, Lookout Rocks, Keurbooms and Bloubankies	Landward migration of the shoreline by ~ 5-20 m is possible, dependant on the dune gradient. This may affect coastal developments where the foredune has already been removed or degraded e.g. between Beacon Island and Lookout Rocks.
Nature's Valley	Landward migration of the shoreline by ~ 20-30 m likely, causing dune migration and the possible movement of dunes into the first line of coastal developments at Nature's Valley (see **Figure 3-5**).

Figure 3-5 Shoreline and tidal reach evolution modelling for a) Knysna and b) Nature's Valley. 2008 shoreline and estuary/river banks represented by red and green lines respectively. 2100 shoreline and estuary/river banks represented by blue and red squares respectively.

Table 3-6 Tidal reach evolution for estuaries within the Eden DM based for a 2 m rise by 2100.

Estuary	Tidal Reach (for 2 m rise by 2100)
Breede	Tidal reach may laterally extend only 30 m inland due to relatively steep river bank slopes. Port Beaufort marinas, jetties and oysterbeds may be inundated however.
Duiwenhoks	The tidal reach may laterally extend by ~ 50-100 m along low gradient flood plains, resulting in flooding risk to farmlands at Mazepa.
Goukou	The tidal reach may extend laterally inland by ~ 100 m along the Goukou Estuary banks, which would require the retreat of large frontal estuary developments. The tidal reach may also extend ~ 30-50 m laterally inland along low gradient river flood plain sections further up the river course.
Gouritz	The tidal reach may extend laterally inland by ~ 50-100 m along low gradient flood plains.
Hartenbos, Klein Brak and Groot Brak	Tidal reach may increase laterally inland by ~ 20-30 m within the Hartenbos Estuary, affecting some development along the estuary banks. This increases to ~ 100 m along the Klein Brak and Groot Brak Rivers and estuaries, affecting Klipheuwel in Klein Brak and Groot-Brakrivier town centre, Bergsig and The Island within the Groot Brak Estuary.
Swartvlei	Tidal reach may extend laterally inland by ~ 50-100 m along the upper low gradient sections of the Swartvlei Estuary, affecting the estuary fronting developments of upper Sedgefield. The lateral tidal reach decreases to ~ 5-10 m seawards due to the increase in coastal foredune gradient.
Goukamma	Tidal reach may extend laterally inland by ~ 50-100 m along the low gradient sections of the Goukamma Estuary at the estuary mouth and along the river floodplains.
Knysna	An increase in lateral tidal reach of ~100 m may occur within the estuary south of Knysna town centre, affecting Thesen's and Leisure Island, decreasing to ~ 20 m towards Brenton and the estuary head (see **Figure 3-5**).
Piesang and Keurbooms-Bitou	Lateral tidal reach at the Piesang Estuary may increase by ~ 50 m in 2100, affecting the caravan park and golf course. Future lateral tidal reach at the Keurbooms-Bitou Estuary varies between ~ 30-100 m, with similar areas identified by the swash run-up modelling being affected.
Groot	Lateral tidal reach may extend by ~ 30-90 m along the western banks of the Groot Estuary, affecting the adjacent estuary developments of Nature's Valley.
Minor estuaries	The Blinde, Maalgate, Gwaing, Kaaimans, Noetzie and Sout Estuaries may have minor lateral tidal reach increases of ~ 5-10 m. This minor lateral reach increase is usually due to steep estuary and river banks formed from river incision into hard geological substrate.

4. RECOMMENDATIONS

Extreme sea level, estuary flooding, shoreline and tidal reach evolution modelling has shown that the Eden DM is vulnerable to coastal hazards induced by sea level rise. Although the future shoreline and tidal reach lines modelled will take ~ 90 years to evolve and migrate at a relatively slow rate, planning must be put in place now to prevent future extensive damage to coastal towns and developments. Extreme sea level and estuary/river flooding events caused by large storms are the present and future concern however, with large coastal areas along the Eden DM coastline being vulnerable to high energy and often highly hazardous events. The following is recommended:

- Western Cape level:
  - Develop large-scale sea level rise flooding models for the remainder of the Western Cape coastline, namely from Gordon's Bay to Witsand (Overberg DM coastline) and from Silverstroom Strand to Hoekbaai (West Coast DM coastline).
  - Conduct modelling updates of these models at least every 5 years. The current modelling undertaken in this project is at a broad scale and coarse, and new global and local climate change data and scenarios, local coastal geomorphic data and methodologies will help improve shoreline evolution prediction.
  - With regards to the Eden DM coastline, future modelling updates should focus on the vulnerable areas identified, in order to improve the resolution of the modelling i.e. each specific stretch of sandy coastline and estuary should have its own future coastal evolution model developed.
- Basic coastal baseline data upgrade:
  - Develop onshore and offshore 1 m x 1m DEMs (with an approximately 0.5 m vertical resolution) for the Eden, Overberg and West Coast DM coastlines.
  - Conduct beach profiling at selected beaches along the coastline, as well as detailed geophysical offshore bathymetry surveys, in order to determine various local variables and parameters that can be used in future detailed numerical modelling (see Eskom Holdings Ltd 2009a, 2009b and 2009c for detailed modelling examples).
  - Collection of all available photographic and remote sensing imagery, ensuring it is correctly georeferenced and stored in a central database for simple access for future coastal modelling.
- Eden District Municipality level:
  - Enforce the coastal buffer zone as defined in the National Environmental Management: Integrated Coastal Management Act (Act 24 of 2008) immediately, and prevent any further development within 100 m of the high water mark.

- Strictly monitor (and preferably prevent) future development below the 6.5 mamsl swash contour and 4.5 m estuary/river flood contour, as well as on any undeveloped portions of foredune that are currently backed by development.

- Ensure development along the coastal foredune takes into account future landward dune migration, and a further dune migration buffer zone should be put in place behind the coastal buffer zone.

- Undertake a coastal education drive to make coastal residents aware of the importance of maintaining indigenous vegetated foredunes, as well as the possible hazards and risks faced if these natural barriers are removed.

5. REFERENCES

Appeaning Addo, K., Walkden, M. and Mills, J. P. (2008). Detection, measurement and prediction of shoreline recession in Accra, Ghana. ISPRS Journal of Photogrammetry and Remote Sensing, 63, 543-558.

Blake, D. and Hartnady, C. J. H. (2009). City of Cape Town Disaster Risk Assessment – Coastal zone hazards. Prepared by Umvoto Africa (Pty) Ltd. in associated with Aurecon for the City of Cape Town Disaster Risk Assessment, City of Cape Town (June 2009), 34pp.

Brundrit, G. B. (1984). Monthly mean sea level variability along the west coast of southern Africa. South African Journal of Marine Science, 2, 195-203.

Brundrit, G. B. (2008). Global climate change and adaptation – A sea-level rise risk assessment. Phase one: Sea-level rise model. Prepared for the City of Cape Town by LaquaR Consultants CC, 36 pp.

Bruun, G. B. (1962). Sea-level rise as a cause of shore erosion. American Society of Civil Engineers, Journal of the Waterways and Harbours Division, 88, 117-130.

Cazenave, A., Chambers, D. P., Cipollini, P., Fu, L. L., Hurell, J. W., Merrifield, M, Nerem, S., Plag, H. P., Shum, C. K. and Willis, J. (2009). Sea level rise: regional and global trends. OceanObs2009, 21-25 September 2009, Italy.

Church, J. A., White, N. J., Aarup, T., Wilsong, W. S., Woodworth, P. L., Domingues, C. M., Hunter, J. R. and Lambeck, K. (2008). Understanding global sea levels: past, present and future. Sustainability Science, 3, 9-22.

Eskom Holdings Ltd. (2009a). Environmental Impact Assessment for the proposed nuclear power station ("Nuclear-1") and associated infrastructure: Appendix E9 – Estimating the 1:100 year flood line from the sea. Prepared by Prestege Retief Dresner Wijnberg (Pty) Ltd for Eskom Holdings Ltd, 15pp.

Eskom Holdings Ltd. (2009b). Environmental Impact Assessment for the proposed nuclear power station ("Nuclear-1") and associated infrastructure: Appendix E16G – Coastal engineering investigations: Thyspunt. Report 1010/02/102. Prepared by Prestege Retief Dresner Wijnberg (Pty) Ltd for Eskom Holdings Ltd, 45pp.

Eskom Holdings Ltd. (2009c). Environmental Impact Assessment for the proposed nuclear power station ("Nuclear-1") and associated infrastructure: Appendix E16H – Numerical modelling of coastal processes: Thyspunt. Report 1010/02/101. Prepared by Prestege Retief Dresner Wijnberg (Pty) Ltd for Eskom Holdings Ltd, 15pp.

Fairhurst, L. (2008). Global climate change and adaptation – A sea-level rise risk assessment. Phase two: Risk and impact identification. Prepared for the City of Cape Town by LaquaR Consultants CC, 82 pp.

Ferreira, O., Garcia, T., Matias, A., Taborda, R. and Dias, J. A. (2006). An integrated method for the determination of set-back lines for coastal erosion hazards on sandy shores. Continental Shelf Research, 26, 1030-1044.

Hughes, P., Brundrit, G. B. and Shillington, F. A. (1991). South African sea-level measurements in the global context of sea-level rise. South African Journal of Science, 87, 447-453.

Intergovernmental Panel on Climate Change (IPCC). (2001). Climate change 2001: The scientific basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom.

Intergovernmental Panel on Climate Change (IPCC). (2007). Climate change 2007: The physical science basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom.

Mather, A. A. (2008). Coastal erosion and sea level rise. IMIESA (Institute of Municipal Engineering of Southern Africa journal), March 2008, 49-70.

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

Moore, L. J. (2000). Shoreline mapping techniques. Journal of Coastal Research, 16 (1), 111-124.

Pethick, J. (1984). An introduction to coastal geomorphology. Edward Arnold, London, United Kingdom, 260pp.

Rahmstorf, S. (2007). A semi-empirical approach to projecting future sea-level rise. Science, 315 (19 January), 368-370.

Republic of South Africa. (2008). National Environmental Management: Integrated Coastal Management Act (Act 24 of 2008).

Small, C. and Nicholls, R. J. (2003). A global analysis of human settlements in coastal zones. Journal of Coastal Research, 19 (3), 584-599.

Smith, A. M., Guastella, L. A., Bundy, S. C. and Mather, A. A. (2007). Combined marine storm and Saros spring high tide erosion events along the KwaZulu-Natal coast in March 2007. South African Journal of Science, 103, 274-276.

Theron, A. K. and Rossouw, M. (2008). Analysis of potential coastal zone climate change impacts and possible response options in the southern African region. Science Real and Relevant: 2nd CSIR Biennial Conference, CSIR International Convention Centre Pretoria, 17-18 November 2008, 10pp.

University of New South Wales (UNSW) Climate Change Research Centre (CCRC). (2009). The Copenhagen Diagnosis: Updating the world on the latest climate science. UNSW CRCC, Sydney, Australia, 60pp.

Vermeer, M. and Rahmstorf, S. (2009). Global sea level linked to global temperature. Proceedings of the National Academy of Sciences, 106 (51), 21527-21532.

Woodworth, P. L., Aman, A. and Aarup, T. (2007). Sea level monitoring in Africa. African Journal of Marine Science, 29 (3), 321-330.