

Preliminary coastal vulnerability assessment for KwaZulu-Natal, South Africa

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ABSTRACT

The KwaZulu-Natal (KZN) coast is a popular tourist zone and therefore one of the most important assets underpinning the economic activities of this South African Province. As with many coastal regions, the disproportionately large human settlement at the coast has led to increased pressure on the coastal zone. Development increases bio-physical changes, leading to an escalation in environmental risks affecting coastal populations, infrastructure and natural coastal environments. The events induced by a rapidly changing climate added to coastal zone development potentially introduce synergistic negative responses that might or might not be predictable. Therefore there is a need to develop methods that assess coastal vulnerability, and determine how best to manage this risk. This paper reports on the development of a technique that investigated the relative coastal vulnerability of the KZN coast to erosion and extreme weather events. A Coastal Vulnerability Index (CVI) was developed based on remotely sensed data whereby a set of physical coastal parameters, which serve as indicators of risk or vulnerability, were captured. The CVI scores were used to rank the coast, based on its relative degree of vulnerability into five classes ranging from very low to very high and highlights what proportion of coast falls within each class. Coastal vulnerability must inform management, thus this assessment attempts to address social, economic and ecological factors by identifying indicators and assessing them in relation to the finding of the CVI to determine what structures and features are within areas of very high CVI scores. The information presented provides input into a decision support tool that will facilitate the effective and user-friendly transfer of this important information.

ADDITIONAL INDEX WORDS: Coastal Vulnerability Index (CVI), erosion, storm events, GIS

INTRODUCTION

In most coastal nations there is an uneven distribution of populations with the highest concentrations and associated developments located in coastal regions. More than a third of people in eastern and southern Africa reside within 100km of the coast (UNEP/Nairobi Convention Secretariat, 2009). The KZN coast is especially popular being one of the densely populated coastal areas in Africa (Department of Environmental Affairs and Tourism (DEAT), 1999). The reasons for human concentrations at the coast include a preferred living environment and as a zone that provides additional ecosystem services, especially in times of drought, war and economic stress (DEAT, 2006). This disproportionate settlement at the coast has led to increased pressure on the coastal zone though resource exploitation, land-based pollution and coastal development (UNEP/Nairobi Convention Secretariat, 2009).

Developments affect natural coastal functioning, in particular, the equilibrium between terrestrial shoreline environments, the beach and near-shore bathymetry. In extreme cases, this leads to the loss of natural coastal functioning leaving the coast vulnerable to the impacts of sea-level rise, coastal erosion, extreme weather and other coastal hazards (O'Connor *et al.*, 2009). It thus follows that coastal populations, infrastructure and natural coastal environments stand to be adversely affected as coastal development escalates (Hinrichsen, 1995; Kumar *et al.*, 2010; Snoussi, Ouchani and Niazi, 2008). In recognition of these risks, there is a need to develop methods that assess coastal vulnerability and how best this can be managed or

mitigated (Cooper and McKenna, 2008; McFadden, Nicholls and Penning-Rowsell, 2007).

The limitations of many past vulnerability assessments have been characterised by having low spatial resolution, relying on averaged global data and simplistic assumptions (Hinkel and Klein, 2009). This, coupled with unprecedented coastal development and climate change risks, makes it imperative that vulnerability assessments are refined and upscaled to include coastal processes at a local scale. The need for local scale assessments is further highlighted by disaster events (McFadden, Nicholls and Penning-Rowsell, 2007), such as the 2007 KwaZulu-Natal (KZN) coastal storm, a significant event which caused extensive coastal erosion and severe damage (Smith *et al.*, 2007; 2010; Mather 2008). Recurrence estimates for the March 2007 event range from 10 to 12 years based on historical erosion events (Mather, 2008), 20 years, based on the historic record (Guastella and Rossouw, 2009), 35 years, based on wave heights (Mather 2008), 500 years (Theron and Rossouw, 2008) and 600 years based on coincidence of the Highest Astronomical Tide and storm wave heights (Mather 2008).

In light of this 2007 event, and the potential for its reoccurrence the KZN provincial government recognised the need to better understand the vulnerability of its coast. This paper reports on the development and testing of a Coastal Vulnerability Index (CVI) that divides portions of the coast into relative, predefined 'risk' classes. Vulnerability is defined as the inherent risk, relating to its physical

predisposition to be affected, or to be susceptible to damage from events (Kumar *et al.*, 2010). The step-based procedure includes 1) Assessing physical coastal vulnerability 2) Listing resources and services 3) Assigning values to these goods and services 4) Identifying the vulnerabilities of each resource/service and 5) Mitigating or removing the risks for the most important resources. CVI assessment is based on remotely sensed data and processed by means of GIS methodology. This method is particularly useful as it does not rely on detailed, precise or long-term data, which when working at a regional scale is rarely available and costly to produce (Bryan *et al.*, 2001).

A limitation of many vulnerability studies is that they focus only on the physical characteristics of vulnerability with little inclusion of economic and ecological aspects (Boruff, Emrich and Cutter, 2005). This assessment identifies social, economic and ecological indicators and assesses them in relation to the finding of the CVI to determine which populations and associated infrastructure are potentially at risk.

STUDY AREA

This research focuses on the 580km sub-tropical coastal zone of KZN, a province on the east coast of South Africa (Figure 1) with a mean annual rainfall of 845mm. The coast is generally linear with few bays and no islands or offshore barriers. About 80% of this coast comprises stretches of sand, with the rest characterised by intermittent rocky outcrops, especially in the south. Sandy beaches, combined with the high-energy, swell-dominated nature of the coast and an average 2m diurnal tidal cycle make the coast vulnerable to erosion (Mather, 2010; Smith *et al.*, 2010), which is exacerbated by sea-level rise (Mather, 2007; Mather, Garland and Stretch, 2009) and increasing storm frequency (Guastella and Rossouw, 2009). This was highlighted recently when a large swell, associated with a cut-off low weather system (Smith *et al.*, 2007) struck on the 2007 March equinox, near the peak of the lunar nodal cycle (LNC) (7/10/2006). This triggered catastrophic erosion (Mather, 2008; Smith *et al.*, 2007) and was further underpinned by a period of unusually high swells (Significant wave height $H_s = 3$ to 5.5m) prior to and during the 2007 austral winter (Smith *et al.*, 2010). Historical image analysis has shown that this coastline experiences bouts of strong erosion alternating with periods of non-erosion and even deposition in some places (Cooper, 1991a; b; 1994). However, this information is coarse due to the lack of availability of continuous imagery for the coast. More recently Smith *et al.* (2010) have suggested that episodic coastal erosion may be linked to the eighteen year lunar nodal cycle (LNC).

The warm climate, rich coastal biodiversity, availability of flat land offering high aesthetic value, coupled with concomitant lifestyle, tourism, wealth for coastal retirement and an increase in holiday-homes has resulted in intense urban development and high population densities along the coast (DEAT, 1999). KZN's coastal municipalities have a combined population density of 322 people per km², while inland municipalities have a population density of only 64 people per km² (Statistics South Africa, 2001). Notwithstanding this high density, the distribution along the coast is not uniform with almost no development in the far north, in the iSimangaliso Wetland Park (a proclaimed World Heritage Site of 332 000 hectares). At other locations, developments and supporting infrastructure have often been poorly planned and sited, frequently increasing the area's susceptibility to coastal hazards, erosion and storm events (*pers obs.*).



Figure 1: Location of the KwaZulu-Natal coastal zone

METHODS

Relative physical coastal vulnerability

The central element of this method involves dividing the coast into 50m by 50m cells and rating each in terms of its degree of vulnerability based on the identification and examination of key indicators of physical vulnerability. Rygel, O'Sullivan and Yarnal (2006) highlighted the usefulness of indicators as proxies for vulnerability assessments, especially if they can be used in identifying and monitoring changes in vulnerability over time and space, thereby improving knowledge about underlying processes of vulnerability and aid in the development of strategies for reducing vulnerability.

The CVI process is designed as a quick method of assessing coastal vulnerability; consequently the list of parameters used is kept short, stressing only the most important and easily assessed. In this assessment seven physical parameters were evaluated and reviewed by specialist consultation¹. These parameters were critically examined as to the relative suitability of each in a coastal vulnerability assessment. Five physical parameters were finally selected as the most suitable indicators, namely: beach width, dune width, percentage rocky outcrop, distance (width) of vegetation behind the back beach and distance to the 20m isobath. It was further noted that the parameters would have different levels of response/protection of the coast depending upon the magnitude of the impact. Thus, each of the parameters was weighted according to its value and corresponding perceived level of risk. This was validated by comparison to historic data from known past coastal erosion event impact sites. Hence the weighting of the magnitude of individual parameters, as outlined in Table 1, was (1) extremely low, (2) low, (3) moderate or (4) high depending on its value and range.

The actual measurement of the indicators was based on ortho-photographs. For the northern and southern coasts (Figure 1) imagery captured in late 2007/early 2008 with accuracy to standard deviation m.s.e. (mean squared error) of 0.25m. For the central coast mosaic imagery captured in 2007 supplied by the eThekweni Municipality were used for this area (Figure 1).

Data were captured as point data along transects between the low water mark and the back beach (Figure 2), with transects roughly at

¹ Involving a group of specialists in geomorphology, oceanography, coastal engineering, coastal management and sociology.

Table 1: Rating of physical parameters

Physical Parameter	Extremely Low (1)	Low (2)	Moderate (3)	High (4)
Beach width	> 150m	100 – 150m	50 – 100m	< 50m
Dune width	> 150m	50 – 150m	25 – 50m	< 25m
Distance to 20m isobath	> 4km	2 – 4km	1 – 2km	< 1km
Distance of vegetation behind the back beach	> 600m	200 – 600m	100 – 200m	< 100m
Percentage outcrop	> 50%	20 – 50%	10 – 20%	< 10%

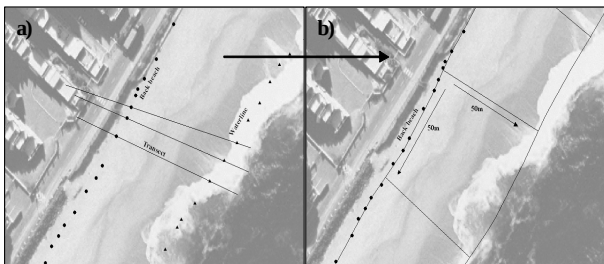


Figure 2: Depicts the method of data capture along transects. a) shows the transects along which data were captured, b) shows the 50m x 50m grid into which data were converted

30m intervals, depending on orientation of the coast. Beach width was calculated directly from transect length, while dune width was based on the width of the dunes behind the back beach coordinates. The distance to the 20m isobath was calculated by identifying the nearest point of the 20m isobath from the back beach coordinates while bathymetric data were derived from South African Navy Hydrographic charts. Percentage outcrop was based on the percentage of rocky outcrop exposed along each transect, while distance of vegetation behind the back beach was determined as the width of vegetation behind the back beach coordinates. To facilitate analysis, point data were then averaged into a grid file of 50m by 50m cells along the littoral active zone of the KwaZulu-Natal coast. Sites that portrayed evidence of historical erosion, primarily as a result of the March 2007 storm event, were identified from orthophotographs and assessed as a subset of the coast.

Statistical analysis and specialist input concluded that beach width, dune width and distance to the 20m isobath were the most critical indicators. The wider the beach, the more wave energy is dissipated. Beach width is also a proxy for beach slope, as areas with lower beach widths are invariably steeper and less able to dissipate energy. Dune width gives an indication of coastal protection and provides an estimate of sediment available to buffer erosion and accommodate leeward deposition of marine derived materials. The offshore distance to the 20m isobath relates to subtidal bedform and wave energy; the greater the distance, the greater the dissipation of wave energy and therefore the greater the reduction of erosive energy (Mather, Stretch and Garland 2010). Thus sites that scored high on all three indicators were at greater risk (Table 1). In order to emphasise their high scores and collective impact, sites were identified and weighted by an additional factor of 4. In addition, due to their sensitive and dynamic nature, estuarine mouths² were also

² Only the mouth was included as this relates to its interaction with the coast and how it could be influenced by coastal processes

weighted by an additional factor of 4, so as to highlight the potential increased risk for these sections of coast. Based on the scoring and weighting, each cell received a *total relative vulnerability score*.

$$\text{Relative CVI} = a + b + c + d + e + f + g$$

Where a = beach width vulnerability score, b = dune width vulnerability score, c = distance to 20m isobath vulnerability score, d = percentage outcrop vulnerability score, e = distance of vegetation behind the back beach vulnerability score, f = additional weighting of highly vulnerable sites (if a, b and c = 4), g = additional weighting if the cell intersects an estuarine area.

Social, economic and ecological components

Key to the method is that physical vulnerability was assessed *a priori* and social, economic and ecological components were evaluated on the physical vulnerability *a posteriori*. A suite of key features was identified (Table 2) and their relationship to very high vulnerability cells assessed. Features were grouped into economic and commercial activities, strategic infrastructure, recreational resources, subsistence areas, ecologically important areas and residential properties (Table 2). These features were seen to be located in one or both of two zones: (i) those that fall directly in the littoral active zone (and seaward), and therefore in areas of very high vulnerability, and (ii) those adjacent to, or inland of the littoral active zone and are therefore areas of very high vulnerability, (Table 2). Only features occurring within 100m of the High Water Mark (HWM) were assessed, based on the coastal zone definition under the South African Integrated Coastal Management (ICM) Act (Act 24 of 2008)³. Data for this phase were sourced from several available spatial databases.

RESULTS

A total of 11 616 cells were identified and evaluated yielding CVI scores ranging from 9 to 28, with a mean of 17 (Figure 3). The distribution of the CVI scores was strongly aggregated around the mean with mid-half (25th to 75th percentiles) of cells falling between CVI's of 15 and 19. Accordingly, the mid-range was considered to be at *moderate risk*, higher values (20–28) at *higher risk* and lower values (9–14) at *lower risk* (Figure 3). The historical erosion site data were processed separately, giving CVI values of 13 to 28 in 1082 cells, with a mean of 20. The 25th to 75th percentiles (mid-half) were in the range of CVI values: 17 to 22, clearly higher than the total coast values (Figure 3). The higher CVI values thus ranged from 23 to 28 and the lower values from 13 to 16. These results were used to “refine” the main dataset by splitting the higher and lower levels of CVI as indicated in Figure 3.

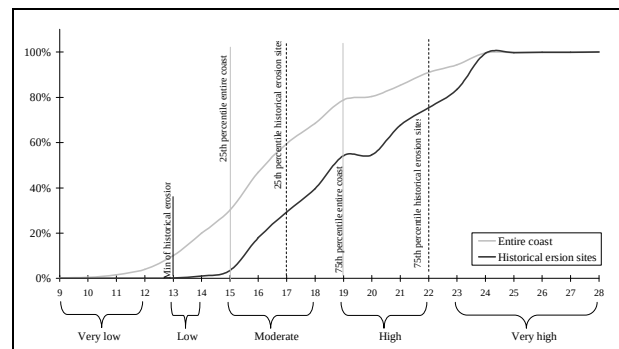


Figure 3: Range of vulnerability scores for the KZN coast

³ The ICM Act defines the coastal zone as being 100m in urban areas and 1000m in rural areas. For the purpose of this assessment only features within 100m of the High Water Mark were considered as features further inland are unlikely to be at risk.

Table 2: The grouping at which social, economic and ecological assets were assessed

Economic & commercial activities	Strategic infrastructure	Recreational areas	Subsistence sites	Ecological important areas	Residential properties
Dune mining	Piers [#]	Boat launch sites [#]	Subsistence fishing sites [#]	Marine Protected Areas [#]	Residential erven
Forest plantation	Roads	Fishing hot spots [#]	Subsistence harvesting sites [#]	Bird sanctuary sites [#]	
Sugar cane	Railway lines	Swimming beaches [#]	Subsistence farming areas	Turtle nesting sites [#]	
Commercial & industrial buildings	Lighthouses	Sports facilities		Estuary mouths [#]	
Commercial farms		Coastal Public Property ⁴		Protected areas (terrestrial)	

The study revealed that 9% of the KZN coast has a relative coastal vulnerability of *very high*, which equates to almost 52km of coastline. Some 12% of the coast (~70km) has a vulnerability of *high*, the majority of the coast at 59% (~343km) of *moderate*, 16% (~93km) of *low* and 4% (~23km) of *very low*. Not surprisingly, analysis of the historic erosion data subset gave significantly different results with 25% as *very high*, 21% as *high*, 53% as *moderate*, 1% as *low* and none for *very low*. Of the 52km of the coast that scored *very high*, 26% of these cells corresponded with historical erosion sites.

Social, economic and ecological component

Features located in or across the littoral zone (Table 2) were considered at relatively higher risk if all, or a proportion of them, fell directly within a cell of *very high* vulnerability. The results are presented in Figure 4. From an ecological perspective, turtle nesting sites and estuary mouths are at the highest risk with 50% and 26% respectively falling within cells of *very high* CVI. Socially, swimming beaches are significantly affected, with 41% falling within cells of *very high* CVI.

Figure 5 shows the risk to inland features, 100m from the HWM. Although dune mining areas and forest plantations were identified as key indicators for economic features, none of these activities are located within 100m of the HWM, but are nevertheless very close to this zone and could still potentially be at risk. Similarly, sports facilities were identified as a recreational indicator but none are located within 100m of the HWM. Rail lines are seen to have the highest proportion at risk, with 70% being adjacent to the HWM of *very high* CVI cells. Other economic features of concern are commercial and industrial buildings and commercial farms with 51% and 50% respectively being located adjacent to the cells of *very high* CVI scores. Socially, subsistence farming is of concern with 59% being located proximal to cells of *very high* CVI scores.

Not all features in the coastal zone (up to 100m from the HWM) of areas adjacent to very high CVI cells are potentially at risk. Rather, this risk is influenced by actual proximity to the HWM. Figure 6 shows the distance of features from the HWM in these zones. It shows proportions within 2, 5, 10, 50 and 100m of the HWM of very high CVI cells. It is evident that of coastal public property within 100m of very high vulnerable cells, 37% are within 2m of the HWM, resulting in significant risk for these areas. Of commercial farms 33% have their seaward boundary within 2m of the HWM. For ecologically significant areas, protected areas have 67% of their seaward boundaries within 2m of the HWM and an additional 33% within 5m.

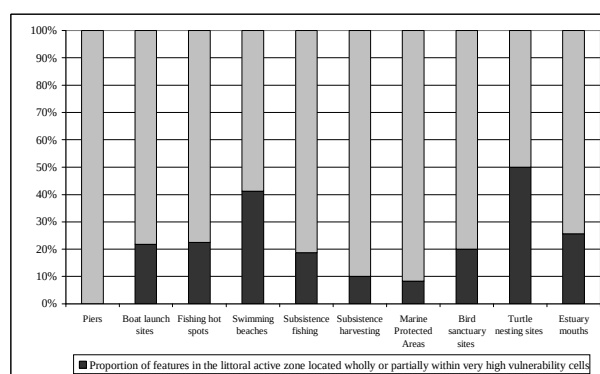


Figure 4: Proportion of features in the littoral active zone located wholly or partially within very high vulnerability cells

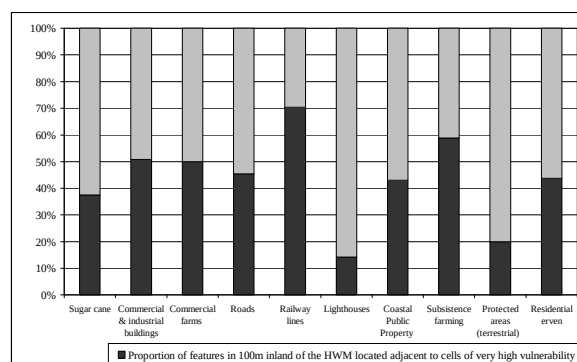


Figure 5: Proportion of features within 100m inland of the HWM and located adjacent to cells of very high CVI

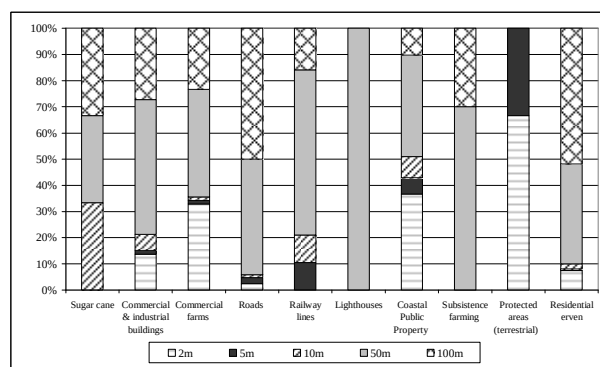


Figure 6: Features within varying distances of the HWM of very high CVI cells

⁴ Coastal Public Property refers predominantly to state owned land in the coastal zone that is vested for the use of citizens in the republic.

DISCUSSION

Through an extensive process of iterative evaluation, five physical parameters were selected as indicators of coastal vulnerability in this study. These were either evaluated individually or given an additional weighting when they operated synergistically. Results were then “validated” by using known data from historic erosion sites. Although the CVI estimates are not an absolute indication of vulnerability, they do provide a relative index. Given that the KZN coastline has experienced considerable erosion damage in the past, and it is evident that there is a repetitive return period associated with these events (Smith *et al.*, 2010) it is to be expected that such events will be experienced again and that the relatively higher CVI sites will be most at risk. Consequently, this provides coastal managers with planning advice and early warning insight for the future.

Some high CVI values corresponded to natural physical parameters, such as narrow beaches, dunes etc. Others are directly attributable to development and other anthropogenic induced changes to the coastal environment. For example, developments too close to the HWM may impede the natural landward retreat of dune and beaches, thereby reducing their effect in preventing structures in these areas being placed at risk. (Figure 7). In terms of future management, authorities should ensure that natural areas where biophysical functionality is unimpeded are maintained and that developments close to the HWM are not approved without due consideration of the need for such development versus the associated negative impacts that may arise. In cases where developments already exist, but have been damaged, rebuilding in the same location should be reviewed or alternatively relocated leewards.

In the context of these social, economic and ecological features a better understanding gained as to the implications of this vulnerability for management. The measure of vulnerability is related to the coverage of the feature in or in proximity to a very high CVI cells and serves to indicate what actions should be taken to manage risk to these assets. Thus consideration was only given to coastal structures and features of social, economic and ecological importance that were located in proximity to the 52km of coast that has very high CVI scores. Proximity to the HWM clearly needs to be considered when evaluating the degree of vulnerability of structures and features that are located further inland. For example, 51% of commercial and industrial properties within 100m of the HWM, are located adjacent to areas of very high CVI scores - a large proportion that potentially are at risk. Proximity of these features to the HWM is key to determining the degree of relative risk (Figure 8), with only 14% of them are within 2m (vertical distance) of the HWM and therefore more likely to be affected than structures further inland (Figure 8).

Evident from this assessment is that zones of vulnerability can be identified for future management focusing on risk. Features that are located directly in the littoral active zone are somewhat easy to address - they are either in a very high vulnerability area or they are not. The implications for management may however be more complicated in urban areas where likely to be little room for retreat/relocation or adaptation under future sea-level rise scenarios (Mather, Roberts and Tooley, 2010) and management interventions need to be carefully planned through the use of Coastal and Shoreline Management Plans. This assessment highlights that sections of the KZN coast are vulnerable to coastal erosion. In some instances social and economically important infrastructure also stand to be affected as it is too close to HWM. Present and future

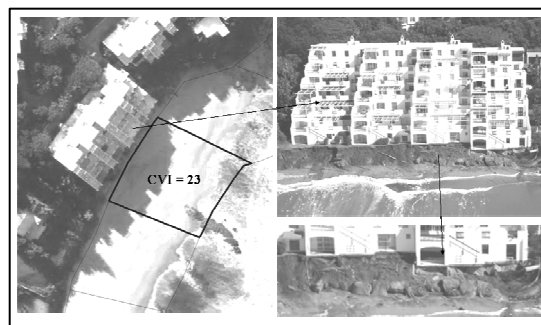


Figure 7: Example of development located too close to the HWM at cells with very high CVI scores (physical properties score low)



Figure 8: Impact on structures, influenced by distance from the high-water mark, building a is more likely to be damaged than building b, due to its location

management needs to determine the best management: leave as is, defend or retreat, depending on the feature's nature, value, lifespan, and potential impact if lost (Mather, 2010).

In order to refine and assess the zone of impact, the following will be taken into account in the second phase of this work: coastal elevation, predicted sea-level rise and shoreline change. Additionally, information presented in this assessment, coupled with future modelling will feed into the final determination of coastal setback lines for the KZN province which, which will all contribute to better coastal management.

CONCLUSION

The methodology described here and its application to the KZN coast is useful in several respects. Notably, the indicators used can be derived from remotely sensed data, which means that a once off flight can derive near-instantaneous data, easily repeated over time. Note that this process develops not an absolute value of CVI, but rather a relative value. The absolute value of risk is to be quantified in terms of severity and likelihood.

The selection of parameters, and their respective weighting, can be adjusted to suit a particular local situation, especially in the context of documented erosion and high vulnerability sites. It is also important to note that historic erosion data strengthens the validation, so that an ongoing process of monitoring and refinement of the technique will result in a progressively better and more accurate decision support system. A further phase of this study is to develop a system that will facilitate the effective and user-friendly transfer of this information as a decision support tool to assist with

general coastal management and coastal developmental authorizations.

Acknowledgements

The KZN Department of Agriculture, Environmental Affairs and Rural Development is thanked for its financial contribution that allowed this research to be undertaken. The following are acknowledged for their specialist input; S. Bachoo (Ezemvelo KZN Wildlife), B. McKelvey (WESSA), A. Theron (CSIR), G. Gerhardus (CSIR), R. Bulman (Phelamanga Projects) and D. Scott (UKZN).

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