**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 1 Report: West Coast District Municipality Sea Level Rise and Flood Risk Literature Review

**First Draft**

**March 2011**

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| **REPORT TITLE** | **:** | **Phase 1 Report: West Coast District Municipality Sea Level Rise and Flood Risk Literature Review** |
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UMVOTO

# EXECUTIVE SUMMARY

(to be included in Final document)

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| | | |
|---|---|---|
| % | - | percent |
| ~ | - | approximately |
| > | - | greater than |
| = | - | equal to |
| °C | - | degrees Celsius |
| AR4 | - | Fourth Assessment Report |
| BP | - | years before present |
| cm | - | centimetre |
| $CO_2$ | - | carbon dioxide |
| CPZ | - | Coastal Protection Zone |
| CCRC | - | Climate Change Research Centre |
| CSIR | - | Centre for Scientific and Industrial Research |
| CZMU | - | Coastal Zone Management Unit |
| DM | - | District Municipality |
| DRR | - | disaster risk reduction |
| DEA&DP | - | Department of Environmental Affairs and Development Planning |
| E | - | east |
| e.g. | - | for example |
| etc. | - | etcetera |
| EEZ | - | Exclusive Economic Zone |
| ENSO | - | El-Nino Southern Oscillation |
| et al. | - | as well as |
| GIA | - | glacial isostatic adjustment |
| GIS | - | Geographic Information System |
| hr | - | hour |
| HAT | - | Highest Astronomical Tide |
| i.e. | - | that is |
| IDP | - | Integrated Development Plan |
| ICM | - | Integrated Coastal Management |
| ICZM | - | integrated coastal zone Management |
| IPCC | - | Intergovernmental Panel on Climate Change |
| km | - | kilometre |
| $km^2$ | - | kilometre squared |
| KZN | - | KwaZulu-Natal |
| LM | - | Local Municipality |
| LAT | - | Lowest Astronomical Tide |
| LGM | - | Last Glacial Maximum |
| LIM | - | Last Interglacial Maximum |
| LLD | - | Land Levelling Datum |
| m | - | metre |
| $m^3$ | - | metres cubed |
| Ma | - | millions of years |
| ML | - | Mean Level |
| mm | - | millimeter |
| Max. | - | maximum |
| MEC | - | member of the Executive Council |
| Min | - | minimum |
| mamsl | - | metres above mean sea level |
| mbmsl | - | metres below mean sea level |
| MHWN | - | Mean High Water Neaps |
| MHWS | - | Mean High Water Springs |
| MLWN | - | Mean Low Water Neaps |
| MLWS | - | Mean Low Water Springs |

| | | |
|---|---|---|
| N | - | north |
| No. | - | number of |
| NAO | - | North Atlantic Oscillation |
| NNW | - | north-northwest |
| NEMA | - | National Environmental Management Act |
| ppm | - | parts per million |
| PDO | - | Pacific Decadal Oscillation |
| PRDW | - | Prestege Retief Dresner Wijnberg |
| R | - | Rand |
| SDF | - | Spatial Development Framework |
| SSE | - | south-southeast |
| SRES | - | Special Report on Emission Scenarios |
| TAR | - | Third Assessment Report |
| TMG | - | Table Mountain Group |
| UNSW | - | University of New South Wales |
| W | - | west |
| WRC | - | Water Research Commission |
| WNW | - | west-northwest |
| WBGU | - | German Advisory Council on Global Change |
| WCDMA | - | Western Cape District Management Area |

# 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 Western Cape coastline within the West Coast District Municipality (DM), from Silwerstroom Strand (at the boundary of the City of Cape Town) to Hoekbaai (at the provincial boundary with the Northern Cape). This forms the second phase (in association with the Overberg DM) in undertaking a sea level rise and flood risk assessment for the Western Cape coastline (other than the City of Cape Town municipal area), with the Eden DM being completed as part of the first phase in 2010 (DEA&DP 2010a, 2010b and 2010c). This project is being done in association with a coastal setback line study for the Overberg DM, with the coastal setback line methodology being established and tested in the City of Cape Town and Saldanha Bay Local Municipality (LM) in 2010 (DEA&DP 2010d and 2010e).

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 be undertaken for this project. 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 West Coast DM, based on a refined rapid assessment methodology described by Blake and Hartnady (2009) and used in the Eden DM sea level rise risk assessment (DEA&DP, 2010c).

This report reviews the literature collected during Phase 1. **Chapter 1** provides a brief introduction to the global issue of climate change sea level rise, and its local relevance. **Chapter 2** describes the administrative, climatic, offshore wave and coastal geology and geomorphology features of the study area. **Chapter 3** provides an overview of current understanding on global sea level rise, whereas **Chapter 4** focuses on sea level rise in the South African context. **Chapter 5** provides a review of current national, regional and local coastal and related legislation. **Chapter 6** concludes this report and provides recommendations.

The Phase 2 and 3 reports detail the sea level and flood inundation GIS model and coastal hazard risk assessment methodologies and results respectively, with Phase 3 also detailing the possible mitigation and adaptation measures for sea level rise.

## 1.2 THE COASTAL ZONE AND CHANGING SEA LEVELS

The coastal zone can be defined as the interface and transition between the sea and land, and plays a number of important ecological, social and economical roles. The wide range of natural habitats results in coastal zones often having very high biodiversities. Approximately 1.2 billion people (23% of the world's 1990 population) live within 100 m elevation and 100 km distance from the shoreline (at a density of three times the global average), while almost 160 million people in turn live less than 1 m below current mean sea level (Small and Nicholls, 2003). In South Africa, approximately 30% of the country's population lives near the coast (Theron and Rossouw, 2008). A large variety of important economic and social activities therefore also take place within the coastal zone, including agriculture, tourism, recreation, manufacturing and transportation to name a few generalised examples. 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 Langebaan and Saldanha Bay area.

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). 34% of the world's and 80% (~ 3000 km) of South Africa's coastline is composed of sandy beaches. Sandy beaches are at highest risk to coastal erosion, and sea level rise will exacerbate the erosion already taking place at 70% of the world's beaches, and possibly initiate erosion in new areas (Mather, 2008). 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 as wetlands, mangroves, estuaries etc.

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 e.g. the $125 billion damage and 1800 deaths caused by Hurricane Katrina (Cartwright, 2009a and Church et al., 2008). People have been adapting to coastal zone variability for as long as human civilization has been present. Climate change induced sea level rise will amplify historic variability and introduce new coastal zone dynamics however, making it difficult for coastal populations to adapt (Cartwright, 2009a). A global sea level rise of 2 mm/year (two thirds of the current rate) would affect approximately 9 million people in forty deltas worldwide by 2050 (without taking into account increased exposure to storm surges) (Church et al., 2008). Small and Nicholls (2003) found that 200 million people lived within the 1 in 1000 year storm surge line in 1990, and this figure was expected to increase to 600-800 million people by 2100. The least developed and poor are often at most risk to sea level rise, and Dasgupta et al. (2007) state that a 1 m and 5 m rise in sea level would affect 56 million and 245 million people in 84 developing countries respectively. Both affluent and non-affluent coastal residents will be affected by climate change induced sea level rise along the West Coast DM coastline e.g. possible damage to high cost holiday homes, as well as fishing harbours that poorer coastal residents make use of for subsistence fishing.

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). Sea levels from the geological past however provide important information on changes in polar ice masses, as well as the rates of and amount of sea level change. These past sea level variations also provide perspective with regards to how the

Earth's processes work over long time periods, instead of focusing on the short term future as many policy developers and much of the public often do. 35 million years ago (Ma) during the Eocene was the last time the Earth was free of ice, and sea levels were 70 m above present mean sea level (German Advisory Council on Global Change (WBGU), 2006). During the Pliocene (~ 3 Ma) average global mean temperature was 2-3 °C warmer, and sea level was 25-35 m higher, corresponding to a 10-30 m rise per degree Celsius (Rahmstorf, 2007). The Last Interglacial Maximum (LIM), at approximately 125 000 years before present (BP) during the Pleistocene, experienced average global sea levels between 4-6 m higher than current sea level (known as the "Eemian High"). Polar temperatures were 3-5 °C higher due to the Earth's orbital variation (i.e. Milankovich cycles), and as a result large scale melting of the Greenland Ice Sheet occurred. The LIM elevated sea levels are reflected in the southern Cape, where beach deposits are present at 6 metres above mean sea level (mamsl) at Swartvlei and 8.5 mamsl at Groot Brak (Carr et al., 2010). These correspond with other 5-7 mamsl shoreline deposits in Durban and the rest of South Africa (Carr et al., 2010). Global sea level fell to 120 metres below mean sea level (mbmsl) during the Last Glacial Maximum (LGM) at 20 000 BP, but rose rapidly again at 10-40 mm/year (1-4 m/century) until 7000 BP (Church et al., 2008). The rate of sea level rise then slowed until reaching present sea level at 3000-2000 BP (Church et al., 2008). Geological records for the last 2000 years prior to tide gauge records indicate minor sea level changes between 0-0.2 mm/year, with the onset of modern sea level rise occurring between 1850 and 1950 (Intergovernmental Panel on Climate Change (IPCC), 2007). Holocene sea level change in South Africa varied slightly from the global average described above. Sea level rose at about 8mm/year between 9000-8000 BP, and continued to rise to a highstand of ~ 3.5 mamsl at approximately 4500 BP (Ramsay, 1995). Sea level then regressed to its present level at ~ 3900 BP, dropped further to ~ 2 mbmsl at 3000 BP, and then rose to ~ 1.5 mamsl at 1600 BP before falling to its present level at 900 BP (Ramsay, 1995). These Holocene sea level changes are well recorded in various coastal geomorphic features along the West Coast DM coastline, including Verlorenvlei at Elands Bay (Meadows et al., 1996), the Sixteen Mile Beach and Dune Complex north of Yzerfontein (Franceschini and Compton, 2006) and Langebaan Lagoon (Compton, 2001). Eleven overlapping Pliocene to Pleistocene (~ 3 Ma to ~ 8000 BP) marine terraces up to 90 mamsl, marked by wave cut platforms and overlain by raised beach deposits (both indicating periods of sea level rise), can also be observed in cliff outcrops north of the Olifants River (De Beer et al., 2002).

Sea levels have risen and fallen extensively during the past, and will continue to do so in the future through natural or human induced climate change. Sustainable and holistic integrated coastal zone management (ICZM) and gender-sensitive disaster risk reduction (DRR) are therefore imperative in order to prevent large ecological, economic and human life losses from more frequent, sea level rise induced coastal hazards in the future.

# 2. PROJECT STUDY AREA

## 2.1 ADMINISTRATIVE GOVERNANCE

The sea level rise assessment study area extends from Silwerstroom Strand, at the municipal boundary with the City of Cape Town, northwestwards to Hoekbaai, at the provincial boundary with the Northern Cape (~ 450 km in length), and falls within the West Coast DM. The West Coast DM covers an area of 31 101 $km^2$ and has a population of approximately 286 751 people (Statistics South Africa, 2008). The West Coast DM is subdivided into five Local Municipalities (LMs), namely the Swartland, Saldanha Bay, Bergrivier, Cederberg and Matzikama LMs, all of which have a portion situated along the shoreline and coastal plain (see **Figure 2-1**). A Western Cape District Management Area (WCDMA01) is also present in three separated segments (north, central and south), with the northern and southern segments having coastal portions (see **Figure 2-1**). The five LMs and WCDMA host a large number of coastal resort towns, which are listed in **Table 2-1**. All these LMs (with the exception of the northern WCDMA01 section), and the associated coastal towns and features were visited as part of a field trip between the 22nd and 25th February 2011, with the route and interesting features noted in **Appendix A**.

**Table 2-1** Coastal towns within the West Coast DM's five Local Municipalities and WCDMA.

| District Municipality | Local Municipality | 2007 Population (Stats SA, 2008) | Coastal Towns |
|---|---|---|---|
| West Coast | Swartland | 77 524 | Ganzekraal (resort), Grotto Bay, Pearl Bay, Yzerfontein |
| | Saldanha Bay | 78 982 | Langebaan, Leentjiesklip, Mykonos/Paradise Beach, Blouwater Bay, Saldanha, Diazville, Jacobsbaai, Gonnemanskraal, Paternoster, Duiker Island, Britannia Bay, Shelley Point, Stompneus Bay, St. Helena Bay, Laingville, |
| | Bergrivier | 44 741 | Velddrif, Laaiplek, Dwarskersbos |
| | Cederberg | 31 942 | Elands Bay, Lambert's Bay |
| | Matzikama | 46 362 | Doringbaai, Strandfontein, Papendorp, De Punt (mine) |
| | WCDMA01 | 7 200 | West Coast National Park (nature reserve), Namakwa Sands (mine) |

Agriculture (potatoes, rooibos, vineyards, fruit farming, grain and livestock) and fishing (Saldanha Bay, St. Helena Bay, Lambert's Bay and Doringbaai) are the dominant activities within the five coastal LMs, although commercial and industrial activities occur in some of the larger coastal towns i.e. the Saldanha Bay area (e.g. Saldanha Steel and Namakwa Sands smelters). Relatively small scale mining occurs in some areas e.g. offshore, beach and terrestrial diamond mining north of Strandfontein by De Beers Namaqualand (Pty) Ltd and Trans Hex Investments (Pty) Ltd (e.g. De Punt); heavy mineral sands (titanium from ilmenite and rutile) at Namakwa Sands near the Northern Cape border and at the Geelwal Karoo deposit (Macdonald and Rozendaal, 1995); and salt works at the Berg River estuary, Papendorp at the Olifants River estuary, Yzerfontein Salt Pan etc.

## 2.2 CLIMATE

The West Coast DM coastline experiences a Mediterranean to semi-arid climate (< 300 mm per annum), with relatively cool, slightly rainy winters and hot dry summers. Unimodal precipitation occurs across the whole coastline stretch, with most rain occurring between May and August from mid-latitude cyclone cold fronts and coastal fog. Annual rainfall decreases northwards along the coastline (~ 314 mm at Yzerfontein in the south to 118 mm at Strandfontein in the north; see **Table 2-2**), as a result of the increasing influence of the cold Benguela Current (resulting in drier air) and the decreasing influence of winter mid-latitude cyclones (i.e. cold fronts don't extend as far north). Average summer and winter temperatures range between 14-28 °C and 7-19 °C respectively. The 30-year (1961-1990) climate record at Langebaanweg (see **Table 2-3**) confirms the Mediterranean to semi-arid climate experienced, and correlates with the amount of rainfall and temperatures observed at the other West Coast DM coastal towns. Southwesterly to southeasterly winds tend to dominate (~ 60 %), with northeasterly to northwesterly winds (~ 25 %) also occurring. Average wind speed tends to range between 20-40 km/hour, with gale force winds (> 52 km/hour) occurring not more than 5 % of the time.

**Table 2-2** Climatic characteristics of coastal towns (moving northwestwards up the coastline) within the West Coast DM (data from SA Explorer, 2008).

| Town | Average Annual Rainfall (mm) | Summer Min. Ave. Temp. (°C) | Summer Max. Ave. Temp. (°C) | Winter Min. Ave. Temp. (°C) | Winter Max. Ave. Temp. (°C) |
|---|---|---|---|---|---|
| Yzerfontein | 314 | 14 | 27 | 8 | 16 |
| Saldanha | 249 | 14 | 25 | 8 | 16 |
| Paternoster | 203 | 14 | 25 | 8 | 17 |
| Velddrif | 190 | 14 | 27 | 8 | 18 |
| Elands Bay | 170 | 15 | 29 | 7 | 19 |
| Lambert's Bay | 152 | 15 | 29 | 7 | 19 |
| Doringbaai | 126 | 15 | 28 | 7 | 19 |
| Strandfontein | 118 | 15 | 28 | 7 | 19 |

**Table 2-3** 30-year (1961-1990) climate record for Langebaanweg (South African Weather Service, 2003).

| Month | Temperature (°C) | | | | Precipitation (mm) | | |
|---|---|---|---|---|---|---|---|
| | Highest Recorded | Average Daily Max. | Average Daily Min. | Lowest Recorded | Average Monthly | Average No. days >= 1mm | Highest 24 hr Rainfall |
| January | 42 | 28 | 15 | 9 | 8 | 3 | 14 |
| February | 41 | 28 | 15 | 9 | 4 | 2 | 10 |
| March | 39 | 27 | 14 | 7 | 11 | 4 | 21 |
| April | 38 | 25 | 12 | 5 | 24 | 6 | 30 |
| May | 33 | 21 | 10 | 2 | 40 | 9 | 30 |
| June | 31 | 19 | 8 | 1 | 41 | 9 | 27 |
| July | 29 | 18 | 7 | 1 | 47 | 10 | 35 |
| August | 33 | 19 | 7 | 1 | 45 | 10 | 57 |
| September | 35 | 20 | 9 | 2 | 24 | 8 | 29 |
| October | 39 | 23 | 10 | 2 | 12 | 6 | 40 |
| November | 42 | 25 | 12 | 5 | 12 | 4 | 23 |
| December | 39 | 26 | 14 | 7 | 10 | 5 | 14 |
| **Year** | **42** | **23** | **11** | **1** | **278** | **76** | **57** |

**Figure 2-1** West Coast DM and associated LM borders and coastal towns.

## 2.3 WAVE CLIMATE AND TIDES

The West Coast DM coastline experiences moderate to high wave conditions, however wave energy is reduced in comparison to the southwestern and southern Cape coastlines (Rossouw and Theron, 2009). Annual mean significant wave height ranges from 2 m to 2.5 m (with a highest wave height of 5.5 m; Rossouw and Theron, 2009). Extreme wave height studies at Duynefontein near Koeberg as part of Eskom's Nuclear-1 study recorded significant wave heights of 5 m and 6.7 m from the southwest, with hindcast data showing a median height of 2.4 m and a maximum wave height of 9.7 m (Eskom Holdings Ltd., 2009b and 2009c). Modelling from the hindcast data (including a climate change increase of 17 % in significant wave height) at 31 mbmsl indicates a 1-year return period for a 6.7 m high wave, 10-year return period for a 8.2 m high wave, and 100-year return period for a 9.6 m high wave. This equates to a wave height of 5 m, 5.3 m and 5.6 m at the 6 mbmsl bathymetric contour respectively, and coastal run-ups of 3.4 mamsl, 3.7 mamsl and 3.9 mamsl respectively (Eskom Holdings Ltd, 2009b and 2009c). The wave climate exhibits a clear seasonality and varies in intensity, with an increasing winter trend of 0.5 m occurring over the past 14 years and the opposite occurring during summer (Rossouw and Theron, 2009). Southwesterly to southerly directed swells dominate (~ 84% of the deep sea waves according to Swart and Steyn, 1981), with less common west-southwesterly and northwesterly directed swell also occurring. The dominant southwesterly directed swells with larger wave heights and periods (8-14 seconds) are generated by surface winds from west to east moving frontal systems in the south Atlantic Ocean, whereas the remainder of the shorter period swell is generated by local winds.

The tides along the South African coastline are regular, semi-diurnal and their range seldom exceeds 2.2 m (i.e. microtidal). The difference between the Highest Astronomical Tide (HAT) and Lowest Astronomical Tide (LAT; both defined by the Saros lunar cycle of 18 years) for Saldanha Bay is 2.04 m, whereas the difference Mean Low Water Springs (MLWS) and Mean High Water Springs (MHWS) is 1.52 m (see **Table 2-4**). Mean High Water Neaps (MHWN) and Mean Low Water Neaps (MLWN) for Saldanha Bay are 0.41 mamsl and -0.17 mamsl respectively.

**Table 2-4** Tidal values for selected tide gauges along the South African and Namibian coastline (South African Navy Hydrographic Office, 2010). Saldanha tide gauge is highlighted in light blue. Values are in Land Levelling Datum (LLD), which for South Africa is mean sea level or 0 metres. The Mean Level (ML) is the average of MLWS, MLWN, MHWN and MHWS.

| PLACE (LLD) | LAT | MLWS | MLWN | ML | MHWN | MHWS | HAT |
|---|---|---|---|---|---|---|---|
| Walvis Bay | -0.97 | -0.70 | -0.30 | 0.01 | 0.32 | 0.72 | 1 |
| Lüderitz | -1.06 | -0.83 | -0.41 | -0.12 | 0.17 | 0.6 | 0.94 |
| Port Nolloth | -0.93 | -0.65 | -0.15 | 0.17 | 0.48 | 0.99 | 1.33 |
| Saldanha | -0.87 | -0.63 | -0.17 | 0.13 | 0.41 | 0.89 | 1.17 |
| Cape Town | -0.83 | -0.58 | -0.13 | 0.16 | 0.44 | 0.92 | 1.20 |
| Simon's Town | -0.84 | -0.60 | -0.11 | 0.16 | 0.45 | 0.95 | 1.25 |

## 2.4 COASTAL GEOLOGY AND GEOMORPHOLOGY

The West Coast DM coastline is comprised of a regionally low gradient, slightly undulating coastal plain, which gently rises to the foothills of the N-W to NNW-SSE trending Voelvleiberge, Groot Winterhoekberge, Piketberge, Uitkomsberge, Cedarberge and Bokkeveld Mountains (see **Figure 2-2**). The coastal plain varies in width, ranging from ~ 70-90 km wide with an elevation range of ~ 0-250 mamsl between Silwerstroom Strand and Velddrif, ~ 15-40 km long with an elevation of ~ 0-250 mamsl between Velddrif and

Lambert's Bay, ~ 40-70 km long with an elevation of 0-150 mamsl between Lambert's Bay and De Punt, and ~ 20 km long with an elevation of 0-150 mamsl between De Punt and Hoekbaai (see **Figure 2-2**). The shoreline can be subdivided into sandy (~ 200 km) and rocky coastlines (~ 250 km).

Geologically, the area is dominated by pre-Cambrian and Cambrian basement rocks (Namaqualand Metamorphic Province, Malmesbury Group, Gariep Supergroup and the Cape Granite Suite), the sedimentary Neoproterozoic Vanrhynsdorp Group and Paleozoic Table Mountain Group (TMG), and the semi-confined to unconfined sediments of the Tertiary to Recent Sandveld and West Coast Groups (for a detailed geological description of the stratigraphy and a visual image of the extent of the units, see Johnson et al. (2006), Theron et al. (1992) and De Beer et al. (2002), and the 1:250 000 3318 Cape Town, 3218 Clanwilliam and 3118 Calvinia geological maps).

The aeolian dune sands of the Springfontyn and Witzand Formations, and the limestone aeolianites (dune rock) and calcretes of the Langebaan Formation (all of which form the Sandveld Group) dominate the coastline from Silwerstroom Strand to Kreefbaai on the southern headland of Saldanha Bay. The Springfontyn and Witzand Formations form the Sixteen Mile Beach and Dune Complex between Yzerfontein and Kreefbaai, as well as the beach and dune complex between Yzerfontein and Grotto Bay. Malmesbury Group metasediments form rocky coastline between Bokpunt and Grotto Bay, while the gabbros of the Yzerfontein Suite form the headland at Yzerfontein. The headlands of Saldanha Bay are formed by granites of the Saldanha Batholith (Cape Granite Suite), which is exposed at Langebaan. The Saldanha Batholith is in fault contact with granites of the Vredenburg Batholith (also part of the Cape Granite Suite), which is exposed along the coastline from Tietiesbaai (where the contact between the two batholiths can be observed) at Cape Columbine, around the edge of St. Helena Bay to Laingville. A small portion of Malmesbury Group outcrops between Laingville and the Berg River mouth.

Between the Berg River and Baboon Point at Elands Bay the coastline is once again dominated by aeolian dune and coastal sands of the Sandveld Group, forming an extensive ~ 55 km sandy coastline, with marine gravels of the Velddrif Formation (also Sandveld Group) outcropping in the vicinity of the Berg River estuary and inland of Laaiplek. Baboon Point is formed by the conglomerates of Piekenierskloof Formation (TMG) and shales and sandstones of the Klipheuwel Group. The Piekenierskloof Formation is also present at various points along the coastline towards Strandfontein, with rocky outcrops often forming points at Grootrif, Duin se Rif, Lambert's Bay, Groothoekbaai and Doringbaai. Quartzites of the Peninsula Formation (TMG) outcrop at Strandfontein and Cliff Point north of De Punt. Sediments of the West Coast Group (upper West Coast analogue of the Sandveld Group) in turn form beach and dune complexes in between the various TMG coastal outcrops, as well as cover sediment inland of the coast.

North of Strandfontein the coastline begins to be dominated by the undifferentiated limestones, quartzites, phyllites and schists of the Widouw and Aties Formations of the Gifberg Group (Gariep Supergroup), giving the coastline a rugged rocky character. Multicoloured sedimentary rocks of the lower Vanrhynsdorp Group, and granites of the Namaqualand Metamorphic Province also form a distinct rugged, rocky coastline from Baai Vals to the Northern Cape border.

**Figure 2-2** Topographic map of the West Coast DM coastline, with coastal features highlighted.

The combination of westward verging, erosion resistant headland points and the dominant southwesterly-directed wave climate (with associated waves being oblique to the shoreline), has resulted in the development of log spiral bays (see **Figure 2-3**). The oblique wave approach and headland obstruction allows for longshore drift to be interrupted, and the development of a sediment starved region in the lee of the headland (Yasso, 1965). The presence of a headland also alters the direction and angle of dominant wave approach, causing wave refraction around the headland and associated wave diffraction and reflection in the lee of the headland (Meeuwis and van Rensburg, 1986). This results in the generation of two distinct zones within the log spiral bay, namely the "shadow zone" in the lee of the headland where sediment starvation causes erosion, and the "tangential end" (Finkelstein, 1982). Wave refraction causes a decrease in wave energy and hence deposition at the tangential end, building the coastline outwards and forming a log spiral i.e. curved or fish hook coastline shape (Finkelstein, 1982).

The western verging headlands along the West Coast DM (Bokpunt, Yzerfontein Point, Saldanha Bay headlands, headlands along the Vredenburg coastline (e.g. Cape Columbine, Shelley Point) and the larger Vredenburg headland itself, and Baboon Point generally protect developed regions to the east and north from the predominantly southwestward directed swell.


**Figure 2-3** Log spiral bay development at Elands Bay. Inset shows wave refraction around Baboon Point.

## 2.5 ESTUARIES AND OTHER COASTAL FEATURES

Estuaries are the meeting place between fresh water from rivers and salt water from the ocean, and are therefore highly dynamic environments. They are also generally geomorphologically unstable, and South African estuary mouths tend to shift and migrate continuously due to the coastline being exposed to and characterised by high-energy waves and strong local offshore and ocean currents. Little is known about most South African estuaries, with 68% of the state of information on South African estuarine systems being nil or poor (Whitfield, 2000). Due to the Mediterranean to semi-arid climate of the region, there are very few permanently open estuaries along the West Coast DM coastline, with the only two being the Berg River and Olifants River estuaries (see **Figure 2-2** and **Table 2-5**). Both of these estuaries fall within the top four estuaries in South Africa with regards to conservation status, and hence have been relatively well studied. The remaining estuaries along the West Coast DM are either non-permanent or ephemeral (e.g. Jakkals River estuary), or have formed coastal lagoons (e.g. Verlorenvlei) or salt pans (e.g. Wadrif Salt Pan). These other coastal features have not been studied in as much detail in comparison to the Berg River and Olifants River estuaries, with the exception of Langebaan Lagoon and Verlorenvlei (see **Figure 2-2** and **Table 2-5**). No studies have been undertaken on estuary, coastal lagoon or salt pan response to sea level rise along the West Coast DM coastline however.

Storm surges and river floods can often break through sedimentary barriers associated with these estuaries (whether permanent or not), rendering them highly unstable, as evidenced by erosion at the mouth of the Jakkals River estuary in Lambert’s Bay. Heavy floods and storm surges often associated with cold front weather systems can also cause extensive backflooding within estuaries and coastal river systems, yet despite this estuaries such as the Berg River have still been extensively developed.

**Table 2-5** Important estuaries, coastal lagoons and salt pans along the West Coast DM coastline and detailed study references (where present).

| Name | Latitude | Longitude | Tidal Reach (km) | Reference |
|---|---|---|---|---|
| Modder River Estuary | -33.483698 | 18.307272 | Ephemeral | - |
| Rooi Pan | -33.331133 | 18.162480 | Salt Pan | - |
| Yzerfontein Salt Pan | -33.326589 | 18.178662 | Salt Pan | - |
| Langebaan Lagoon | -33.157151 | 18.068326 | Marine | Anchor Environmental, 2010b |
| Berg River Estuary | -32.772639 | 18.144408 | 30-69 | Anchor Environmental, 2008a |
| Rocher Pan | -32.600201 | 18.305419 | Salt Pan | - |
| Verlorenvlei | -32.321110 | 18.390291 | Closed | Sinclair et al., 1986 |
| Wadrif Salt Pan | -32.206846 | 18.340901 | Salt Pan | - |
| Jakkals River Estuary | -32.085008 | 18.314365 | Closed | - |
| Olifants River Estuary | -31.695027 | 18.190763 | 10-36 | Morant, 1984; Anchor Environmental, 2008b |
| Goerap Salt Pan | -31.240640 | 17.866701 | Salt Pan | - |

# 3. GLOBAL SEA LEVEL RISE

## 3.1 FUTURE CLIMATE CHANGE

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 (IPCC, 2007). The IPCC uses a range of scenarios (which replaced the IS92 scenarios developed in 1990 and 1992), termed the Special Report on Emission Scenarios (SRES), to predict the future range of possible increases in temperature due to changes in greenhouse gas concentrations (Arnell et al., 2004). These scenarios described a range of socio-economic futures and values i.e. future world states based on plausible “storylines”, which would influence greenhouse gas concentrations in the 21$^{st}$ century (Arnell et al., 2004). Four SRES storyline marker families have been developed, namely A1 and A2 (with the A storylines describing a “business as usual world” where materialistic and consumerist values dominate) and B1 and B2 (with the B storylines focusing on increased environmental priority and decreasing emissions using clean and efficient technology) (Arnell et al., 2004). The A2, B1 and B2 families have one scenario each, whereas the A1 family has three scenarios (A1B, A1T and A1F1). The B scenarios have the lowest predicted carbon dioxide ($CO_2$) concentrations by 2100 (600 ppm for B1 and 800 ppm for B2), and hence the lowest predicted rise in temperature by 2100 of approximately 1.8 °C (IPCC, 2007). The A scenarios, with the exception of A1T (700 ppm), have the highest predicted $CO_2$ concentrations by 2100, ranging from 850 ppm for A1B to 1550 ppm for A1F1 (worst case scenario) (IPCC, 2007). This equates to a 4 °C rise in global mean temperature by 2100 if the A1F1 scenario occurs (IPCC, 2007). Whichever scenario occurs, global mean temperature will still increase by at least 0.2 °C over the next two decades, and by 0.1 °C even if greenhouse gases are reduced to below 2000 levels (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).

## 3.2 RATES AND PROJECTIONS OF SEA LEVEL RISE

Historical records of global sea level change prior to 1993 are determined from tide gauge records, however there are only a small number (less than 25) of high quality tide gauges from around the world on isostatically stable land regions (IPCC, 2007). Most of these tide gauges are also on northern hemisphere continental margins, resulting in the non-uniform distribution of results (Cazenave, 2009). Since 1993 however, satellites in the form of TOPEX, Poseidon, Jason-1, Jason-2 and GRACE have allowed for the introduction of satellite altimetry sea level measurements. Satellite altimetry measurements are not affected by local isostatic land movements as sea level is measured with respect to the Earth’s centre of mass, and data is also adjusted for large scale basin deformation by glacial isostatic adjustment (GIA) (Cazenave, 2009).

These tidal gauge and (since 1993) satellite altimetry measurements have shown that sea level has risen 20 cm since 1870, with the rise during the 20$^{th}$ 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 (see **Figure 3-1**) (Cazenave, 2009). This spatial variability is due to non-uniform changes in temperature, salinity and ocean circulation from regional yearly to decadal climatic systems such as the El-Nino Southern Oscillation (ENSO), North Atlantic Oscillation (NAO) and Pacific Decadal Oscillation (PDO) (Cazenave, 2009). This spatial variability has only been identified since the onset of satellite altimetry measurements in 1993, and it is still unknown whether these spatial global sea level rise patterns are decadal in length or longer (Cazenave, 2009). That said, the highest magnitude sea level changes have occurred in the Western Pacific and East Indian Oceans, largely as a result of ENSO (Cazenave, 2009). This increasing rate of sea level rise is problematic with respects to the initial predictions of future sea level rise by the IPCC TAR, which ranged from 20-70 cm (with an upper limit of 88 cm) by 2100, and the IPCC Fourth Assessment Report (AR4) (2007), which ranged from 18-59 cm (with an upper limit of 79 cm). Both these predictions did not take into account dynamic ice sheet response of the Greenland and Antarctic Ice Sheets to climate change, and only used mass balance calculations. Sea level rise is hard to predict using models based on physical mass balance processes alone however, due to the uncertainty surrounding ice sheet dynamics and ocean heat uptake (Vermeer and Rahmstorf, 2009). The highly non-linear response of ice flow is proving to be important in the 21$^{st}$ century. Current future predictions taking into account new ice sheet understanding are twice the range of the IPCC AR4 projections, with an upper limit of sea level rise of 2 m expected by 2100 (see **Figure 3-2**) (Rahmstorf, 2007, Vermeer and Rahmstorf, 2009 and the UNSW CCRC, 2009). Even after the cessation of greenhouse gas emissions, it will still take centuries to millennia for global temperature to stabilise (IPCC, 2007). Warming in this century may in turn commit future generations to 4-6 m of sea level rise and sea level rise rates of a metre per century if emissions continue, as it takes time for the oceans and ice sheets to fully respond to climate change (Overpeck and Weiss, 2009). The Antarctic Ice Sheet is still currently responding to warming since the LGM, with past natural warming in turn also contributing to current sea level rise (Church et al., 2008). To reduce sea level rise by less than 1 m beyond 2100, deep emission reductions will therefore be required, more so than the current global warming target of below 2 °C above pre-industrial temperatures.

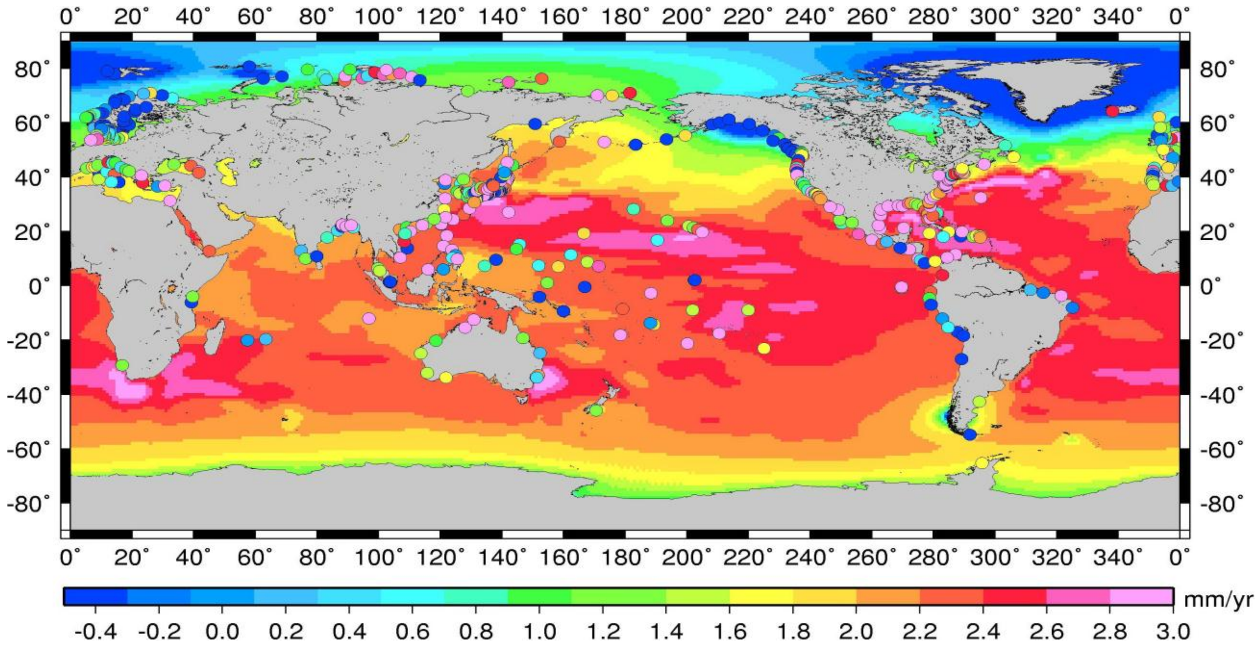


**Figure 3-1** Regional variability in sea level trends from 1900-2007 using thermal expansion data, tide gauges, satellite altimetry and GIA (Shum and Kuo, 2009). Note the 2.4-3 mm/year rise (red to pink colouring) for the South African coastline.

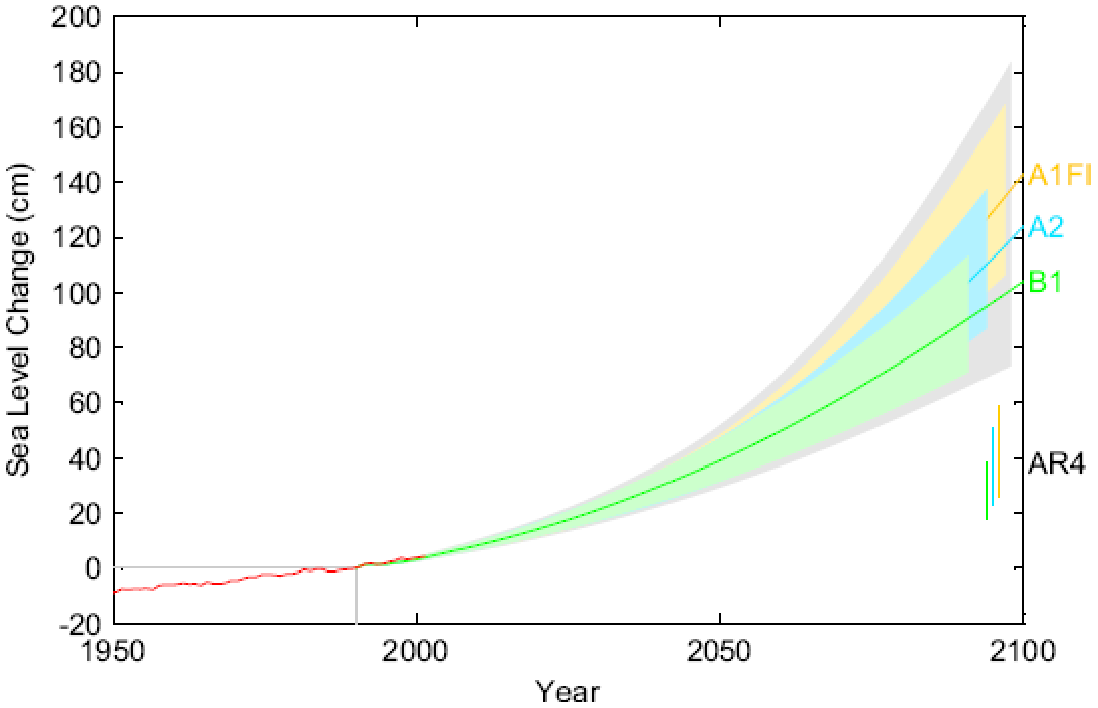


**Figure 3-2** Vermeer and Rahmstorf (2009) sea level rise projections based on the IPCC SRES scenarios. The IPCC AR4 assessment for the same scenarios is in the bottom corner.

## 3.3 GLOBAL AND REGIONAL SEA LEVEL CHANGE

### 3.3.1 Global sea level rise

Global or eustatic sea level rise is caused by the change of water volume in the global ocean. It occurs through two main processes, namely thermosteric (thermal) expansion and the melting of land based ice sources (whether they be continental or mountain glaciers, or the Greenland and Antarctic Ice Sheets). Minor causes of eustatic sea level rise include anthropogenic land hydrology changes, changes in water storage in the atmosphere, and large scale changes in the shape of ocean basins. The net anthropogenic contribution to sea level rise (with regards to the storage of water in the hydrosphere) has been estimated at approximately 0.05 mm/year over the past 50 years (Church et al., 2008). This includes groundwater abstraction, dam impoundment, oil and gas abstraction, sediment compaction in deltaic areas due to development, wetland drainage, deforestation and catchment land use changes resulting in a change in sediment deposition rates. The atmosphere contains enough water in storage to raise sea levels by 35 mm only, with other climate driven effects including an increase in soil moisture, which may be countered by an increase in evapotranspiration in other areas (IPCC, 2007 and Church et al., 2008).

Thermosteric or thermal expansion of the ocean (i.e. the physical expansion of water molecules) is caused by more than 80% of the heat added to the climate system being absorbed by the ocean (IPCC, 2007). This has resulted in a temperature increase in the world's oceans to a depth of at least 3000 m (IPCC, 2007). As described earlier, thermosteric expansion is highly variable globally due to the effect of regional climate systems. Thermosteric expansion contributed approximately 40% of the total sea level rise between 1961 and 2003 (at a rate of ~ 1.5 mm/year between 1993-2003), although its contribution dropped to 20% between 2003 and 2008, as ice sheet loss became the major contributor (Church et al., 2008). Correspondingly, glacier and ice sheet loss contributed to approximately 60% of sea level rise between 1961 and 2003, and 80% between 2003 and 2008 (Church et al., 2008). Continental ice caps and glaciers (excluding the Greenland and Antarctic Ice Sheets) hold enough water to raise sea level by 15-37 cm, assuming all the melt water reaches the oceans (Church et al., 2008 and Cazenave, 2009).

Greenland is covered by a 1.6 km thick ice sheet, which holds enough water to contribute 7.3 m of sea level rise (Shum et al., 2008). Since 1990 there has been a significant increase in outlet glacial flow, although there is a lot of uncertainty and poor understanding around dynamic ice sheet response processes at present. It is thought that dynamic ice sheet flow and calving could occur through various processes. These include summer melt drainage moving through crevasses and forming large subglacial lakes, lubricating the ice-bedrock interface; frictional heat melting the base of the ice sheet quicker due to faster flow, resulting in a positive melt feedback; or, as in the case of the West Antarctic Ice Sheet (WAIS) and exemplified by the collapse of the Larsen B ice shelf on the Antarctic Peninsula, warmer sea water penetrates below the ice shelf causing melting and collapse due to the ice sheet being graded below sea level (WBGU, 2006 and Church et al., 2008). Using just a mass balance approach and not taking into account dynamic ice loss processes, the Greenland Ice Sheet contributed to sea level rise by 0.2 mm/year between 1993 and 2003, increasing to 0.5 mm/year between 2003 and 2008 (Church et al., 2008 and Shum et al., 2008). The temperature rise at which melting occurs at a greater rate than precipitation in Greenland is 4.5 °C over Greenland, which correlates to a 3.1 °C mean temperature rise above pre-industrial levels globally (Church et al., 2008). This shift could lead to the whole scale melting of the Greenland Ice Sheet, although the time scale is unknown, and could take millennia (through surface melting) to a few centuries (if dynamic ice sheet melting is dominant) (Church et al., 2008).

The Antarctic Ice Sheet (which is subdivided into the potentially unstable WAIS and larger, more stable East Antarctic Ice Sheet (EAIS)) is the most important source of fresh water on Earth, and contains 90% and 70% of the world's ice and fresh water respectively (Shum et al., 2008). 98% of Antarctica is covered by a 1.6 km thick ice sheet, which stores enough water to cause 56.6 m of sea level rise if completely melted, with the WAIS contributing to ~ 5 m of this possible rise and the EAIS the remainder (Sheperd and Wingham, 2007 and Shum et al., 2008). An even larger uncertainty exists over the Antarctic Ice Sheet with regards to present and future contributions to sea level rise compared to the Greenland Ice Sheet. Future projections show the Antarctic to be too cold for large-scale surface melting, and may increase in mass due to climate change causing an increase in snowfall (IPCC, 2007). However as is the case with the Greenland Ice Sheet, net ice loss may occur in the future through dynamic ice discharge (IPCC, 2007). Recent work by Pingree et al. (2011) suggests that the Eemian High rise of 6 mamsl during the LIM was caused by a total collapse of the WAIS, as well as part of the adjacent EAIS in contact with the WAIS. The important question is will global mean temperature pass a critical point in the 21$^{st}$ century that will lead to the irreversible melting of the Greenland and WAIS for centuries to come, and if part of the EAIS can collapse during the LIM (as proposed by Pingree et al., 2011) what is stopping it from collapsing during the current interglacial period we are in?

### 3.3.2 Regional sea level change

Regional, relative, local or isostatic sea level change is affected by a mix of location dependent factors that operate at a range of time scales (Plag et al., 2009). Regional sea level change is affected by global sea level rise, but the local factors in turn do not affect global rise. Regional sea level change can be affected by high frequency factors such as waves, tides and atmospheric forcing events such as storm surges and tsunamis. These factors can act at a scale of a few centimetres change to a few metres (in the case of meso to macrotidal regimes, large waves and storm surges), to over ten metres (in the case of tsunamis) (Plag et al., 2009). Low frequency factors include all of those that cause global sea level rise, as well as long-period tides (e.g. Saros cycle LAT and HAT), changes in salinity due to increases in fresh water input to the ocean from melting, changes in local sedimentary basins, GIA, and linear and non-linear vertical isostatic land movement (uplift or subsidence other than GIA) (Plag et al., 2009).

## 3.4 SEA LEVEL RISE AND EXTREME SEA LEVELS

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 and stronger wind regimes, 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. Zhang et al. (1997) found that exposure to higher water levels from extreme storms increased from less than 200 hours/year between 1910-1920, to 700-1200 hours/year during the 1990s. Studies along the Australian east and west coasts have also shown extreme sea levels have occurred three times more frequently in the last half of the 20$^{th}$ century compared to the first half (Church et al., 2008).

## 3.5 COASTAL GEOMORPHIC RESPONSE TO SEA LEVEL RISE

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 Bruun Rule is represented by the simple mathematical formula of:

Shoreline erosion (R) = (Profile width (X) x Sea-level rise (S')) / Profile depth (Z)

The Bruun Rule is an empirical model, and hence can only be applied to conditions similar to which it was based on, namely unconsolidated, sandy shorelines that exhibit an equilibrium profile. It is assumed that present wave climate will remain as sea-level rise occurs, and does not take into account longshore drift. The Bruun Rule can hence only be used in certain instances or with continuous adjustment and refinement to local coastal conditions, as all coastal profiles change as sea-level rise occurs (Cooper, 1995).

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). Associated erosion occurs on the seaward side of the barrier as a result of increasing sea level. 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.

# 4. SEA LEVEL RISE ALONG THE SOUTH AFRICAN COASTLINE

## 4.1 RATES OF SEA LEVEL RISE IN SOUTH AFRICA

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). 50 years or more of data is required to calculate long-term trends, with only six stations in Africa having mean sea level series of greater than 40 years (Woodworth et al., 2007). Three of these stations are from South Africa, but large data gaps are present, reflecting the data problems associated with acoustic tide gauges used in the 1990s (Woodworth et al., 2007). These gaps are often patched by incorporating regional trends with data from adjacent stations (Hughes et al., 1991a).

The current South African tide gauge network is comprised of tide gauges at presently used or past large ports and harbours, namely Port Nolloth, Granger Bay (Cape Town), Simon's Town, Mossel Bay, Knysna, Port Elizabeth, East London, Durban and Richards Bay (see **Figure 3-1**). Brundrit (1995) and Hughes et al. (1991a) analysed southern African tide gauge records that covered a period of 30 years (Port Nolloth, Simons Town, Mossel Bay and Luderitz in Namibia), and found that sea level was rising at a rate of 1.8 mm/year along the western South African coast. Mather et al. (2009) recently conducted the first detailed analysis of all tide gauge sites along the southern African coastline, building on work done by Mather (2007) with regards to the Durban tide gauge (which at the time was the most detailed sea level change analysis for a tide gauge along the east African coastline). Mather et al.'s (2009) analysis also takes into account the effect barometric pressure and vertical crustal movements have on sea level change along the southern African coastline for the first time. The analysis shows that over the past 50 years, sea level rise along the southern African coastline has not been constant, and it is incorrect to apply a globally calculated sea level rise (currently ~ 2.4-3 mm/year) value uniformly across the coastline (Mather et al., 2009). The variation in sea level change along the coastline is a result of various physical factors, namely the interactions between the Agulhas and Benguela Currents, water temperature changes, barometric air pressure (which increases from the West to East Coasts, causing a relative rise and fall in sea level respectively due to the "inverted barometric response") and vertical crustal movement (which decreases from the East to West Coasts) (Mather et al., 2009). Mather et al. (2009) subdivided the southern African coastline into three regions with regards to ocean current circulation, sea level change and tidal gauge distribution, namely:

- Western region – Runs from Cape Columbine to Walvis Bay, and is influenced by the cold Benguela Current. The area includes the Port Nolloth, Alexander Bay, Luderitz and Walvis Bay tide gauge stations and associated records. Regional sea level rise is 1.87 mm/year (1959-2006), with eustatic sea level rise (sea levels corrected for barometric pressure and vertical crustal movement) for the area being 0.42 mm/year (Mather et al., 2009). The low eustatic sea level rise could be a result of the limited data set, and the influence of the large negative barometric trend on the data (Mather et al., 2009).

- Southern region – Runs from Cape Columbine to Port Elizabeth, and is an area where mixing of the Benguela and Agulhas Currents occurs. The area includes the Table Bay, Granger Bay, Simon's Town, Hermanus, Mossel Bay and Knysna tide gauge stations and associated records. Regional sea level rise is 1.48 mm/year (1957-2006), with eustatic sea level rise for the area being 1.57 mm/year (Mather et al., 2009). Analysis of the Mossel Bay tide gauge indicates a sea level fall of –0.40±19 mm/year (Mather et al., 2009). This corresponds to other analyses by Brundrit (1995), with Woodworth et al. (2007), which also show no persistent upward rise in sea level at Mossel Bay. This is in contrast to other stations in the area, and a previously measured rise of 1 mm/year from 1960-1988 for Mossel Bay (Mather et al., 2009). Mather et al. (2009) believe that data or tide gauge errors may be the reason for the Mossel Bay records indicating a sea level fall, although further investigation and improvement of data quality is required.

- Eastern region – Runs from Port Elizabeth to Richards Bay, and is influenced by the warm Agulhas Current. The area includes the Port Elizabeth, East London, Durban and Richards Bay tide gauge stations and associated records. Regional sea level rise is 2.74 mm/year (1967-2006), with eustatic sea level rise for the area being 3.55 mm/year (Mather et al., 2009). Increased crustal uplift in the area and positive barometric pressure are responsible for the almost 1mm/year difference between the regional and eustatic sea level changes. The high eustatic sea level rise, which is slightly greater than the global rate of sea level rise (~ 3.4 mm/year), is a result of the region being fed by warm (and increasingly expansive) water from the equator (Mather et al., 2009).

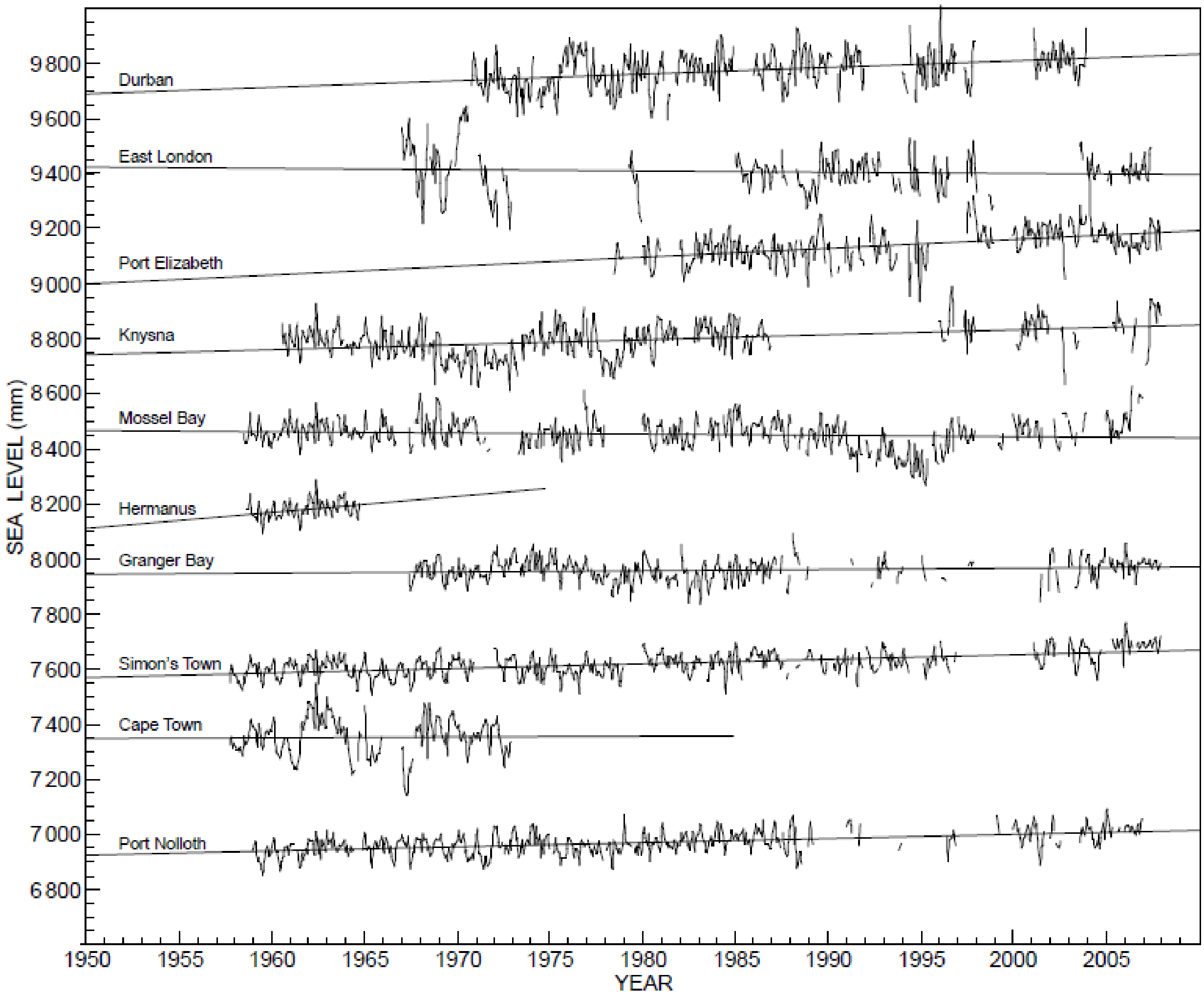


**Figure 4-1** Tide gauge time series for the different tide gauge stations along the South African coastline, with general sea level change trends overlaid (from Mather et al., 2009).

## 4.2 LOCAL SEA LEVEL RISE CASE STUDIES

Various sea level change studies have been conducted along the South African coastline, ranging from basic shoreline adjustment mapping along the KwaZulu-Natal (KZN) coast for planning purposes (Cooper 1991, 1993 and 1995), to more detailed individual case studies along the City of Cape Town (Hughes and Brundrit, 1991 and Hughes et al., 1991b) and Namibian (Hughes et al., 1992) coastlines. Hughes and Brundrit (1991) used the Bruun Rule and a sea level rise of 1 m to predict lateral shoreline erosion of 50-150 m along a series of transects from Glencairn to Gordon's Bay within False Bay. Hughes et al. (1991b) used the same methodology to predict shoreline erosion of 60-140 m for the Diep River/Rietvlei system in the Milnerton area of Cape Town. Both studies also identified developments and communities that would be vulnerable to shoreline retreat and saline groundwater intrusion, as well as what measures would be required to mitigate against future sea level rise in these areas. Hughes and Brundrit (1995) also investigated the possible effects of sea level rise on estuary geomorphology and evolution along the South African coastline.

The most recent national, regional and local sea level rise studies have been carried out by Theron and Rossouw (2008), Midgley et al. (2005), DEA&DP (2010a, 2010b and 2010c) Cartwright et al. (2008) and Prestedge Retief Dresner Wijnberg (PRDW) (2009) respectively. Theron and Rossouw (2008) described the possible large scale, regional impacts of climate change along the southern African coastline. Average wind speeds are expected to increase in all seasons in South Africa by a modest 10%, resulting in a 12% increase in wind stress and a possible 13-26% increase in wave height and 10-21% increase in total storm surge (Theron and Rossouw, 2008 and PRDW, 2009). A possible 13-26% increase in wave height might cause up to an 80% increase in wave power with an associated 80% increase in longshore sediment transport, which will have a definite impact on the geomorphology of South African coastlines (Theron and Rossouw, 2008). These coastal changes will be difficult to predict though, because climate change will also affect rainfall, runoff and in turn fluvial sediment yields, which control coastal sediment budgets (Theron and Rossouw, 2008). Higher sea levels will also change the offshore bathymetry of the shoreline, causing a change to wave climate and wave energy regimes, hence affecting longshore drift (due to the possible change in wave approach) and future coastal evolution. Theron and Rossouw (2008) identified Saldanha Bay, Table Bay, northern False Bay, Mossel Bay to Nature's Valley, Port Elizabeth and KZN coastal developed areas (Southbroom on the south coast to Ballito on the north coast, including Durban) as being the most vulnerable to the effects of sea level rise. Midgley et al. (2005) identified similar vulnerable areas along the Western Cape coastline. The City of Cape Town sea level rise risk assessment (Brundrit, 2008 and 2009, Cartwright, 2008 and 2009b, Fairhurst, 2008 and Cartwright et al., 2008) carried out a storm surge assessment for wave runups of 2.5 mamsl, 4.5 mamsl and 6.5 mamsl along the 307 km of coastline (Melkbos to Gordon's Bay) administered by the city. Cartwright (2008) found that these surges could cost the City of Cape Town between R5 billion to R20 billion in the next 25 years. Hughes and Brundrit (1992) developed a vulnerability index to assess sea level rise risk, using the southern Cape coastline between Witsand and Nature's Valley as a test example. The vulnerability of what is now the Eden DM coastline was assessed using a desktop methodology with regards to extreme sea level events (i.e. storm surges), ground water contamination, greater tides, flooding and erosion. As with the more recent studies mentioned above, Hughes and Brundrit (1992) identified the areas most vulnerable to a combination of all five hazards as Groot/Klein-Brakrivier, Wilderness, Stilbaai, Knysna, Keurbooms, Sedgefield, Nature's Valley, Plettenberg Bay and Hartenbos (in decreasing order of vulnerability). To date no specific sea level rise risk studies have been undertaken along the West Coast DM coastline of South Africa.

## 4.3 EXTREME SEA LEVELS ALONG THE SOUTH AFRICAN COASTLINE

The combination of cut off and coastal low generated swell systems during spring highs in February, March and September, and swell generated by winter cold fronts are responsible for the present highest sea levels along the West Coast DM coastline (see **Figure 4-2**). Searson and Brundrit (1995) provide an overview of extreme sea levels along the South African coastline. Analysis of records from Simon's Town for extreme sea levels indicates that the 30 year high water return period was exceeded four times between 1965 and 1995, with three of these events occurring after 1980 (Searson and Brundrit, 1995). Brundrit (2008) states that the maximum storm water level at Simon's Town in the past 30 years was +39 cm, with 15 events of +25 cm also being recorded during this time. A 30-year storm of +39 cm on a HAT for Simon's Town of 1.24 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 19$^{th}$ and 20$^{th}$ March 2007 storm along the 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 21$^{st}$ March 2007) (Brundrit, 2008, Smith et al., 2007 and Smith et al., 2010). This combination represented a 1:500 year extreme sea level event (Theron and Rossouw, 2008). Approximately 9 years worth of sediment (~ 3.5 million $m^3$) was eroded from Durban's beaches, with 4-5 mamsl and 6-7 mamsl swash zones on sandy and headland adjacent beaches respectively causing R1 billion damage to the KZN coastline (see **Figure 4-3**). 1:100 year flood lines from the sea caused by possible extreme events of 4-7.5 mamsl have been modelled for the proposed Duynefontein (near Koeberg) Eskom Nuclear-1 site just south of the West Coast DM, while a maximum water level caused by a combination of a possible tsunami with storm surge, high tides and run-ups was modelled at 9.5 mamsl (Eskom Holdings Ltd, 2009a and 2009b). 1:100 year run-up levels have also been determined for Paradise Beach (4.5 mamsl) and Leentjiesklip (5.1 mamsl) in Langebaan (DEA&DP, 2010e). 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).

**Figure 4-2** Large storm swell at Kalk Bay harbour in False Bay (Cape Town), generated as a result of a spring cut off low in September 2008.

**Figure 4-3** Extensive coastal erosion at Umkomaas, southern KZN, as a result of the 19$^{th}$ and 20$^{th}$ March 2007 KZN storm (Mather, 2008).

# 5. SOUTH AFRICAN COASTAL LEGISLATION

## 5.1 INTERNATIONAL OBLIGATIONS AND AGREEMENTS

South Africa is treaty to 35 international obligations and agreements that deal with the coastal or marine environment, such as the Blue Flag International programme, United Nations Convention on the Law of the Sea, and various bilateral and regional agreements. These international obligations and agreements generally deal with resource rights within national and regional waters as well as the conservation of coastal and marine biodiversity and habitats, with no specific agreements focusing on the coastal impacts of climate change.

## 5.2 NATIONAL COASTAL LEGISLATION

South Africa has an excellent piece of coastal legislation in the form of the National Environmental Management: Integrated Coastal Management Act (Act 24 of 2008) (for a user-friendly guide to the Integrated Coastal Management (ICM) Act, see Celliers et al. (2009)). The main aim of the ICM Act is to provide a clear definition of the coastal zone, in order to allow for effective ICZM to take place along the South African coastline. The ICM Act divides the coastal zone into five areas, namely the Exclusive Economic Zone (EEZ), coastal public property, coastal buffer zone, coastal access land and specially protected coastal areas (previously designated nature reserves etc.). The EEZ extends from 200 to 12 nautical miles out at sea, and includes the continental shelf and all natural resources within those boundaries. Coastal public property has two components, namely the seashore and coastal waters. Coastal waters include all water influenced by tides (estuaries, harbours, rivers, etc.) and the sea from the low water mark to the 12 nautical mile limit, while the seashore defines the area between the low and high water marks.

Coastal access land is defined as land that the public can use to gain access to coastal public property. The coastal buffer zone includes the area that extends 100 m (for developed areas that have already been zoned for residential, commercial, industrial or multiple use purposes) and 1 km (for non-zoned natural or rural areas) from the coastal public property boundary (i.e. the high water mark). This coastal buffer zone boundary is relatively arbitrary however, and there are procedures in the ICM Act that allow the member of the Executive Council (MEC) to establish coastal set-back lines to define the coastal buffer zone on a case by case basis. Interested and affected parties also have an opportunity to contribute to the process of demarcating or adjusting the boundaries. Once the coastal set-back line or coastal buffer zone boundary has been defined, it will be managed as a Coastal Protection Zone (CPZ). Specified developments within this zone will require the undertaking of an Environmental Impact Assessment, as defined by the National Environmental Management Act (NEMA) (No. 107 of 1998). Development inside the CPZ can be considered in developed areas where existing rights exist.

The DEA&DP (2010d and 2010e) developed a methodology for determining set-back lines in the Western Cape, which in turn was tested in the City of Cape Town and Saldanha Bay Local Municipality. The methodology stated that prior to the establishment of detailed coastal set-back lines in the Western Cape, a set-back line of the greater of a) 100 m from the high water mark, or b) distance from the high water to the 10 mamsl contour, be selected as an initial default line (DEA&DP, 2010d). Following this, detailed no development/coastal process and limited/controlled development set-back lines are to be developed by a coastal process practitioner (DEA&DP, 2010d). These set-back lines should take into account a future sea level rise of 1 m, shoreline retreat for storm/short term/long term erosion, dune collapse, estuary channel migration, wind blown sand and wave run-up (DEA&DP, 2010d). The set-back lines also need to take into account public access, aesthetic factors, shading by structures and significant landscapes (DEA&DP, 2010d).

The ICM Act promotes risk aversion and the application of the precautionary principle, and highlights sea level rise and the possible effects thereof to the coastal environment. A bigger link is required to DRR legislation however, and especially the Disaster Management Act (Act 57 of 2002), in order to take extreme sea level events such as storm surges and tsunamis into account with regards to ICZM. The ICM Act requires the development of national, provincial and municipal coastal committees (as well as lead provincial agents in the form of organs of state), in order to implement respective national, provincial and municipal coastal management programmes. An important feature of the ICM Act is that it forms the highest level of legislation within the defined coastal zone (other than the Constitution of South Africa (Act 108 of 1996)), with all other acts, policies, Integrated Development Plans (IDPs) and Spatial Development Frameworks (SDFs) having to follow the act's requirements. Other national legislation and policy not mentioned above that regulate the South African coastline in some form includes:

- Marine Living Resources Act (Act 18 of 1998)
- Environmental Conservation Act (Act 73 of 1989)
- Municipal Systems Act (Act 32 of 2000)
- Atmospheric Pollution Prevention Act (Act 45 of 1965)
- Hazardous Substances Act (Act 15 of 1973)
- National Water Act (Act 36 of 1998)
- National Climate Change Response Strategy for South Africa (2004)
- National Environmental Management: Waste Act (Act 59 of 2008)
- National Environmental Management: Biodiversity Act (Act 10 of 2004)
- National Environmental Management: Protected Areas Act (Act 57 of 2003)

## 5.3 WESTERN CAPE COASTAL POLICIES

The Draft Coastal Zone Policy for the Western Cape (2001) was developed prior to the passing of the ICM Act, and hence requires revision in order to meet the requirements of the ICM Act. The Western Cape Coastal Zone Policy takes a bioregion and spatial planning approach to the Western Cape coastal plain as a whole. There is a strong focus on ecological variables and challenges, however there is little to no mention of geomorphological processes along the shoreline, especially with regard to their response to climate change and sea level rise. The Climate Change Strategy and Action Plan for the Western Cape (DEA&DP, 2008) provides a much more holistic overview of the effects of climate change on the Western Cape coastline however, and acknowledges the possible effects of climate change induced sea level rise (storm surges, coastal inundation, erosion etc.). The action plan also details a research strategy to understand and mitigate against these possible future sea level changes.

### 5.3.1 West Coast DM and associated Local Municipality IDPs

The IDPs of the various LMs of the West Coast DM and the West Coast DM IDP itself make very little to no mention of climate change, sea level rise, coastal processes, coastal hazards, and coastal development planning. The West Coast DM 2007-2011 IDP mentions climate change with regards to its effects on agriculture and the Millennium Development Goals, but mentions nothing on climate change and coastal issues. The Bergrivier Local Municipality 2007-2008 IDP makes mention of climate change and coastal management the most out of all the West Coast DM LMs, stating "the need for the comprehensive management of the coastline (undeveloped) and numerous vleis and pans, including the agriculture interface (i.e. buffer)", as well as noting the hazard of salt-water intrusion and the need for alternative renewable energy resources to reduce the impact of climate change. An audit implementation of a coastal development plan from Velddrif to Elands Bay was listed as a key municipal activity to be completed by 2007, however this is still to be done. Climate change, coastal issues and coastal management is mentioned to an even lesser extent in the other LM IDPs:

- The Cederberg LM 2009-2010 IDP mentions the coastline as being sensitive, and that minor tourism orientated growth of the area between Elands Bay and Lambert's Bay is required;

- The planned SDF resulting from the Matzikama LM 2007-2011 IDP will need to focus on Strandfontein and Doringbaai, where new coastal development is envisioned;

- Nothing with regards to climate change or coastal issues/development is mentioned in the Saldanha Bay LM 2006-2011 IDPs;

- The Swartland LM 2007-2011 IDP mentions the need to manage flood risks.

As stated, the ICM Act forms the highest level of legislation within the defined coastal zone (other than the Constitution of South Africa (Act 108 of 1996)), with all IDPs and SDFs having to follow the act's requirements. The LMs of the West Coast DM (and especially Saldanha Bay LM, due to it having the highest coastal industrial and residential development in the West Coast DM) and the West Coast DM itself therefore need to include the principles of the ICM Act in the next round of IDP and SDF revisions.

The biodiversity sector plan for the Saldanha Bay, Bergrivier, Cederberg and Matzikama Municipalities (Maree and Vromans, 2010), as well as the Berg (Anchor Environmental, 2010a), Olifants (Anchor Environmental, 2009) and Verlorenvlei (CSIR, 2010) estuary management plans provide good examples of how environmental issues need to be taken into account in spatial planning. The estuary zonation plans and critical biodiversity areas all take into account restrictions such as building below the 1:100 year flood line, and are explicit in the importance in taking into account coastal set-back lines to assist with development planning and reduce the impact of sea level rise and coastal and estuarine flooding.

(waiting for local community coastal organisation information from Charles Malherbe)

# 6. RECOMMENDATIONS

Eustatic sea level has been rising globally at 3.4 mm/year over the last 17 years, and from 0.42 mm/year (West Coast) to 3.55 mm/year (East Coast) along the South African coastline over the past 50 years. Due to the absence of tide gauge stations along the West Coast DM coastline, regional sea level rise in the area could range from between 1.48-1.87 mm/year. The West Coast DM coastline has approximately 200 km of sandy beaches, which are highly vulnerable to sea level change and could be developed in the near future e.g. proposed tourism zone between Elands Bay and Lambert's Bay, extensive residential development north of the Berg River etc. After a lull of 15 years of research and a series of recent extreme storm surge events, South Africa is starting to realise the importance of understanding the processes behind climate change induced sea level rise and its associated effects. New national, provincial and local legislation and policies are beginning to drive this new research and understanding, and are ensuring the South African coastline is managed sustainably and holistically into the future. It is recommended that:

- National level:
    - Development of a South African coastal and sea level rise literature database with an accessible online reference list e.g. the Consortium for Estuarine Research and Management website and online bibliography (http://www.upe.ac.za/cerm/). The database should be housed and maintained at a coastal university or research institution, and will allow for all sea level rise data and literature to be easily accessible for future sea level rise studies along the coastline.
- West Coast District Municipality level:
    - Each LM and the West Coast DM as a whole must develop a coastal zone management strategy (currently underway with regards to the West Coast DM).
    - Requirements of the ICM Act are included in the next round of the West Coast DM and associated LM SDF and IDP revisions, promoting the evolution of shoreline as the most important factor to take into account during development planning within the coastal zone.
    - The West Coast DM and associated LMs must develop coastal edge development policies and delineate coastal set-back lines.
    - More local, detailed studies are funded for specified areas (as identified in the Phase 2 and Phase 3 reports) within the coastal LMs at risk to various coastal hazards. These can be packaged as one, two or five-year projects, depending on the size of the study area, the type of coastal hazard and the modelling detail required.
    - A detailed tide gauge network is established at the various harbours along the West Coast DM coastline (namely Saldanha Bay, St. Helena Bay, Lambert's Bay and Doringbaai). This will allow for a database of sea level records to be collected over time, and local sea level rise along the West Coast DM coastline to be calculated and analysed more accurately.

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# APPENDIX A

# WEST COAST DISTRICT MUNICIPALITY COASTAL FIELD VISIT