Council for Geoscience

Western Cape Unit

P.O. Box 572 Bellville 7535 SOUTH AFRICA c/o Oos and Reed Streets Bellville Cape Town

Reception: +27 (0) 21 946 6700 Fax: +27 (0) 21 946 4190

Geohazards in coastal areas

R. Wigley

Council for Geoscience Report number: 2011-0066

Contents

Figures

1 Introduction

The South African coastline stretches for some 3000 km from the Orange River at the Namibian border in the west to Kosi Bay near the Mozambique border in the east. The coast is generally considered to be rugged with the shores exposed to high wave energy and with very few truly sheltered bays. Existing bays along the South African coastline tend to serve as major nodes of urban development and settlement, e.g. Saldanha Bay, Table Bay, False Bay, Mossel Bay, Algoa Bay and Durban Bay (Burns et. al. 1999). Eighty percent of the South African coastline consists of sandy beaches, usually backed by low sand dunes (Theron and Rossouw, 2008a; b). Burns et al. (1999) note that approximately 1 to 2 million tonnes of sediment are transported past any given point on either the east or west coast each year, where the driving force is considered to be the predominantly south-westerly swell that results in a net littoral drift along both coasts. Approximately 300 river outlets intersect the South African coastline, ranging from small water bodies that are only occasionally connected to the ocean, to large, permanently open systems, and coastal lakes connected to the sea via a narrow channel (Harrison et al. 2001). Estuaries being areas of high productivity are one of the most important features of the South African coastline because of the role they play in the life cycles of many plants.

Approximately 40% of South Africa's population lives within 100 km of the coast[1] and coastal resources are relied on for commercial opportunities as well as for food, recreation and transport, thereby facilitating job creation and general economic upliftment (Atkinson and Clark, 2005). The coastal zone is subject to significant anthropogenic modifications and both coastal ecosystems and human populations are especially susceptible to the negative impacts of any changes, including natural geohazards (IGOS, 2006).

Definition of what is meant by the coastal zone can be a problem in itself, although the coastal zone always includes the shoreline and the interface between land and sea. It has been suggested that the coastal zone can be considered to include that strip of land up to 100 m above sea level or 100 km inland (or to the first major terrain change), depending on which is the most useful when considering impacts on people (IGOS, 2009 and references therein).

2 Coastal Geohazard processes

The impacts of geohazards in coastal regions are typically considered to a significant impact in two priority areas, namely:

1. Coastal Populations
2. Coastal Ecosystems

Both these natural and human elements of coastal zones are vulnerable to disturbances associated with natural processes in conjunction with anthropogenic forcing.

The most common geohazards in coastal areas can be considered to result from:

1. Inundation associated with sea-level rise and associated storm surge flooding;
2. Changes in sediment dynamics (coastal erosion/deposition etc.);

1 Department of Environmental Affairs and Tourism and Council for Scientific and Industrial Research (2005) http://soer.deat.gov.za/indicator.aspx?m=216) *(accessed March 2011)*

3. Landslides / rockfalls;
4. Earthquakes;
5. Tsunamis.

The latter three are not considered further in this report as they are described elsewhere.

2.1 Global climate change

There is an increased awareness of the potential impacts of climate-change on the coastal and ocean environment. Estimated current rates of eustatic sea-level rise range from 2 to 9mm/yr (Intergovernmental Panel on Climate Change, 2001), which is two to four times higher than for the previous 100 years. Recent studies based on satellite altimetry (utilising TOPEX/Poseidon, Jason-1 and Jason-2) show global mean sea level rising at a rate of 3 mm / year since 1992 (Nerem et al., 2010). Local measured sea-level trends measured from the station at Port Nolloth (Brundrit, 1995) and from Durban (Mather, 2007) are in agreement with global trends, suggesting that global data can be used for models along our coastline.

The vulnerability of coastal regions will increase, assuming the projected, global warming-induced environmental changes result in higher sea levels with the associated coastal inundation as well as changes in the location, number, frequency and intensity of storms and associated storm surges increase (Sidle, et al., 2004; Tralli et al., 2005). Rising sea level, in combination with large storms, flooding and increased wave energy is driving increased rates of erosion of beaches, bluffs and other coastal features, where storm buffering provided by beaches and dunes, as well as floodwater storage by wetlands is being affected (Heinz Center, 2002).

The probable impacts of the sea-level rise on coastal areas can be divided into five general groups in approximate order of significance (Midgley et al., 2005 and references therein):

a) Increased exposure to extreme events (which themselves might increase in frequency or intensity);

b) Increased saltwater intrusion and raised groundwater tables;

c) Greater tidal influence;

d) Increased flooding (frequency and extent);

e) Increased coastal erosion.

The highly exposed South African predominantly sandy coastline is going to be susceptible to increased erosion by wind, wave processes etc due to the expected increased storminess. For example, the March 2007 storm in Durban had maximum run-up levels of +10m above mean sea level (MSL) (Smith et al., 2007). Although this storm event occurred during a highest astronomical tide, rising sea-levels will result in increased recurrence rates of such storms in the future (Theron and Rossouw, 2008b).

2.2 Local impact studies

A number of different studies along the South African coastline (Hughes, 1992; van Ballegooyen et al., 2003; Midgley et al, 2005; Theron et al., 2010; Umvoto Africa, 2010 and references therein) indicate that areas with the greatest and most immediate risk were considered to reflect a combination of rising sea levels and extreme storm events, especially in the relatively sheltered environments like tidal inlets, estuaries, coastal wetlands and marinas.

The local effects of a global rise in sea level depend on a number of factors, including coast line type. Hard or rocky shores will most likely respond with a simple landward migration of the high-water mark according to overall slope above the present high water mark. The geology of the rocky shoreline will play a significant role, with increased erosion typically resulting in increased cliff-retreat.

Sandy shores, such as high energy South African beaches, are likely to be more susceptible to increased erosion, where a number of different models by Bruun (1988) as well as those by Davidson-Arnott (2003) and Stive (2004) have been proposed (Theron and Rossouw, 2008b) to model these expected changes. However, the relationship between global climate change and the resultant local erosion is not a simple model and depends on a number of factors, including the nearshore slope, existing beach and back-beach profiles, dune cementation, sediment supply, grain size, sediment transport mechanisms (via long-shore drift, wind, river etc), presence of coastal dunes and the role of the built-environment in altering natural equilibrium processes amongst others. Van Ballegooyen et al. (2003) proposed that the physical process of erosion and/or under-scouring of foundations and structures; flooding and inundation; direct wind and wave impacts (occasionally currents) were the most significant factors to consider based on a study of significant marine hazards relevant to the Western Cape.

Theron and Rossouw (2008b) identified the most vulnerable coastal areas resulting from impacts associated with predicted climate change to include:

- Northern False Bay;
- Table Bay;
- Saldanha Bay area;
- The South Cape coast;
- Mossel Bay to Nature’s Valley;
- Port Elizabeth;
- The developed areas of the KwaZulu-Natal Coast.

Midgley et al. (2005) identify a number of vulnerable areas and possible impacts within the Western Cape, including similar vulnerable areas along the southern Cape coastline, namely Mossel Bay, Knysna, Plettenberg Bay and Nature’s Valley.

Another expected result of global climate change is an expected increase in the average wind velocities throughout all seasons in South Africa (Hewitson, 2006). Theron and Rossouw (2008a; b) show that a modest 10% increase in wind velocity results in a 12% increase in wind stress and a 26% increase in wave height which may be equated to an 80% increase in wave-power. This implies that the potential increase in cross-shore transport increase in the order of 40-100%. However, sediment budgets result from a complex interaction between wind field, sediment availability, 3D-changes in nearshore bathymetry and local currents, geology and the local (and regional) built environment. The lesson learnt must be that the likelihood is that coastal erosion processes, including shoreline erosion / accretion, cliff retreat and dune migration will vary considerably with anticipated global climate change into the future and monitoring of changes in the coastal environment will be important.

3 Physical vulnerability index

To predict changes in the coastal system for use as a decision-support tool, there is a need to:

- Characterise the geomorphology and beach profile characteristics (slope, elevation, wave approach angle etc) geology, topography, and bathymetry that determines the physical and ecosystem response to external factors;
- Monitor the physical processes and energy inputs that drive coastal systems (waves, storm characteristics, currents, water levels etc.)
- Monitoring the resource development, changing patterns in land use and land cover and other human activities that affect the coastal area (USGS, 2009 and the USGS Plan for a Comprehensive National Coastal Program[2]

A variety of coastal vulnerability indices are available, where the USGS coastal vulnerability index for the US Atlantic margin (Thieler and Hammar-Klose, 1999) considered the six physical variables described below (see Figure 1) as an essential requirement to rank the physical vulnerability of the coastal environment, namely :

- geomorphology
- shoreline erosion and accretion rates (m/yr)
- coastal slope (percent)
- rate of relative sea-level rise (mm/yr)
- mean tidal range (m)
- mean wave height (m)

[2] *(http://marine.usgs.gov/coastal-plan/usgs-ntl-coastal-plan.pdf).*

	Ranking of coastal vulnerability index				
	Very low	Low	Moderate	High	Very high
VARIABLE	1	2	3	4	5
Geomorphology	Rocky, cliffed coasts Fiords Fiards	Medium cliffs Indented coasts	Low cliffs Glacial drift Alluvial plains	Cobble beaches Estuary Lagoon	Barrier beaches Sand Beaches Salt marsh Mud flats Deltas Mangrove Coral reefs
Coastal Slope (%)	> .2	.2 – .07	.07 – .04	.04 – .025	< .025
Relative sea-level change (mm/yr)	< 1.8	1.8 – 2.5	2.5 – 2.95	2.95 – 3.16	> 3.16
Shoreline erosion/ accretion (m/yr)	>2.0 Accretion	1.0 – 2.0	-1.0 – +1.0 Stable	-1.1 – -2.0	< - 2.0 Erosion
Mean tide range (m)	> 6.0	4.1 – 6.0	2.0 – 4.0	1.0 – 1.9	< 1.0
Mean wave height (m)	<.55	.55 – .85	.85 – 1.05	1.05 – 1.25	>1.25

Figure 1: The USGS coastal vulnerability index for the US Atlantic margin (Thieler and Hammar-Klose, 1999).

A recent "Coastal Vulnerability Index" study for the KwaZulu Natal coastline, undertaken by the Oceanographic Research Institute (ORI) over 2½ years, assessed vulnerability of the coast in three phases, namely[3]:

1. Assessment of the physical vulnerability based on the physical parameters of the coast.
2. The second phase looked at social, economic and ecological vulnerabilities.
3. Social, economic and ecological vulnerabilities are related to the physical vulnerability, as a means to identify areas potentially at risk.

This study indicates that 23% of the KwaZulu Natal coastline is a high risk zone whereas 47% is a moderate risk zone, where physical risks are mostly considered to be due coastal erosion associated with sea-level rise and increased storm activity.

Theron et al. (2010) selected to follow a method for a South African Coastal Vulnerability Index outlined by Coelho (2006) based on studies of coastal vulnerability in Portugal that utilises nine variables; and includes geology, ground cover and land-use (urban impact) in addition to those factors utilised by the USGS scheme. In addition Theron et al. (2010) argue that it is also necessary to consider degree of protection from prevailing wave energy (coast configuration and bathymetry); erosion potential using a Bruun type model and geomorphology of protective fore-dune buffer when determining vulnerability indices for the South African coastal environment.

Smith et al (2007) noted that the severity of coastal erosion and consequent damage along the KwaZulu Natal coast during the March 2007 storm was dependent on 5 main factors:

1. Proximity to high water mark of urban development within coastal environment

3 http://www.kzndae.gov.za/Home/JohnsontotheRescueofourCoast.aspx (accessed March 2011)

2. Coastal profile – low profile coastlines are most susceptible to damage

3. Coastal shape – headlands, promontories and the high-energy side of bays were hardest hit

4. Coastal type – mixed coastlines (rock and sand) were associated with greatest damage (if scouring prevented by a rocky shelf, the increase in reflected wave energy enhanced erosion). Natural vegetation and dunes acted as protection, with erosional impact increasing as alien and exotic species increased.

5. Coastal modification – increased erosion in areas of land reclamation and along sea-walls etc.

These five factors, amongst others, will therefore need to be considered in all future vulnerability studies for the South African coastal environment.

Although a number of studies for coastal vulnerability have been undertaken, there does not yet exist a coherent database for the South African coastline as a whole. The factors considered significant in the determination of the KwaZulu Natal vulnerability study still need to be ascertained as this data is as yet, unpublished.

4 Impact of coastal geohazards

Coastal flooding/inundation is considered globally to be one of the most significant impacts of any geohazard and results in damage to both coastal populations, the built environment and ecosystems. The coastal relief (see Figure 2) for much of South Africa, in conjunction with the location of existing developments, results in relatively few developed areas being sensitive to flooding and inundation resulting from the projected sea level rise to 2100 (Theron and Rossouw' 2008a).

The expected increase in storm surges and the effects on local physical processes, including sea-conditions, will, however, directly affect all built environments within a short distance of the shoreline, where indirect impacts may be much broader if infrastructure and services such as waste-water treatment facilities, ports, agriculture, and power plants are incapacitated (IGOS, 2006). The associated expansion of population, particularly in poorer urban coastal areas, exacerbates this vulnerability. For example, the March 2007 storm along the KwaZulu Natal coastline resulted in damage worth an estimated R1 billion (Smith et al., 2007). Cartwright (2008) found that the expected increased storm surge damages could cost the City of Cape Town between R5 billion to R20 billion in the next 25 years, based on a study undertaken for the 307 km of coastline (Melkbos to Gordon's Bay) administered by the city.

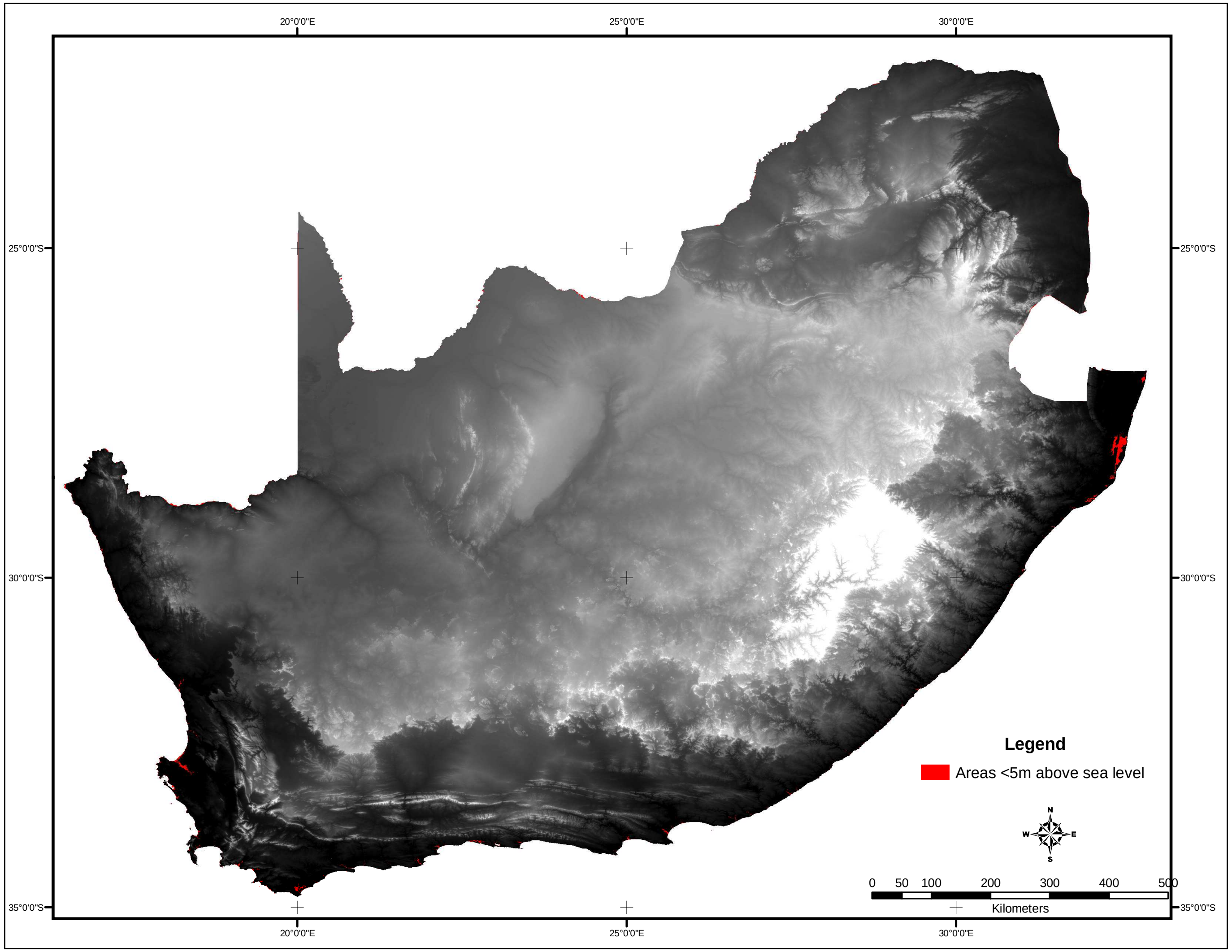

Figure 2: Areas in red located at or below 5 m above Mean Sea Level, using the global The Shuttle Radar Topography Mission (SRTM) dataset, emphasising the minor role of inundation alone on the coastal environment of South Africa.

5 Recommendations

There is, therefore, clearly a need to create a coherent coastal vulnerability index map for South Africa, utilising and combining a number of different assessments undertaken to date. However, as it has been shown that local effects (e.g. wave run-up) are significant in determining the response to sea-level rises and increased storminess (Theron et al, 2010), this will further complicate the definition of these vulnerabilities. This phase will clearly require, at a minimum, collaboration with the CSIR and ORI teams that have already undertaken a considerable amount of work towards creating an understanding of the significant processes.

There is also a need for monitoring and assessment of the coastal environment to understand current erosion rates and modifications resulting from the physical processes associated with climate change, sea-level rise and coastal flooding and the related issues of coastal erosion and accretion, in order to understand, manage and possibly mitigate the potential risk to both coastal populations and ecosystems (IGOS, 2006). Gutierrez et al. (2001) argue that is important to identify "critical coastal erosion areas", which can be undertaken by the monitoring of historical shoreline erosion rates. The application of a satellite remote sensing will also contribute much needed baseline and time series data, as part of an integrated global observation strategy (Tralli et al., 2005).

One of the other important effects of climate change in coastal system is considered to be inundation of wetlands and altered tidal ranges, prisms and circulation in estuarine systems (NCCOE, 2004). According to Tol (2004), by 2100 South Africa will lose some 11% of its wetlands due to coastal protection measures and structures erected to mitigate sea level rise impacts, making South Africa potentially the 5th most vulnerable country worldwide in terms of wetland losses. Most of the larger estuaries in South Africa have some degree of built environment along the shoreline. Pressures on these vulnerable coastal systems have been identified to include urban development and the resultant habitat transformation, changes in sediment transport through upstream activities (climate change, industry, agriculture etc) as well as changing dynamic resulting from fresh-water extraction from within and upstream of estuaries (Burns et al., 1999). It is proposed that a case study of estuarine dynamics could be undertaken using a combination of a time-series of aerial imagery, in conjunction with detailed DEM's obtained through both LIDAR and InSAR remote sensing techniques. This will also allow for evaluation of the different remote sensing techniques. The Bot River estuary, is extensively anthropogenically modified, and is characterised by significant seasonal variations in both beach sand bar/berm height and water levels making it an appropriate choice for an initial case study allowing for monitoring of changes associated with this system.

6 References

Atkinson, L. and Clark, B., 2005. Marine and Coastal Ecosystems: Background Research Paper produced for the South Africa Environment Outlook report on behalf of the Department of Environmental Affairs and Tourism (National State of the Environment Report).

Brundrit, G. B., 1995. Trends of southern African sea level: statistical analysis and interpretation. South African Journal of Marine Science, 16, 9-17.

Bruun, P., 1988. The Bruun rule of erosion by sea-level rise: a discussion on large-scale tow and three-dimensional usages. Journal of coastal Research, 4 (4), 627-648.

Burns, M., Connell, A., Makhaye, S., Monteiro, P., Morant, P. and Taljaard, S., 1999. Marine and Coastal Systems and Resources. http://www.ngo.grida.no/soesa/nsoer/issues/coast/index.htm

Cartwright, A. (2008). Global climate change and adaptation – A sea-level rise risk assessment. Phase three: A sea-level risk assessment for the City of Cape Town. Prepared for the City of Cape Town by LaquaR Consultants CC, 65 pp.

Coelho, C., Silva, R., Gomes, F.V., Pinto, F.T., 2006. A vulnerability analysis approach for the Portuguese west coast. In Risk Analysis V: Simulation and Hazard Mitigation, 91, pp. 251–262. Ed. by V. Popov, and C. A. Brebbia. Wessex Institute of Technology, WIT Transactions on Ecology and the Environment, UK. 400 pp.

Davidson-Arnott, R.G.D., 2005. Conceptual model of the effects of sea level rise on sandy coasts. Journal of Coastal Research 21 (6): 1166 – 1172.

Gutierrez, R., Gibeaut, J. C., Smyth, R.C., Hepner, T.L. and Andrews, J.R., 2001. Precise Airborne Lidar Surveying for Coastal Research and Geohazards Applications. International Archives of Photogrammetry and Remote Sensing, Volume XXXIV-3/W4 Annapolis, MD, 185-192.

Harris, L., Nel, R., and Schoeman, D., 2011. Mapping beach morphodynamics remotely: A novel application tested on South African sandy shores, Estuarine, Coastal and Shelf Science (in press), doi:10.1016/j.ecss.2010.12.013.

Harrison, T. D., Hohls, D. R., Meara, T. P. and Webster, M. S., 2001. South African Estuaries: Catchment Land-Cover National Summary Report (Prepared for Department of Environmental Affairs & Tourism)

Heinz Center, 2002. Human links to coastal disasters. The H John III Center for Science, Economics and the Environment. http://www.heinzctr.org/publications/PDF/Full_report_human_links.pdf

Hughes P. (1992). The impacts of sea-level rise on the South African coastal environment. Ph.D. thesis, University of Cape Town, South Africa.

Nerem, R.S., Chambers, D.P., Choe, C. and Mitchum, G.T., 2010. Estimating Mean Sea Level Change from the TOPEX and Jason Altimeter Missions. Marine Geodesy, http://www.informaworld.com/smpp/title~db=all~content=t713657895~tab=issueslist~branches=33 - v3333 (S1), 435 – 446.

IGOS, 2006. A Coastal Theme for the IGOS Partnership — For the Monitoring of our Environment from Space and from Earth. Paris, UNESCO 2006. 60 pp. (IOC Information document No. 1220)

Mather, A.A., 2007. Linear and nonlinear sea-level changes at Durban, South Africa. S. Afr. J. Science, 103 (11-12)

Midgley, G. F., Chapman, R. A., Hewitson, B., Johnston, P., de Wit, M., Ziervogel, G., Mukheibir, P., van Niekerk, L., Tadross, M., van Wilgen, B. W., Kgope, B., Morant, P. D., Theron, A., Scholes, R. J. and Forsyth, G. G. (2005). A status quo, vulnerability and adaptation assessment of the physical and socio-economic effects of climate change in the Western Cape. Report to the Provincial Government of the Western Cape: Department of Environmental Affairs and Development Planning. CSIR Report No. ENV-S-C 2005-073, Stellenbosch, South Africa, 156pp.

NCCOE, 2004. Guidelines for Responding to the Effects of Climate Change in Coastal and Ocean Engineering. The National Committee on Coastal and Ocean Engineering, 64 pp.

Sidle, R.C., Taylor, D., Adger, W.N., Lowe, D.J., de Lange, W.P., Newnham, R.M. and Dodson, J.R., 2004. Interactions of natural hazards and society in Austral-Asia: evidence in past and recent records. Quaternary International, 118–119, 181–203.

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. . S. Afr. J. Science, 103 (7-8)

Thieler, E.R. and Hammar-Klose, E.S., 1999. National Assessment of Coastal Vulnerability to Sea-Level Rise: Preliminary Results for the U.S. Atlantic Coast U.S. Geological Survey Open-File Report 99-593 (http://pubs.usgs.gov/of/1999/of99-593/index.html)

Theron, A.K. and Rossouw, M., 2008a. Analysis of potential coastal zone climate change impacts and possible response options in the southern African region http://www.csir.co.za/nre/coupled_land_water_and_marine_ecosystems/pdfs/CPO-0029_standard.pdf

Theron, A.K. and Rossouw, M., 2008b. Quantification of risks to coastal areas & development: wave run-up and erosion (http://researchspace.csir.co.za/dspace/bitstream/10204/2561/1/Theron_2008.pdf)

André Theron, A.K., Rossouw, M., Barwell, L., Maherry, A., Diedericks, G. and de Wet, P., 2010. Quantification of risks to coastal areas and development: wave run-up and erosion. CSIR Science real and relevant conference 2010.

Hughes P. (1992). The impacts of sea-level rise on the South African coastal environment. Ph.D. thesis, University of Cape Town, South Africa.

Tol, R.S.J., 2004. The Double Trade-off Between Adaptation and Mitigation for Sea Level Rise: An Application of Fund (Working Paper FNU-48) http://www.fnu.zmaw.de/fileadmin/fnu-files/publication/working-papers/slradaptmitigatewp.pdf

Tralli, D.M., Blom, R.G., Zlotnicki, V., Donnellan, A. and Evans, D.L., 2005. Satellite remote sensing of earthquake, volcano, flood, landslide and coastal inundation hazards. ISPRS Journal of Photogrammetry and Remote Sensing, 59 (4), 185-198.

Umvoto Africa. (2010). Sea Level Rise and Flood Risk Assessment for a Select Disaster Prone Area Along the Western Cape Coast. Phase 1 Report: Eden District Municipality Sea Level Rise and Flood Risk Literature Review. Prepared by Umvoto Africa (Pty) Ltd for the Provincial Government of the Western Cape Department of Environmental Affairs and Development Planning: Strategic Environmental Management (May 2010).

USGS, 2009. The Framework of a Coastal Hazards Model—A Tool for Predicting the Impact of Severe Storms By Patrick L. Barnard, Bill O'Reilly, Maarten van Ormondt, Edwin Elias, Peter Ruggiero, Li H. Erikson, Cheryl Hapke, Brian D. Collins, Robert T. Guza, Peter N. Adams and Julie Thomas. Open File Report 2009–1073, 25pp.

Van Ballegooyen, R., Theron, A.K., Wainman, C., 2003. Final input to the Risk and Vulnerability Assessment (RAVA) for the Western Cape (included in the final report to the Provincial Government of the Western Cape).