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Quantification of risks to coastal areas and development: wave run-up and erosion

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Abstract

In support of the effective implementation of the Integrated Coastal Management Act (Act No 24 of 2008), a review is presented of coastal hazard assessment methods. In particular the ICM Act legislates the establishment or change of coastal setback lines to protect coastal public property and private property, amongst others. In this paper a practical method applicable to Southern African conditions, and the available data, was identified and further adapted to include additional forcing factors considered to be most relevant under Southern African conditions. In South Africa, the most important drivers of risk to coastal infrastructure from erosion and flooding are waves, tides and future sea level rise. It is the combination of extreme events (sea storms occurring during high tides in conjunction with sea level rise) that will have the greatest impacts and will be the events that increasingly overwhelm existing infrastructure. Appropriate extreme values of wave conditions and tidal levels were combined with reasonable scenarios of sea level rise. Practical methods were developed to model wave run-up based on these inputs and combined with simple methods of estimating erosion due to sea level rise. Further interpretation of these outputs enabled mapping of vulnerable areas and a local test case was conducted to demonstrate the outcomes. The results were incorporated into a Geographic Information System (GIS) database and mapped using fine scale elevation data to spatially depict the results. An output of this study is thus a methodology for assessing, and predicting, wave run-up lines which include the effects of long-term erosion due to sea level rise. Coastal areas within Table Bay near Cape Town were selected to illustrate how such run-up calculations can be used to identify present and future vulnerable areas. It is believed that this approach will be useful in assessing and mapping vulnerable coastal areas in South Africa and to contribute to the determination of future coastal development setback lines as defined in the ICM Act.

1. Introduction

The Integrated Coastal Management Act (Act No 24 of 2008) (the ICM Act) legislates the establishment or change of coastal setback lines in order to (a): (i) protect coastal public property, private property and public safety; (ii) protect the coastal protection zone; (iii) preserve the aesthetic values of the coastal zone; or (iv) for any other reason consistent with the objectives of this Act; and (b) prohibit or restrict the building, erection, alteration or extension of structures that are wholly or partially seaward of that coastal setback line (Clause 25).

Targeted at providing scientific evidence in support of the implementation of Clause 25, a primary objective of this ongoing research is the development of a suitable approach to hazard assessment of the coastal zone. Knowing the potential risk to both human and natural elements of the coastal zone facilitates the mapping of vulnerable areas. In particular, this research includes the identification of potential impacts to man-made development, but does not consider the risk to all goods and services provided by the natural environment. It is acknowledged that several other components of the coastal socio-ecological system should be considered when conducting a holistic coastal hazard assessment, but the focus of this research is on the abiotic physical coastal aspects which include factors linked to climate change. A guiding principle in the compilation of this coastal vulnerability assessment method is that it should be tailored to the South African context, which should enable decision-makers to make informed decisions using the available information.

The Southern African wave climate is characterised by high intensity storms. This often makes coastal settlements vulnerable to a variety of associated natural processes. This threat is of special concern considering that urban coastal zones are densely populated and growing rapidly.

In this paper an overview is presented of the wave climate around the South African coast and possible trends reflected in the data are highlighted. Since 2005, the KwaZulu-Natal coastline experienced a particularly high number of extreme storms which caused coastal erosion and flooding in parts. Not all parts of the coast experienced the same amount of erosion and this illustrates the importance of being able to determine which parts of the coast are more vulnerable than others under present conditions and for future climate scenarios.

It is well known that the prime factor that influenced the amount of storm damage in the past was the physical location of development relative to the high water mark. This so-called development setback line is also a determining factor in assessing the vulnerability under future climate change scenarios. The need therefore exists to determine safe areas which, in turn, require prediction of future shoreline locations. Studying the hazards associated with coastal processes and dynamics (including climate change) will aid the planning and safe location of new development areas and infrastructure. Such knowledge will also assist in the identification of appropriate adaptive options for existing developments that are assessed to be at risk.

2. Methods of assessing vulnerability of coastal areas and developments

2.1. Relevant literature and identification of suitable methods

Following is a brief discussion of only those documents considered most applicable to the Southern African context.

Van Ballegooyen *et al.* (2003) identified all significant marine hazards relevant to the Western Cape. A hazard is defined by the Authors as an event or process (natural or anthropogenic) that results in a potentially deleterious impact on a desirable *status quo*. Marine hazards may be due to natural events or anthropogenic activities, but are typically a combination of these two causes. Their article points out that the full extent of the risk of loss of life and financial loss is not always fully appreciated, and cites as an example the long-term financial losses due to coastal erosion which are often poorly understood, particularly by local authorities. It can be said that all the items in the hazard inventory of Van Ballegooyen *et al.* (2003) result from either erosion and/or under-scouring of foundations and structures; flooding and inundation; direct wind and wave impacts (occasionally currents); and, broadly speaking, algal blooms and pollution. Focussing on the abiotic hazards to infrastructure and developments in the coastal zone, the main metocean drivers are thus waves and sea water levels (and to a lesser extent winds and currents in some instances). This is generally confirmed by the literature review of coastal vulnerability assessment methods, where the identified indicators almost all relate to parameters that affect vulnerability/resilience to erosion/under-scouring and flooding/ inundation.

Breetzke *et al.* (2008), although not providing a vulnerability assessment method per se, contains information and guidelines on risks and response to coastal erosion that is particularly relevant to the South African scenario. The coastal vulnerability index (CVI) devised by the US Geological Survey and founded on six physical variables, is found to be useful to assess the vulnerability of the coastline to climate change (Theiler and Hammar-Klose, 2000). These six variables are: geomorphology; coastal slope; relative sea level change; shoreline erosion/accretion rate; tidal range; and wave height. Another indicator, the coastal social vulnerability index (CoSVI) developed by Boruff *et al.* (2005), is used to determine the socio-economic vulnerability of coastal areas to sea level rise (SLR). These indices can also be combined to give an overall vulnerability index, which appears to be a viable approach to the South African situation. Dutrieux *et al.* (2000) is considered to be more useful for integrated coastal zone management aimed at sustainability and the protection/management of the natural environment, and is particularly useful for guidance in more detailed vulnerability mapping of smaller areas (e.g. islands).

The methodologies recently developed and applied in Portugal and Spain have a practical approach and are well-suited to the South African context. Jimenez *et al.* (2009) developed good coastal storm vulnerability assessment methods, but the input data requirements are considered to be too onerous for wide-scale application in the Southern African context. Jimenez (2008) provides a good description of how coastal vulnerabilities can be assessed for multiple hazards. From the literature study it was concluded that the set of parameters included in the method developed by Coelho *et al.* (2006) would be pragmatic and most relevant for application to the Southern African coast.

2.2. Adaptation of suitable method for Southern Africa

The first part of the Coelho *et al.* (2006) method is to assess the degree of exposure and vulnerability to coastal processes using the following nine indicators as the basis: foreshore elevation; distance (e.g. infrastructure) to shore; tidal range; wave height; historical erosion/accretion rate; geology (type of rock or sediment); geomorphology type; (e.g. rocky cliff or river mouth); ground cover (e.g. forest/mangrove or urbanised/industrial); and anthropogenic actions (e.g. shoreline stabilisation intervention or sediment sources reduction). Specific limit values associated with each of the indicators were defined and the assessment is done by selecting the appropriate range of values for each indicator. A vulnerability classification of Very Low (Vulnerability Score = 1) to Very High (Score = 5) is then derived.

Reflected below are three additional indicators, relevant to the Southern African coast, which the Authors have identified and added to the Coelho *et al*. assessment methodology:

- Degree of protection from prevailing wave energy (site location, coast configuration, bathymetry). Scoring is done according to wave exposure as listed below, in increasing order of exposure. Additionally, if sites are located close to a river/estuary mouth, the vulnerability is scored more severely;
  - Leeside of large island or extensive spit on opposite side of incident waves
  - Leeside of headland, rocky point or peninsula
  - Partially sheltered from deep-sea wave energy
  - Directly exposed to waves only slightly refracted from deep-sea
  - Directly exposed to storm wave attack, with narrow surf zone
- Sea level rise Bruun erosion potential (i.t.o. inshore slope; see Section 3.4). Sea level rise is likely to result in flooding/inundation and coastal erosion. However, flooding/inundation vulnerability is already accounted for in the elevation and distance to shore. Thus, only the Bruun erosion potential needs to be assessed: for a specific amount of sea level rise, the erosion is directly related to inshore slope (alternatively, the parameter to quantify could be taken as distance to the 10, 15 or 20 m depth contour; the choice depends on the “active” nearshore profile depth);
- Relative height (ideally volume) of the protective foredune buffer (i.e. the available sand reservoir).

In the tropics (e.g. Mozambique) two important additional indicators have been included by the Authors: cyclones (e.g. occurrence per annum) and corals/fringing reefs (alongshore extent as a percentage of total shoreline length). Potential additional factors to consider in future are: characteristics of winds (velocities above 12 km/h that dominate during the dry season with an onshore component for more than 20 percent of the time); pressures from human activities (to dunes/vegetation); and existing cross-shore beach width (e.g. to accommodate storm erosion or long-term trends).

Nevertheless, it is important to keep in mind which data is readily available to quantify a specific factor. “Double counting” must also be avoided, e.g. distance and elevation already account for slope on land, so if distance and elevation are assessed, slope on land should not also be added as a factor. Seaward slope is, however, independent of on-land slope and is used specifically to assess vulnerability to erosion due to SLR.

Having developed such an assessment method to identify hazardous coastal areas, each particular hazard can be investigated further to quantify the risk of occurrence or to determine which locations within an area are at risk from a specific event. As indicated in the literature review, probably the most significant driver of deleterious impacts on the South African coast is sea storms combined with high water levels. Thus, the remainder of this paper is focussed on the quantification of these specific aspects/drivers of coastal hazard.

3. Quantification of some primary hazards: extreme water levels, sea storms, wave run-up and future erosion

3.1. Extreme inshore sea water levels

Significant drivers of high inshore sea water levels are tides, wind set-up, hydrostatics set-up, wave set-up and, in future, SLR (due to climate change). These drivers all affect the still-water level at the shoreline. The drivers/components of extreme inshore sea water levels most significant to the Southern African context are the tides (South African spring tides are about 1 m above mean sea level (MSL), but reach up to +3.7 m MSL in Mozambique), potential SLR and wave run-up. Theron (2007) has estimated that during extreme events in the South African setting, these components could each contribute between about 0.35 m to 1.4 m to MSL and by 2100 SLR is now estimated to be in the 0.5 to 2 m range. Note that potential additional impacts of climate change (e.g. more extreme weather events) on wind-, hydrostatic- and wave set-up are not included in the above.

The drivers of inshore water levels should not be confused with the added effect of wave run-up which, in the South African context, can reach much higher elevations. Wave run-up is the rush of water up the beach slope beyond the still-water level in the swash zone. According to surveyed elevations (Smith *et al.*, 2010), maximum run-up levels on the open KwaZulu-Natal (KZN) coast near Durban during the March 2007 storm (which coincided with the highest astronomical tide), reached up to about +8.5 m MSL. Note that wave set-up and run-up are both accounted for in these levels. The maximum wave run-up alone during the 2007 KZN storm is estimated to have been up to about 7 m, resulting from significant nearshore wave heights of about 8.5 m.

Around Southern Africa wave run-up is thus clearly the dominant factor, which may be considerably exacerbated by tides and future SLR. Hence, the focus of this paper is now placed on wave climate, resulting wave run-ups and the combined impact of waves, tides and SLR/climate change effects.

3.2. South African wave climate and extremes analyses

The general weather climate of Southern African is influenced by different types of synoptic patterns (MacHutchon, 2006). Waves significantly affecting maritime activities are generated mainly by passing frontal systems from the Southern Atlantic, cut-off low systems along South Africa's southern to eastern coast and occasionally by tropical cyclones moving down the Mozambican channel.

The wave climate around the South African coast shows clear seasonality and varies in intensity and directionality around the coast. The most severe wave conditions occur on South Africa's south-west and south coasts, with the magnitude decreasing along the west and east coasts. The distribution of wave period remains fairly constant due to the swell propagating northwards. Wave directions are predominantly south-west, but swing more toward a south-south-westerly direction on the east coast.

As the wave conditions are a primary driver of extreme seawater levels and potential flooding/inundation of areas, it is necessary to quantify the extreme wave conditions encountered around the coast. Thus, the wave climate was analysed and the statistical distributions most applicable to the west and east coasts was found to differ, namely Fisher-Tippet and Weibull respectively. Rossouw and Rossouw (1999) provide a description of these distributions and their application to wave statistics. Offshore wave heights corresponding to return periods from 1 to 100 years applicable to the various sectors of the South African coast were derived for the prediction of wave run-up levels. The results are indicated in Figure 1.

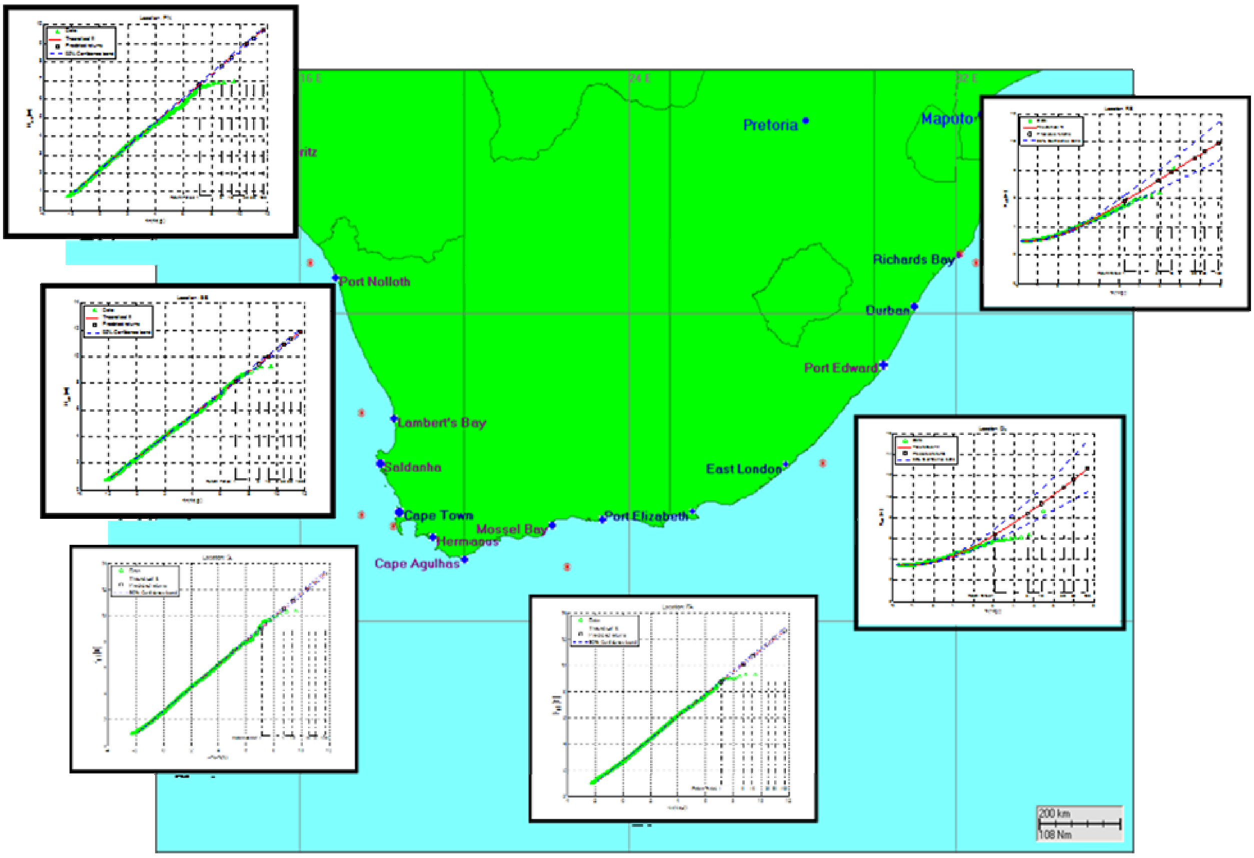

Figure 1: Extremes analysis of South Africa's offshore wave climate indicating wave heights for return periods up to 100 years (based on NCEP (National Centres for Environmental Predictions) satellite wave data).

As can be anticipated, a more severe wave climate (or indirectly a more severe oceanic wind climate) will have greater impact on run-up and flooding levels and therefore necessitate the prediction of future trends in the wave climate. Although the available wave record is shorter than ideally required to determine long-term trends, a preliminary analyses was conducted. It was found that the annual mean significant wave height (H_{m0}) and corresponding standard deviation for the wave data set, collected off Richards Bay, and the annual mean wave height (H_{m0}) for the long-term data set, collected offshore of Cape Town, indicate no real progressive increase. This may appear to contradict the findings of the Intergovenmental Panel on Climate Change (IPCC) as presented in PIANC (2008) (The World Association for Waterborne Transport Infrastructure). However, these results may reflect a regional aspect of the impact of climate change.

Although the averages appear to remain constant, there seems to be some change in individual storms. For example, considering the peaks of individual storms during the more extreme winter period (June to August), an increasing trend of about 0.5 m over 14 years is observed (Figure 2). The trend may be indicative of a significant increase in the “storminess” over the next few decades. It is also worth noting that the opposite occurs during summer: there is a general decreasing trend over the last 14 years with regard to individual storms.

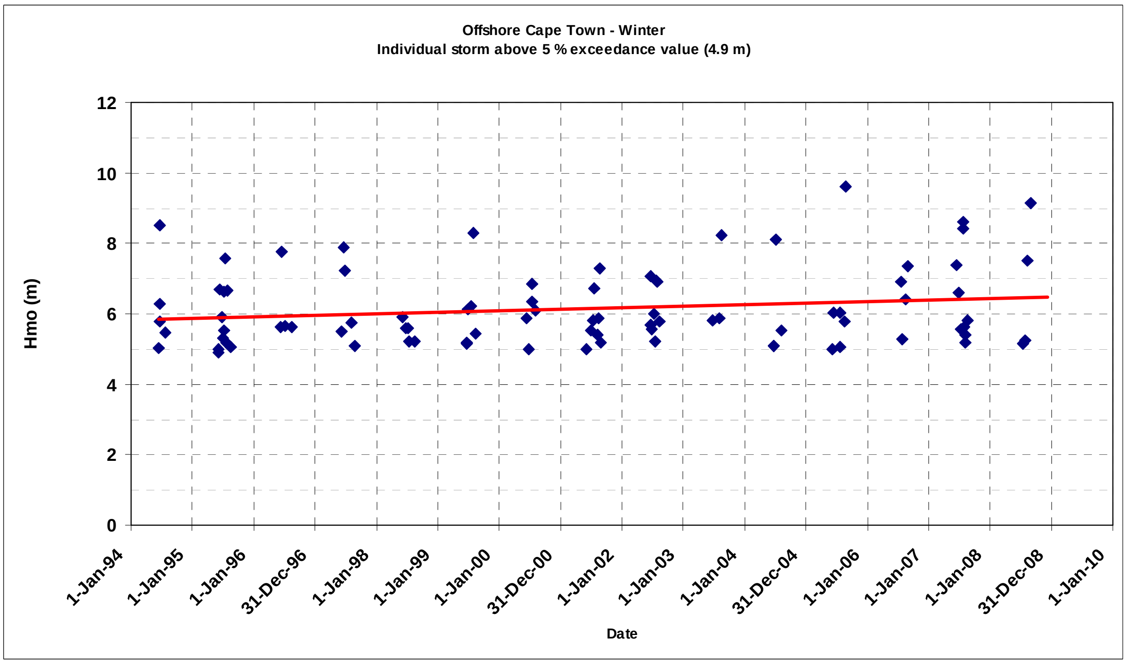

Figure 2: Peaks of individual storms over 14 year-period – offshore Cape Town (based on recordings by CSIR on behalf of TNPA).

Of further interest is the effect of El Niño and La Niña. The individual storm events over the past 14 years, in terms of wave height, are shown in Figure 3, with the El Niño and La Niña events also indicated. A more detailed analysis is required to find possible links between these events and the corresponding wave conditions. It is also important to keep in mind that the waves observed along the coast or through a wave recording system are the consequence of atmospheric events that took place during the preceding hours and days.

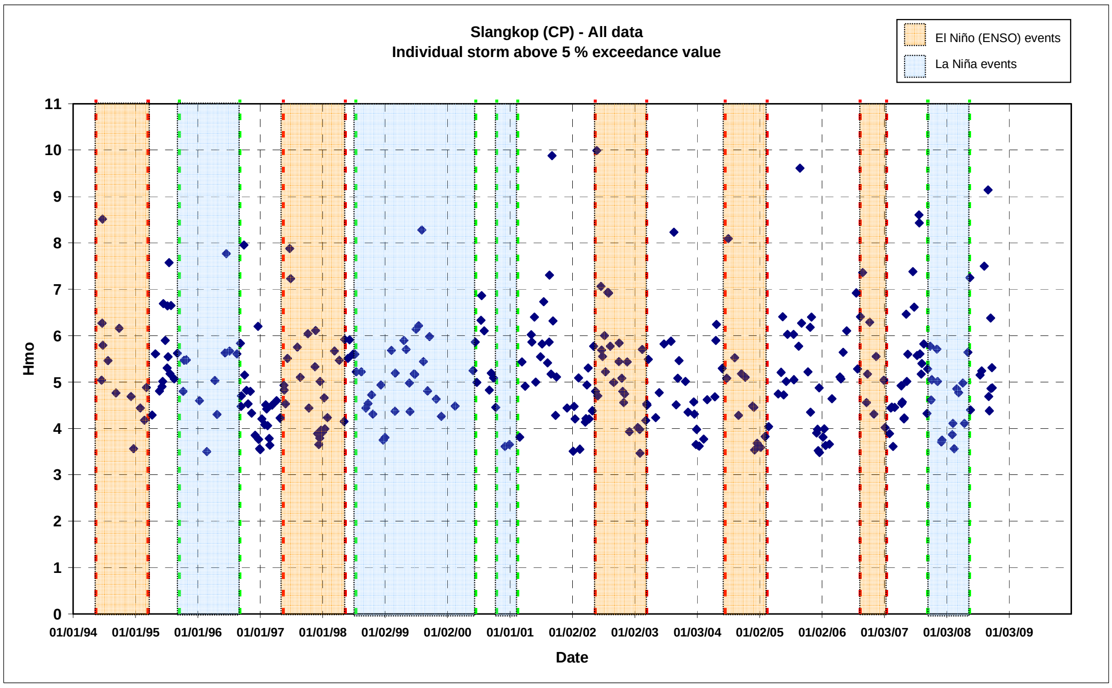

Figure 3: Peaks of individual storms over 14 year-period – offshore Cape Town, including ENSO and La Niña events (based on recordings by CSIR on behalf of TNPA).

3.3. Prediction of wave run-up

Since 2005, the KwaZulu-Natal coastline has experienced a particularly high number of extreme weather events, with an exceptionally extreme sea storm along the KwaZulu-Natal coast during March 2007. Since the monitoring of wave conditions along the South African east coast began nearly three decades ago, only one other storm has been recorded that has had a similar intensity. Storm events are referred to by their return period, that is, the estimated time period in which a storm of similar magnitude is expected to occur again. For example, the wave height return period for the March 2007 storm was found to be in the order of 1-in-10 to 1-in-35 years, which means that under present conditions such a storm will most probably occur again within the next 10 to 35 years. The impact of the storm waves was further increased due to the storm occurring during a period which coincided with the highest astronomical tide, i.e. the sea level was higher than during a normal high tide and the waves could run further across the beach. Direct infrastructure damages alone resulting from this storm are estimated to be over R 400 million and possibly as much as R 2 billion.

Climate change is expected to have a number of consequences which will detrimentally affect coastal resources. These are, among others: higher sea levels; higher sea temperatures; changes in precipitation patterns and sediment fluxes from rivers; changed oceanic conditions; as well as changes in storm tracks, frequencies and intensities. The apparent increase in storm activity and severity will be the most visible impact and the first to be noticed, since higher sea levels will require smaller storm events to overtop existing storm protection measures.

The March 2007 KZN storm is of particular importance, not just in terms of its severity, but also because the chances of such an extreme storm coinciding with the highest astronomical tide are, under present conditions, very small. However, due to the predicted SLR, the tidal levels reached during this storm (the 19-year highest astronomical tide level) will effectively be reached during ordinary spring tides every two weeks by about 2100 (Theron, 2007). This factor alone means that the potential return period of a similar event will be much reduced (i.e. occur more frequently). In addition, should climate change increase sea storminess, similar storm wave heights could occur more often in future. In other words, the same conditions could potentially occur much more frequently in future due to SLR and increased sea storm frequency. This storm should thus serve as a timely warning of the potential impacts that could be incurred on a much more frequent basis in future due to the effects of climate change.

One of the impacts of SLR is that waves will reach further inland than at present. This implies that current coastal development setback lines (of which few exist) have to be adapted. A coastal development setback line is a line landward of which fixed structures (e.g. houses, roads, etc.) may be built with reasonable safety against the physical impacts of the coastal processes (e.g. sea storms, wave erosion and run-up). Factors which co-determine the location of setback lines are storm wave run-up elevations and how far the shoreline will retreat due to erosion, which are in turn affected by the amount of sea level rise that is expected and the predicted increases in storminess. Thus, realistic scenarios of sea level rise and potential increases in wave heights were determined, as well as preliminary calculations of the resulting effects on erosion and run-up.

As mentioned, an important step in calculating setback lines is the determination of wave run-up, i.e. the maximum point that storm waves can reach. In a literature review of wave run-up prediction methods, 15 such methods were considered of which seven were evaluated in more detail. These were: Battjes (1974); Nielsen and Hanslow (1991); three formulations by Ahrens and Seelig (2001); two formulations by Ruggiero *et al.,* (2001); Guza and Thornton (1982); and Stockdon *et al.*, 2006. The empirical formulations of Nielsen & Hanslow and Ruggiero *et al.,* appear to be the most suitable, with the former being easier to apply. The Nielsen and Hanslow (1991) model requires the wave height and period, beach slope and water level, Their set of formulations was therefore used in the compilation of a computer routine, which was verified and tested against the only available set of South African field data. Figure 4 shows the results, considered surprisingly good (R^2 = 0.79) if the relatively few parameters included in the formulation are kept in mind.

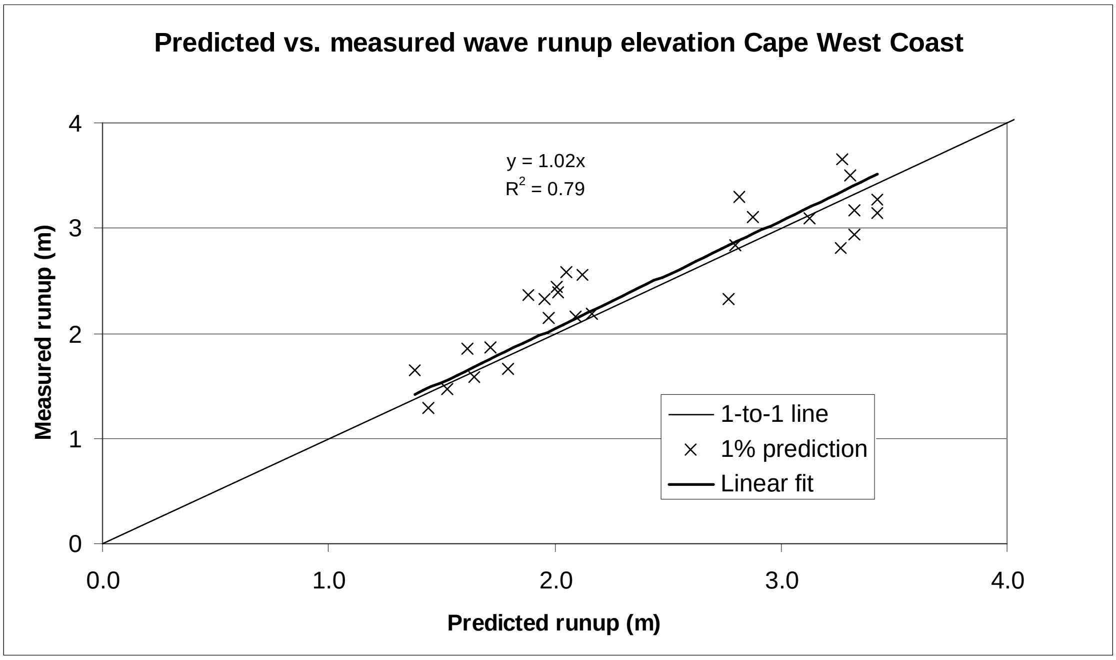

Figure 4: Verification of wave run-up model: predicted vs. measured run-up elevations (CSIR).

Having found that the Nielsen and Hanslow model is valid and applicable to local conditions, the same methodology was applied to investigate the impact of SLR on run-up return periods and occurrences. The mean value of the IPCC Fourth Assessment Report SLR predictions is about 0.4 m by 2100 (AR4 Report, IPCC 2007). Using this prediction of future sea levels, it was found that the same extreme wave run-up elevations as occurred during the 2007 KZN storm, would be reached by waves 10% lower (H_{m0}) than those recorded during the peak of the 2007 storm. This means that, based on the calculated return period of the 2007 storm (and assuming that the statistical distribution of extreme waves remains about the same over the next 100 years), the return period for the same extreme run-up heights is effectively halved. In other words, the probability of such extreme conditions occurring again is basically doubled, or statistically, such situations are likely to occur about twice as often over the long term for a SLR of only 0.4 m.

In view of newer SLR predictions, the effects of a 1 m SLR on run-up levels were also quantified. It was calculated that a wave height of 24% less than the 2007 KZN storm would result in similar run-up elevations if the sea level rose by 1 m. The results are alarming, as the return period of the 2007 event would effectively be subject to a six-fold reduction. In other words, the probability of such extreme events as those experienced during 2007 happening again would be six times greater, or statistically, such impacts are likely to occur six times as often in the long run due to a SLR of 1 m.

The Nielsen and Hanslow (1991) model was used to calculate the run-up at various locations along the South African coast. The 1-in-10 year wave height was used in the calculations and these were determined from measured wave conditions along the South African coast as described in Section 3.2. In South Africa spring tides occur every two weeks, which means that the chances of storm waves coinciding with spring high tides are relatively high. Therefore, the input water level was set at spring high in the run-up modelling. Two general beach slope categories typical of the South African coast were selected, namely mild slopes and steep slopes. The present day wave run-up levels for these two slopes with the present day 1-in-10 year measured wave data are presented in Figure 5 for various locations along the coast. The possible effects of climate change were included in these calculations by assuming that the wave heights may increase by 10% due to stronger winds over the ocean (caused by climate change effects). Another effect that was considered was SLR, for which a value of 0.5 metres was selected; these two effects were also combined.

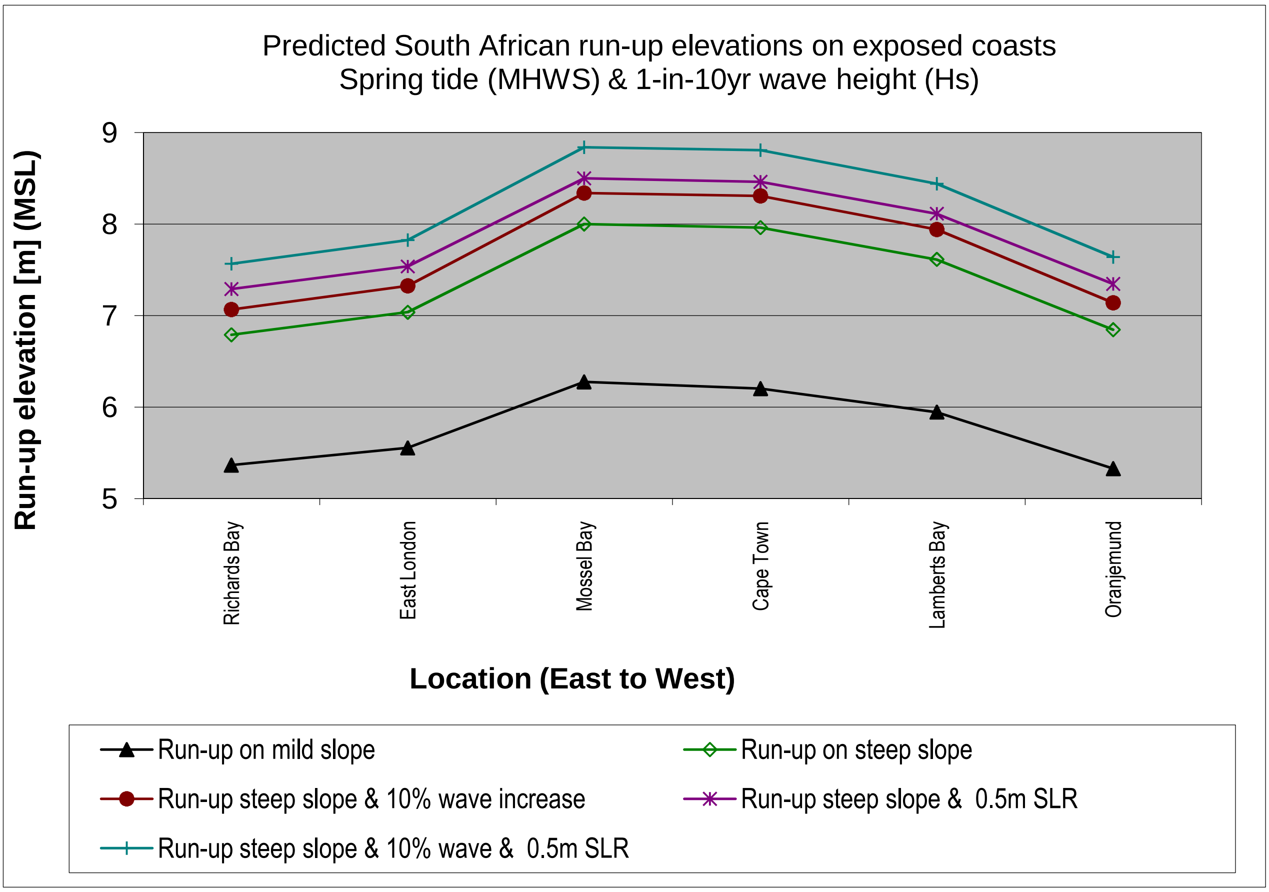

Figure 5: General run-up levels predicted for different locations along the South African coast. Also included are potential effects of climate change (higher waves and/or sea level rise (SLR)).

3.4. Coastal erosion due to climate change

Changes in the shape of sandy coastlines depend on a number of factors of which the most important is the availability and distribution of sediment (sand). Sand along the coast is moved mostly by waves, while the waves approaching the coast are, in turn, affected by bottom topography. As the sea level rises, existing topographic features will be located in deeper water and will have a different effect on waves approaching the coast. Features landward of the breaker zone will be in deeper water and will either have an amplified or dampened effect on the wave climate compared to the present. Deep water features may deepen to the degree that their effect on the wave climate is negligible. The points of wave energy convergence and divergence will change. The new locations of wave energy convergence could be expected to experience an increase in erosion while those locations currently subject to energy convergence could accrete if they are exposed to less energy in future. Changes in wave approach will change longshore currents and longshore sediment transport.

The Southern African coastline includes many sandy areas with very little hard protection, or none at all, and where wave conditions are regarded as having high energy. This leads to a high potential for erosion of these sandy coastlines. The most widely known (and applied) formula for estimating erosion as a result of SLR was proposed by Bruun in 1988 (Figure 6). The main parameters that are taken into account in Bruun's unsophisticated rule are the amount of SLR and the slope of the nearshore (Theron, 1994). The Bruun rule can be applied to give a first estimate of possible erosion of "soft" sandy beaches. In some cases, broad dunes and wide beaches could mitigate such erosion. In other situations, narrower beaches backed by hardened dunes will resist erosion, resulting in less erosion than predicted by the Bruun rule.

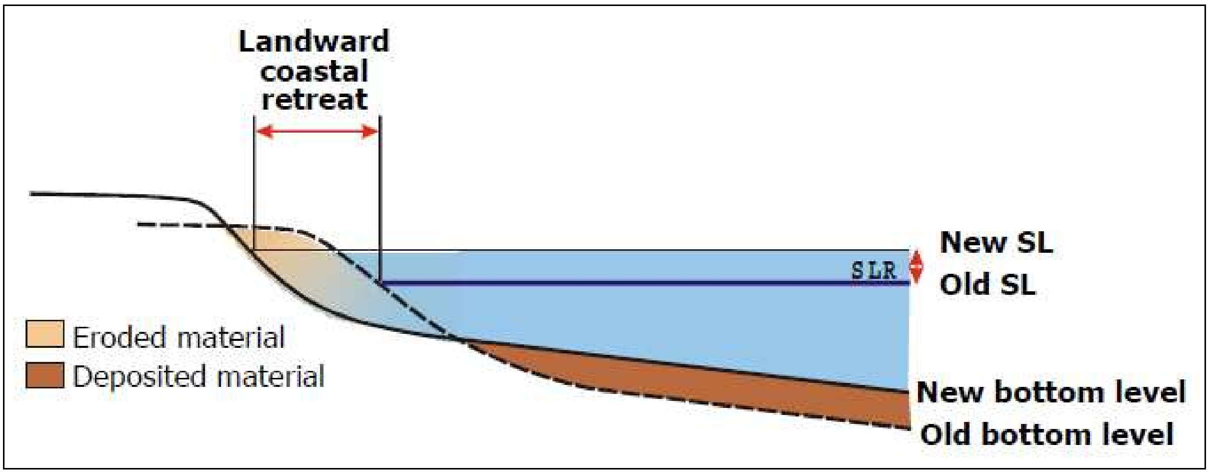

Figure 6: Schematic illustration of the Bruun model of profile response to rise in sea level, showing erosion of the upper beach and nearshore deposition from Davidson-Arnott, 2005.

The Bruun rule is sensitive to the chosen values of the input parameters and these values are also sometimes difficult to determine. Many other factors besides the amount of SLR and the slope of the nearshore need to be taken into account to predict future coastal evolution on longer time and space scales. Site specific aspects such as local geology, hydrology and sedimentology; near- and offshore bathymetry; exposure to waves, currents and general climatology; and local geographical features as well as human influences, should all be considered. The Bruun rule can be used only as a first indicator of where broader investigation of future impacts may be required.

4. Application of prediction methodology for extreme water levels, sea storms, wave run-up and SLR erosion: a case study

Coastal areas within Table Bay (Bloubergstrand to Melkbosstrand) near Cape Town were selected to illustrate how such run-up calculations may be used to highlight present and future vulnerable areas. The Western and Southern Cape, including the study areas, part of which are illustrated in Figure 7, were subject to significant storm impacts as recently as 1 September 2008. Run-up data was collected by the CSIR following the 2008 storm and part of these run-up lines are presented in Figure 7. Although this storm had a return period of about 1-in-10 years, the impact on the coast was not as severe as that of the 2007 storm on the KwaZulu-Natal coast. It may be noted again that the storm of March 2007 had run-up levels in the vicinity of Durban that reached about 8.5 meters above MSL. One of the main reasons why the KwaZulu-Natal coast is more severely impacted by storms of a similar nature is the greater level of density in coastal development close to the high water line in that area.

The Geographical Information System (GIS) used in the mapping of areas which are susceptible to wave run-up requires coastal topographical data as input. This data was provided by the Cape Metropolitan Council and the beach slopes that were used in the calculation of the run-up levels for the two sites were obtained from beach profiles surveyed by the CSIR. Recent literature give a wide range of SLR scenarios, but most “physics/process based” projections (since 2007) for 2100 are in the 0.5 m to 2 m range (Rossouw and Theron, 2009; Shore and Beach Special Review Issue, November 2009). Accordingly, this is the SLR range selected for use in the example shown in Figure 7. The impacts of climate change on wave run-up at these two sites are illustrated by calculating the run-up levels with increased sea levels of 0.5 m, 1 m and 2 m. The most severe impact is, as is to be expected, observed when a SLR of 2 m and 10% increase in the storm wave heights coincide.

The run-up mapped for the 2008 storm does not indicate significant impacts in this area, which is borne out by observations during the storm. However, according to the predicted run-up mapped in Figure 7, even a 1-in-20 year storm (without adding any sea level rise effects) will start causing problems for existing developments. As progressively higher sea levels are added and the scenarios become more severe (as they may well over time), the predicted run-up increases and the vulnerable areas become increasingly larger. Clearly, once sea level rise exceeds about 1 m, a mere 1-in-20 year sea storm could cause major problems in the highly built-up areas near Bloubergstrand. In addition, major transport infrastructure (the coastal trunk road) is also at risk from an increased sea level; all the more so were sea storm occurrence also to heighten.

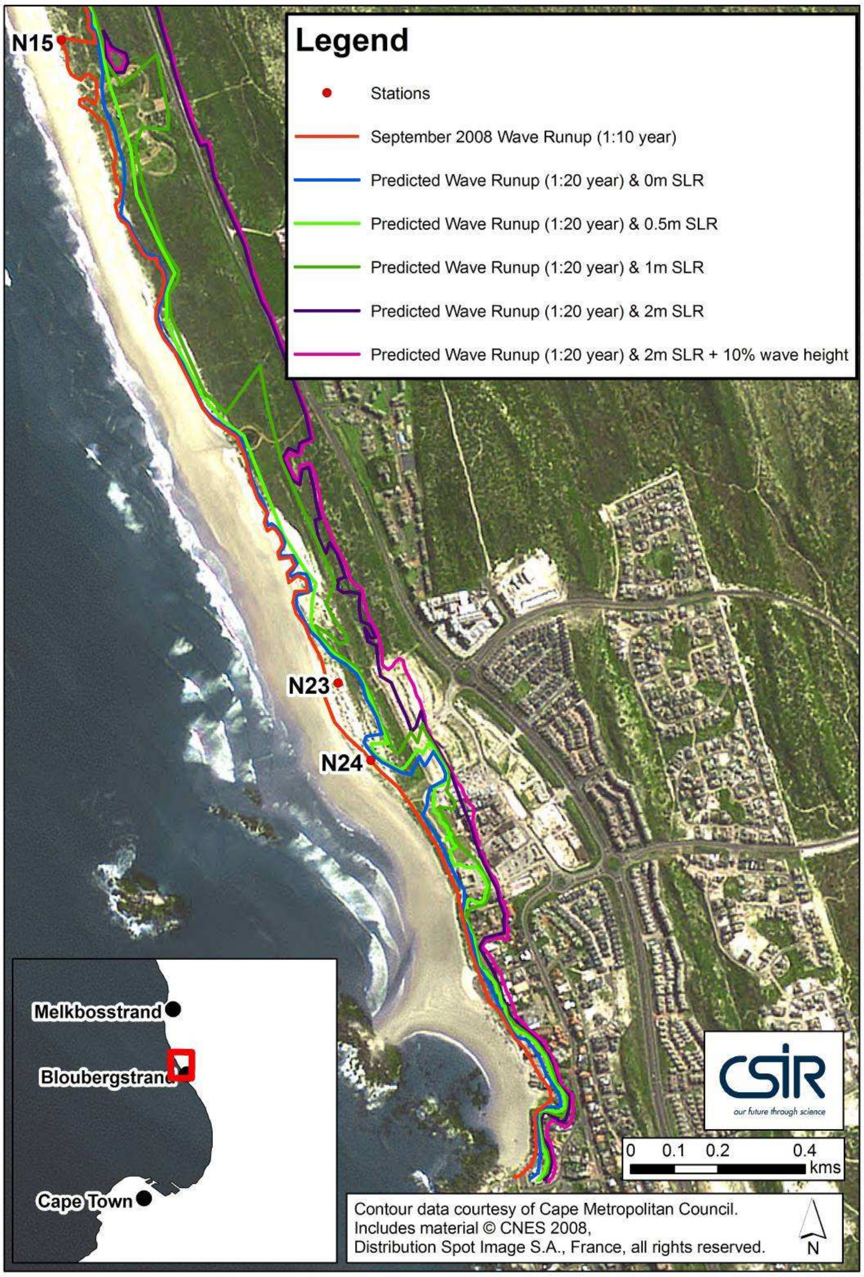

Figure 7: Illustration of predicted effects of climate change on coastal run-up lines near Bloubergstrand.

By assuming that Bruun's erosion rule is applicable in the study area and using bathymetric data obtained from the South African Navy's bathymetric charts, the potential shoreline erosion for the previously selected three scenarios – a SLR of 0.5, 1.0 and 2.0 m – were investigated. The exercise predicts that sandy areas along the Table Bay coastline, with a steeper nearshore slope, will erode between about 100 m to 370 m for the given scenarios, while the areas with relatively milder or flatter nearshore slopes are predicted to erode between about 20 m to 80 m. The ranges and average potential erosion for each SLR scenario are presented in Table 1.

Table 1. Potential erosion according to Bruun's rule in the Bloubergstrand area

Amount of sea level rise (m)	Potential erosion range from (m)	to (m)	Potential erosion average (m)
0.5	21	94	51
1	41	187	103
2	83	374	206

Despite the relatively modest mean predicted for SLR, it is the interaction with changing storm intensities and wind fields that is likely to produce sea conditions that could overwhelm existing infrastructure. The implications of the possible combined effects of shoreline erosion and wave run-up are alarming. For example, for a 1-in-20 year wave height (which is not extreme), a SLR of only 0.5 m would lead to a wave run-up 4.6 m to 6 m above present MSL. In addition, the 0.5 m SLR could result in average erosion of 50 m. This means that the already high wave run-up point (elevation of 4.6 m to 6 m to MSL) would also shift landward by about 50 m. Thus, the combined impacts of higher storm wave run-up levels and potential coastal erosion due to even higher SLR scenarios (1 m to 2 m) are anticipated to be severe in the longer term. Figure 8 illustrates what the combined impacts of shoreline erosion and higher wave run-up could mean for a 0.5 m rise in sea level and a 1-in-20-year sea storm.

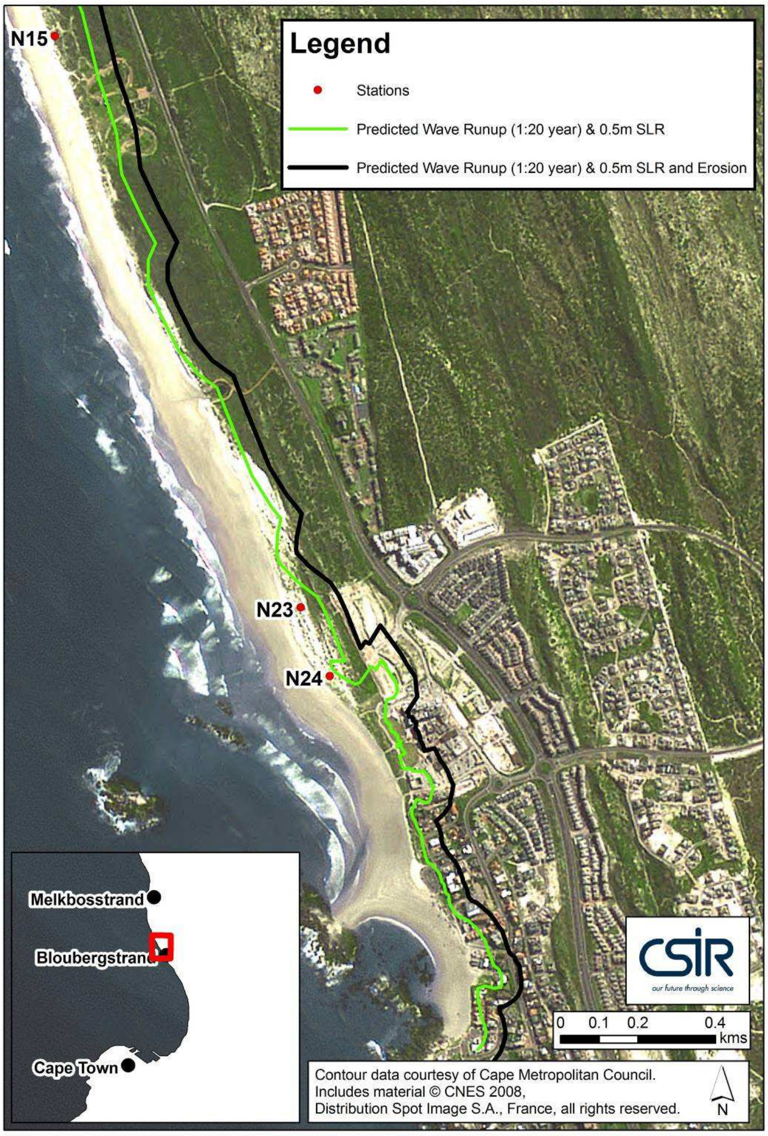

Figure 8. Predicted combined effects of potential shoreline erosion with Bruun's rule and higher wave run-up for 0.5 m rise in sea level and a 1-in-20 year sea storm on Blouberg coast.

5. Discussions and conclusions

In the UNESCO framework (e.g. Dutrieux *et al.*, 2000), the three concepts of hazard analysis, vulnerability assessment and risk and risk mitigation framework, are sequential. First there is hazard identification and quantification. Hazard analysis is followed by the measurement of vulnerability (people, physical assets, economy), and finally, assessing the risk. Risk is the integration of hazard probability and vulnerability. The risk assessment could be followed by mitigation of risk. This paper is intended to inform the first aspect of the framework. The hazard analysis is the first and critically important step in a process that tends to get more "fuzzy" as people, their condition and needs are considered.

Underpinning Clause 25 of the Integrated Coastal Management Act (Act No 24 of 2008), the calculation of future coastal setback lines demarcates safe coastal areas, enables the definitions of areas at risk of being eroded and infrastructure potentially vulnerable to the effects of SLR and inundation due to wave run-up. For example, an erosion setback line determined safe under present coastal conditions (i.e. present seawater levels and storm intensities) cannot be expected to remain safe under more extreme climate-changed conditions (i.e. raised seawater levels and/or more stormy sea conditions). Thus, predicted setback lines will support municipalities and city planners as well as developers, home owners and persons involved in coastal zone management in meeting the requirements of the ICM Act. The results derived from this research enables coastal stakeholders to base decisions on an informed understanding of the present and likely future risks associated with climate change scenarios.

In South Africa the most important drivers of risk to coastal infrastructure from erosion and flooding are waves, tides and future SLR. Appropriate extreme values of wave conditions and tidal levels were combined with realistic scenarios of SLR and practical methods were developed to model wave run-up based on these inputs. Shoreline erosion depends on a number of factors, some operate on a large scale and others are of a local nature. In this study it was highlighted that the local effects are very important. The predicted wave run-up was combined with the results of a simple method for estimating erosion due to SLR. The outcomes were incorporated into a Geographical Information System (GIS) database and mapped at a local scale using fine scale elevation data to spatially depict the results. It is believed that this approach will be useful in assessing and mapping vulnerable coastal areas in South Africa and determining future development setback lines. The case study has highlighted that simply choosing a higher contour line to that of the current line to represent a future shoreline is insufficient in quantifying the hazard and delineating safe areas. More realistic wave run-up and erosion prediction techniques, as applied in this research and illustrated in the Figures above, are required. Requirements to further improve the predictions of future shorelines and safe setback distances include an improved understanding of interconnected sea state and coastal/physical processes (e.g. the interaction between SLR and changing storm intensities) and a coastal model that reliably predicts the changes of the beach profile.

In the face of the predicted effects of climate change, appropriate vulnerability assessment and hazard quantification methods (such as those described in this paper) are highly relevant. Midgley *et al*. (2005) and Theron (2007) suggest that, in terms of responding to climate change threats to the South African coast, the best approach appears to lie in planning- and research-related activities. To this end, they propose the quantification of increased storminess; determination of appropriate coastal erosion and development setback lines; instigation and maintenance of measurement programmes; identification of important thresholds of dangerous change; development of a GIS-based operational system to highlight vulnerable areas; drawing up Shoreline Management Plans; and the design of coastal protection/structures, specifically to compensate for the effects of climate change. It was also recommended that current plans for disaster management should be expanded and adapted to include measures for more intense meteorological and metocean events.

The determination of setback lines that are safe in the long-term therefore requires, firstly, an acknowledgement and quantification of hazards. In addition, the mobilization of resources, solid policy guidelines and planning, as well as appropriate legislation, will mitigate the risks posed by future SLR to coastal areas and developments. Planning of adaptation options can further be enhanced with information gleaned from realistic scenario modelling, regional connectivity modelling and calculation of regional sediment budgets. A prediction of the actual response of the coast to the marine climate will depend on the holistic understanding of its effects on the coastal system. To determine future setback lines for the entire South African coastline will require a characterisation of the coast (for example an assessment of the erosion resistance of the coast, i.e. being sandy or rocky, etc.); expected future sea-states; local coastal topography (contour lines up to 12 m above sea level; and seafloor depth contours to 20 m below sea level); as well as predictions of shoreline response and evolution.

The method of coastal hazard assessment applicable to Southern African conditions and the available data proposed in this paper, are considered to be relevant and practical to assist in defining a key component of the required coastal setback line definition as required by the ICM Act.

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7. Endnote

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