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Assessing vulnerability to sea-level rise using a coastal sensitivity index: a case study from southeast Australia

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Abstract Many of the world's coasts appear vulnerable to the impacts of climate change and sea-level rise. This paper assesses the application of a coastal sensitivity index (CSI) to the Illawarra coast, a relatively well-studied shoreline in southeast Australia. Nine variables, namely (a) rock type, (b) coastal slope (c) geomorphology (d) barrier type (e) shoreline exposure (f) shoreline change (g) relative sea-level rise (h) mean wave height and (j) mean tide range, were adopted in calculation of the CSI (the square root of the product of the ranked variables divided by the number of variables). Two new variables, shoreline exposure and barrier type, were trialled in this analysis and the extent to which these increased the discriminatory power of the index was assessed. Four iterations of the CSI were undertaken using different combinations of ranked variables for each of 105 cells in a grid template, and the index values derived were displayed based on quartiles, indicating sections of coast with very high, high, moderate and low sensitivity. Increasing the number of variables increased the discriminatory power of the index, but the broad pattern and the rank order were very similar for each of the iterations. Rocky and cliffed sections of coast are least sensitive whereas sandy beaches backed by low plains or dunes record the highest sensitivity. It is difficult to determine shoreline change on this coast, because individual storms result in substantial erosion of beaches, but there are prolonged subsequent periods of accretion and foredune rebuilding. Consequently this variable is not a good indicator of shoreline sensitivity and the index is unlikely to provide a clear basis for forecasting future recession of beaches. The results of this study provide a framework for coastal managers and planners to prioritize efforts to enhance the resilience or consider adaptation measures in the coastal zone within a study region. Sensitivity of the coast if considered in conjunction with other social factors may be an input into broader assessments of the overall vulnerability of coasts and their communities.

Keywords Sea-level rise · Coastal sensitivity index · Coastal vulnerability assessment · Southeast Australia · Illawarra coast

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Introduction

Sea-level rise threatens coastal ecosystems and settlements, and a number of approaches have been adopted to assess vulnerability of different coasts (Nicholls et al. 2007). Identifying sections of shoreline susceptible to sea-level rise is necessary for more effective coastal zone management, in order to increase resilience, and to help reduce the impacts of climate change on both infrastructure and human beings.

There have been several approaches to vulnerability analysis that have used physical characteristics of the coastal system to classify the coast, producing a ranking of sections of shoreline in terms of its sensitivity to a rise in relative sea level (Thieler and Hammar-Klose 1999). An index, based on physical variables such as coastal landforms, relief, geology, relative sea-level rise, shoreline displacement, tide range and wave height, has been used to assess the vulnerability of coasts in the USA, Europe, Canada, Brazil, India and Argentina (Gornitz 1991; Shaw et al. 1998; Thieler and Hammar-Klose 1999; Pendleton et al. 2004; Doukakis 2005; Diez et al. 2007; Nageswara Rao et al. 2008). In a study of the western Peloponnese in Greece, Doukakis (2005) used digitised maps at 1:500 scale to examine those sections of the coast that appeared to have high vulnerability.

Vulnerability indices of this type have not been adopted in Australia, and even where such indices have been used elsewhere, they have rarely been tested by comparison with observational data. The purpose of this paper is to assess the degree of susceptibility of a section of the southeast Australian coast to impending sea-level rise semi-quantitatively using this type of index approach. This study outlines a modification of the methods used elsewhere, to a well-researched part of the Australian coast to assess the extent to which such indices capture relative susceptibility. This study uses the term 'sensitivity' in preference to 'vulnerability', the term that was used by Gornitz and Kanciruk (1989) on the United States coasts and which continues to be adopted by the United States Geological Survey (USGS) (see Pendleton et al. 2004). The distinction is made because the approach assesses only the physical aspects of the coast and not socio-economic variables, such as population. Vulnerability is generally perceived in terms of people being vulnerable to particular hazards and therefore requires a consideration of socio-economic factors. The latter, if added, as by Boruff et al. (2005) in their synthesis of physical and socio-economic variables, might extend 'sensitivity' as a measure of susceptibility to enable it to address vulnerability. This paper uses a coastal sensitivity index (CSI) to characterise susceptibility, as applied on the Canadian coast (Shaw et al. 1998) rather than calling the index a CVI as applied to the United States coasts (Pendleton et al. 2004). Despite the difference in terminology, both CSI and CVI follow a similar methodology.

Study area

The Australian coastline is one of the longest (>30,000 km long) and most diverse of any coastline in the world. The coastline consists of numerous islands, reefs, beaches, rocky cliffs and muddy shores (Short and Woodroffe 2009). This extensive shoreline and the great diversity of landforms make developing a coastal sensitivity index for the whole of the Australian coast a challenging task, and may explain why there has been little consistency or uniformity to date in the way in which Australian researchers have assessed the vulnerability of the Australian coast to the impacts of climate change (Harvey and Woodroffe 2008; Department of Climate Change 2009). A CVI of the type applied widely in the US and adopted elsewhere has not been trialled in Australia; instead, an approach that maps the form (landform type) and fabric (substrate characteristics) developed by Sharples (2006) in Tasmania has recently been extended to produce a first-pass geomorphological description of the entire Australian coastline (Department of Climate Change 2009). Our study represents a preliminary attempt to apply the CVI methodology, developing a CSI for a relatively well-researched part of the coast of southeast Australia.

The Illawarra, on the south coast of New South Wales (NSW) (Fig. 1), extends for 167 km from Stanwell Park in the north to Shoalhaven Heads in the south. The coast consists of a narrow coastal plain (up to 50 km wide) backed by a steep escarpment on its western margin and a relatively narrow and steep continental shelf (80%>50 m) to seawards (Roy and Thom 1981). It is a wave-dominated coast comprising 34 beaches alternating with steeply cliffed headlands (Short 2006). A major headland at Red Point near Port Kembla divides the central part of the Illawarra coast into two morphologically dissimilar regions (Fig. 1). The coastal plain is narrower and the escarpment approaches the coast and forms sections of steep cliffs in the north, in contrast to a broader plain interspersed with estuarine environments in the southern section. Seven Mile Beach is the longest beach and is backed by a beach-ridge plain on which a series of relict foredunes are preserved, indicating that it has prograded seawards as a result of accretion of riverine sediments from the Shoalhaven River. Perkins Beach is the second longest beach with well-developed dunes at its northern end, and is the seaward margin of the sand barrier which impounds Lake Illawarra, a wave-dominated barrier estuary connected to the ocean by a narrow inlet channel.

Methods of study and ranking of variables

Sensitivity has been defined *in this study* in terms of a number of semi-quantifiable variables, comprising six structural and three process variables. The six structural variables are: (a) rock type, (b) coastal slope (c) geomorphology (d) barrier type (e) shoreline exposure, and (f) shoreline change. The three process variables are: (g) relative sea-level rise (h) mean wave height and (j) mean tide range. The mapping of the Illawarra coast was undertaken using orthorectified aerial photography taken over the Wollongong area in 2006 by AAMHatch and over the Kiama area in 2002 by the Department of Lands, LPI, NSW. Fieldwork was undertaken between April and August, 2007 to confirm interpreted features using Global Positioning Systems (GPS) to obtain locations of particular landforms. Cliffs and inaccessible areas such as Port Kembla and Kiama Heights were mapped from aerial photography alone. Data for shoreline exposure was

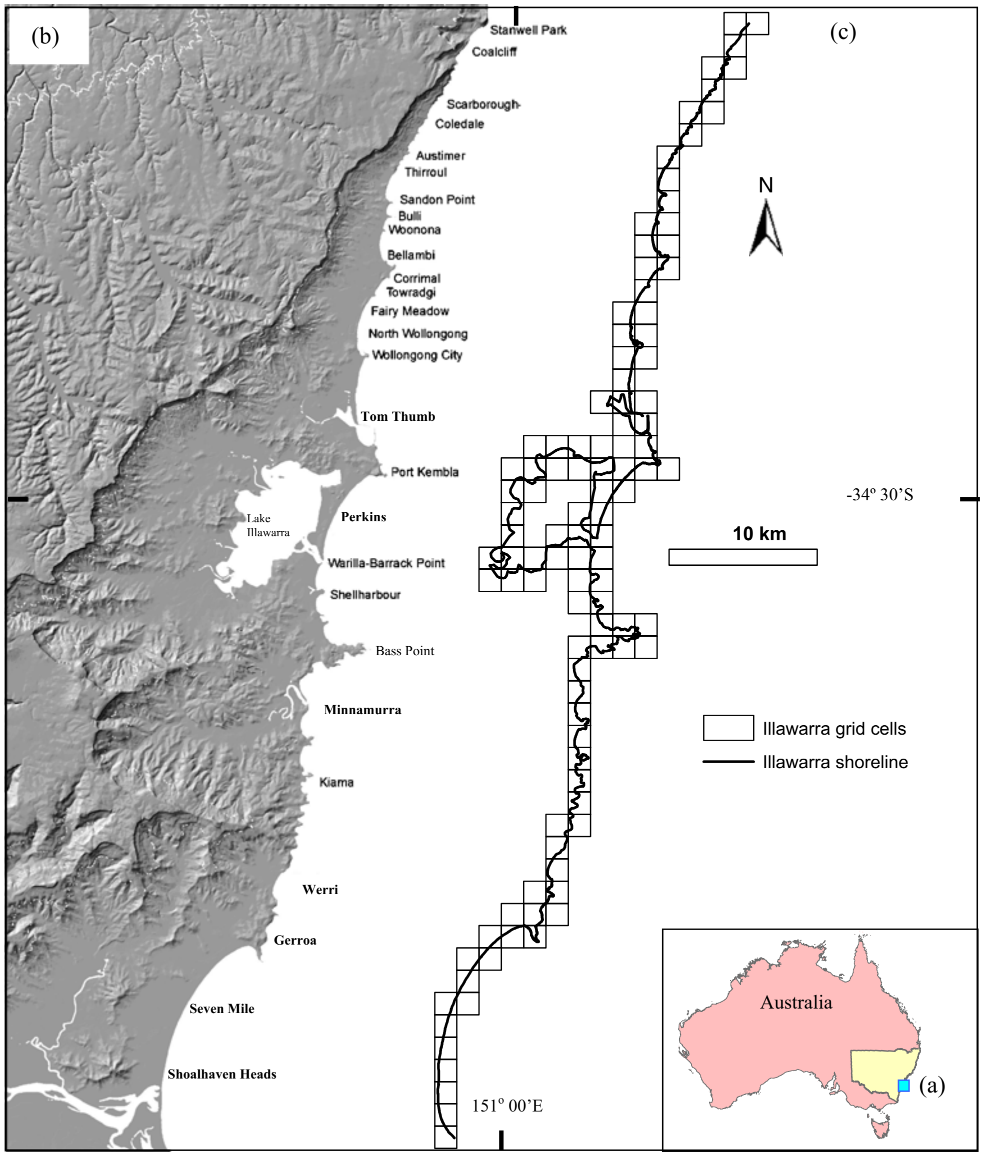

Fig. 1 Location of the Illawarra coast (**a**) within New South Wales, Australia. (**b**) extent of the study area, with 22 beaches identified by name, from Stanwell Park to Shoalhaven Heads. Note the hillshaded digital elevation model (DEM) showing the extent of low-lying coastal plains that may be susceptible to natural hazards and effects of sea-level rise. (**c**) 105 cells of 1.5 km by 1.5 km comprising a grid template for the Illawarra coast. (**b**) was created from a 25 m Digital Elevation Model (DEM) supplied by the Department of Lands and Property, LPI, NSW. Data for these (**a**) and (**c**) and for the subsequent figures were acquired from GEODATA COAST 100 k 2004

derived using existing orthorectified aerial photographs for the Illawarra coast taken in 2006 by AAMHatch and verified during fieldwork. The aspect of each coastal segment was determined in relation to the dominant wave direction, in this case the south-south-east (SSE). GIS software, ArcGIS, provided the platform for the coastal mapping.

Six of the nine variables (b, c, f, g, h, j) have been widely applied in previous coastal vulnerability studies (see Nageswara Rao et al. 2008; Pendleton et al. 2004; Shaw et al. 1998), and can be viewed as conventional variables used to derive similar indices in international studies. Two variables, barrier type (d) and shoreline exposure (e) are new, or modified from similar approaches, and have been used in this study for the first time, to evaluate whether they provide further insight into coastal sensitivity. The remaining variable, rock type (a), or lithology, was included in early derivation of CVI, but has been omitted from many of the more recent studies; it has been determined for the study area and is included in the nine-variable assessment in our study.

The shoreline change variable attempts to capture the historical trend of shoreline movement, by determining overall patterns of erosion or accretion. It is one of the more complex of the physical variables, particularly on this coast, as the trend is usually variable over time. As part of a broader study of this coastline, shoreline change has been examined from a time-series of aerial photographs (Abuodha 2009). Photo interpretation of aerial photographs from six time periods between 1961 and 2006 was undertaken, using georeferenced images (GDA-1994-MGA-Zone 56). Time-series analysis using the digital shoreline analysis system (DSAS) software version 3.2, an ArcGIS extension for calculating historic shoreline change

(Thieler et al. 2005), was carried out in order to track changes in vegetation and high water lines for 11 beaches along the Illawarra coast. It could be argued that the pattern of shoreline change observed is not so much a physical attribute of the section of shoreline under study but rather a manifestation or outcome of the interaction between process and structure. With this in mind, shoreline change variable has been purposefully omitted in one of the iterations in this study (CSI8b, see below), in order to assess whether it might be more appropriately used instead as a means to test or validate the sensitivity of the shoreline.

In order to display the results of the index, derived from integration of the variables, a template of grid cells of 1-min (1.5 km by 1.5 km) has been derived for the coast (Fig. 1c). The cell-based template follows the early 'raster' approach of Thieler and Hammar-Klose (1999). The template has been used to store and portray data for each of the variables in an attribute table (in vector format using shapefiles in ArcGIS), for adjacent cells along the Illawarra coast. Grid cells of 1.5 km resolution appear appropriate for applying the CSI tool at this broad regional scale. For each of the variables, a ranking on a scale of 1–5 was assigned to each cell following the classification scheme outlined in Table 1. The classes defined and the rankings adopted for coastal slope, geomorphology, and shoreline exposure have been developed using similar concepts to those used by Sharples (2006) in mapping the coast of Tasmania, in order to promote consistency around the Australian coastline and because of the availability of similar source data.

An index is derived using the approach that has been widely used overseas, by determining the square root of the product of the ranked variables divided by the total number of variables as shown in Table 2, and outlined below. Several iterations were undertaken with different combinations of variables to assess the degree to which these increase the discriminatory power of the approach. The grid format has been retained for display of the output, resulting in a 'cell-based' approach similar to that initially adopted in the US by Thieler and Hammar-Klose (1999). A total of 105 cells represent the 165 km of shoreline as shown in Fig. 1. Cells are shaded based on a quartile representation of the final index values. It is possible to transform the cells into a line format, and this may be useful to more easily compare the classification with other indices, or line segmentation approaches, such as the geomorphological mapping approach used by Sharples in Tasmania (Sharples 2006) and recently modified and extended to the entire Australian coast (Department of Climate Change 2009). However, the cell-based portrayal is retained here for ease of display, and because it retains the spatial scale at which the analysis is undertaken, which is not so apparent when the output data are transformed (Abuodha 2009). The nine variables including justification of the ranking adopted together with the results obtained are described below.

Deriving structural and process variables

Figures 2, 3, 4, 5, 6, 7 and 8 display the ranked variables that were mapped and this section describes the methods used to derive the values that populate the grid template (Fig. 1c) for the structural variables (rock type, coastal slope, geomorphology, barrier type, shoreline change and shoreline exposure) and process variables (relative sea-level rise, mean wave height and mean tide range).

Rock type

The rock type variable represents the bedrock occurring at, or underlying, the shoreline. Data for the rock type variable were interpreted from published geological maps of the Wollongong area at a scale of 1:250,000. The coastal configuration of the Illawarra is strongly controlled by bedrock, which outcrops along the shoreline as headlands, rock platforms and cliffs having a maximum relief of 30–70 m. The interpretation adopts a simplified geologic classification in which old resistant rocks (the Shoalhaven Group), sedimentary rocks (the Narrabeen Group and the Illawarra Coal Measures) and unconsolidated sediments (Quaternary sediments) are differentiated. Rocks that are resistant to wave attack such as the Shoalhaven Group commonly form headlands. Embayments are generally cut in less resistant material such as Permian Illawarra Coal Measures. There are lithological variations within each of the Shoalhaven Group, Illawarra Coal Measures and Narrabeen Group but a simplified geological classification of rock types at the 'group' level was used to subdivide the rock types into the four ranked types (Table 1).

Unconsolidated Quaternary deposits are dominated by sand that occurs on the beaches and dunes; these were considered to be most sensitive to the effects of climate change and sea-level rise. The Permian Illawarra Coal Measures comprise a sequence of sandstone, siltstone, shale and coal with minor conglomerate and tuffaceous beds (Bamberry 1991), and are softer and prone to undercutting and erosion by wave action compared to the overlying sedimentary rocks. The Narrabeen Group consist of shale units which also experience erosional instability and have been assigned a rank value of 3. The Shoalhaven Group is composed of marine deltaic sand, and red, brown and grey volcanic sandstones (Doyle 2000), and underlie the more resistant parts of the coast (Fig. 2). On the basis of these sensitivity rankings, Quaternary sediments are the most extensive of the rock type variable along the Illawarra coast, accounting for in 60 cells (57.1%), with 35 cells mapped as Shoalhaven Group (33.3%), six cells mapped as

Table 1 Coastal sensitivity index classes developed for the Illawarra coast. The colour scheme depicts the level of sensitivity with blue indicating very low sensitivity while red indicates very high sensitivity

	Ranking of Coastal Sensitivity Index (CSI)					
	Structural variables					
ID	**Variable**	**Very low (1)**	**Low (2)**	**Moderate (3)**	**High (4)**	**Very high (5)**
a	**Rock types**	-	Shoalhaven Group	Narrabeen Group	Illawarra Coal Measures	Quaternary sediments
b	**Coastal slope (degrees)**	Cliffed coast (> 45)	Steep slopes (> 20.1 - 45)	Moderate slopes (10.1-20.0)	Gentle slopes (6.1 - 10.0)	Low plains (0.0- 6.0)
c	**Geomorphology**	High hard rock sea cliffs	Medium hard rock sea cliffs	Coastal re-entrants	Sandy shores backed by bedrock & artificial structures	Sandy shores backed by dunes and plains
d	**Barrier type**	Prograded barriers	Mainland beach barriers	Stationary barriers	Transgressive dune barrier	receded Barriers
e	**Shoreline exposure (degrees)**	-	Sheltered (> 135)	Semi-exposed (45-135)	Exposed (30-45)	Fully exposed (0-30)
f	**Shoreline change (m/yr)**	> +2.0	1.0 - +1.9	± 0.9	- 1.0 – 1.9	< -2.0
	Process variables					
g	**Relative sea-level rise (mm/yr)**	< 0.0	0.0 - 0.9	1.0 – 2.0	2.1 – 3.0	> 3.1
h	**Mean wave height (m)**	0.0 – 0.5	0.6 – 1.0	1.1 – 1.5	1.6 – 2.0	> 2.1
j	**Mean tide range (m)**	> 2.1	1.6 – 2.0	1.1 – 1.5	0.6 – 1.0	0.0 - 0.5

Illawarra Coal Measures (5.7%) and four cells mapped as Narrabeen Group (3.8%).

Coastal slope

The slope of the immediate hinterland is one of the most important factors to be considered in estimating the impact of sea-level rise on a given coast (Nageswara Rao et al. 2008). Steep slopes experience less flooding compared to gentle- to moderately-sloping coasts where any rise in sea level will inundate larger extents of land. The coastal slope is the generalised topographic gradient of the coastal zone that extends from the high water mark (HWM) inland to a reference distance. In this study the reference distance chosen was 500 m which is consistent with that adopted for mapping the Tasmanian coast by Sharples (2006). The slope was calculated using ArcGIS Spatial Analyst Extension. The input raster was obtained from a 25 m Digital Elevation Model (DEM) supplied by the Department of Lands and Property, LPI, NSW and covered the full extent of the Illawarra coast. The slope output measurement was performed in degrees (Table 1).

The coastal slope variable distinguishes low-lying coastal flats typically backed by the Holocene coastal deposits from shores backed by moderately or steeply sloping bedrock terrain (Sharples 2006). The steep profile class is indicative of resistant coastal rock types that tend to form an abrupt shore profile particularly where exposed to high wave energies

Table 2 Details of the four iterations of the CSI, including variables and formulae used and the range of index values determined

	Conventional CSI6	All variables CSI9	CSI9– rock type CSI8a	CSI9– shoreline change CSI8b
a) Rock type		X		X
b) Coastal slope	X	X	X	X
c) Geomorphology	X	X	X	X
d) Barrier type		X	X	X
e) Shoreline exposure		X	X	X
f) Shoreline change	X	X	X	
g) Relative sea-level	X	X	X	X
h) Mean wave height	X	X	X	X
j) Mean tidal range	X	X	X	X
Formula	$\sqrt{\frac{b*c*f*g*h*j}{6}}$	$\sqrt{\frac{a*b*c*d*e*f*g*h*j}{9}}$	$\sqrt{\frac{b*c*d*e*f*g*h*j}{8}}$	$\sqrt{\frac{a*b*c*d*e*g*h*j}{8}}$
Range of index values	3.5 – 27.9	13.9 – 250	9.5 – 118.6	10.4 – 118.6
Number of discrete index values	19	35	33	28

(Fig. 3). The cliffed coasts have a near-vertical slope and have a height of more than 50 m along the shoreline. The portrayal of the coastline in terms of the coastal slope variable (Fig. 3) resulted in 75 cells mapped as low plains (71.4%), 13 cells mapped as gentle slopes (12.4%), 10 cells mapped as moderate slopes (9.5%), six cells mapped as steep slopes (5.7%) and one cell mapped as cliffed coast (1.0%).

Geomorphology

The geomorphology variable reflects the nature of the landforms on the coast and their relative resistance to erosion (Thieler and Hammar-Klose 1999). Whereas rock type captures the relative resistance of underlying bedrock, geomorphology captures the actual landforms in the foreshore and backshore. Discrimination of geomorphology classes in this study was undertaken using recent orthorectified aerial photographs and the different landforms recognised were classified as shown in Table 1. Compared with sandy shores, hard rock sea cliffs are stable and are able to withstand the impacts of coastal hazards such as storms and sea-level rise. Sandy beaches with or without offshore bars are the commonest landform on the NSW coast. Open ocean sandy shores backed by dunes and plains are very sensitive to the effects of natural processes and human modifications of the coast because they are composed of unconsolidated sand-sized sediments directly exposed to open ocean waves and swells.

Sandy shores backed by bedrock and artificial structures are considered less susceptible. Although the beach in front of bedrock or the artificial structure has the potential to undergo erosion in the event of climate change and sea-level rise, further recession is likely to be constrained by the presence of bedrock or artificial structures. Coastal re-entrants are coastal water bodies that are connected to the open sea continuously or intermittently by a channel. They are composed predominantly of sandy shores and are low-lying and therefore sensitive to effects of storm surges, tides and relative sea-level rise; they are given a rank of 3. Hard rocks protrude on the coast as sea cliffs and headlands. Cliffs of the weaker lithologies or medium elevations were assigned a sensitivity ranking of 2, whereas the higher cliffs and strongest lithologies offer maximum resistance and were classed with a rank of 1. Figure 4 portrays the coastline in terms of the geomorphology variable showing 36 cells mapped as sandy shore backed by dunes or low plains (34.3%), 33 cells mapped as high hard rock sea cliffs (31.4%), 27 cells mapped as coastal re-entrants (25.7%), six cells mapped as sandy shores backed by bedrock and artificial structures (5.7%) and three cells mapped as medium hard rock sea cliffs (2.9%).

Barrier type

The coastal dune, beach and shoreface collectively make up coastal barriers, and embayments along the NSW coast are filled to differing extents by barriers of Holocene and Late Pleistocene age. Barriers are elongated, shore-parallel sand bodies that extend above sea-level and several different types of barrier have been described along these wave-dominated coasts, several of which are represented in the Illawarra (Roy et al. 1994; Hesp and Short 1999). The barrier type is an additional variable which was considered for inclusion as one of the variables used to determine the CSI because barriers record the pattern of Holocene sand accumulation with such distinctively different barrier types as prograding, stable and receded barriers implying contrasting modes of shoreline development. The variable is intended to discriminate different shoreline behaviours at millennial time scales based on the assumption that past

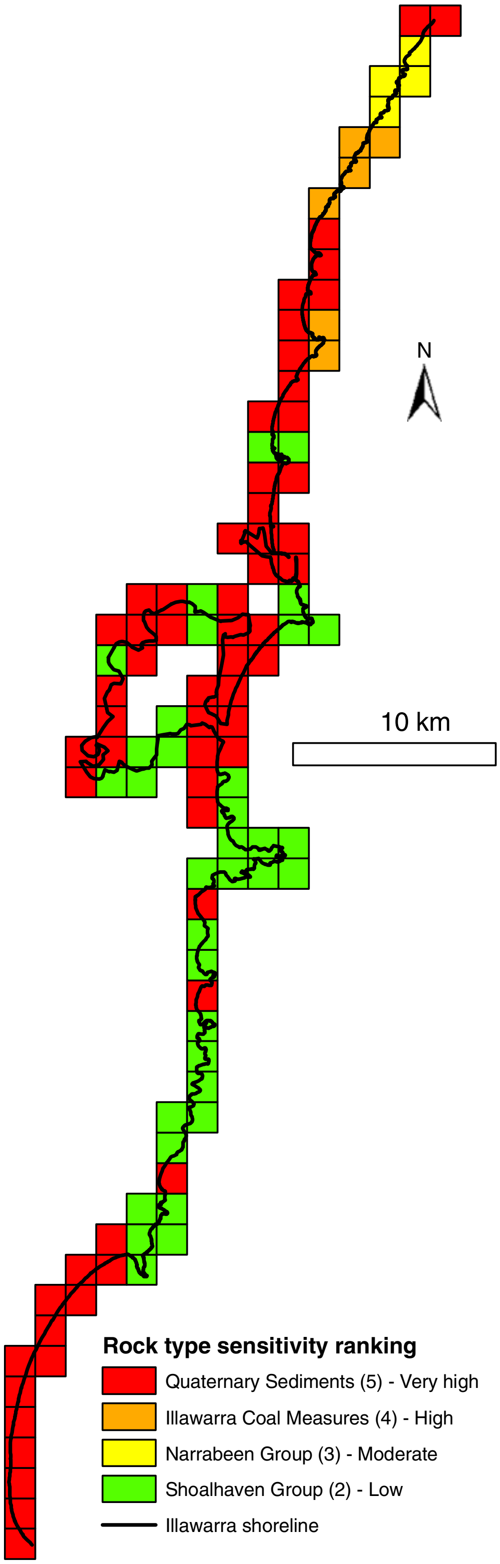

Fig. 2 The relative ranking of the rock type variable for the Illawarra coast

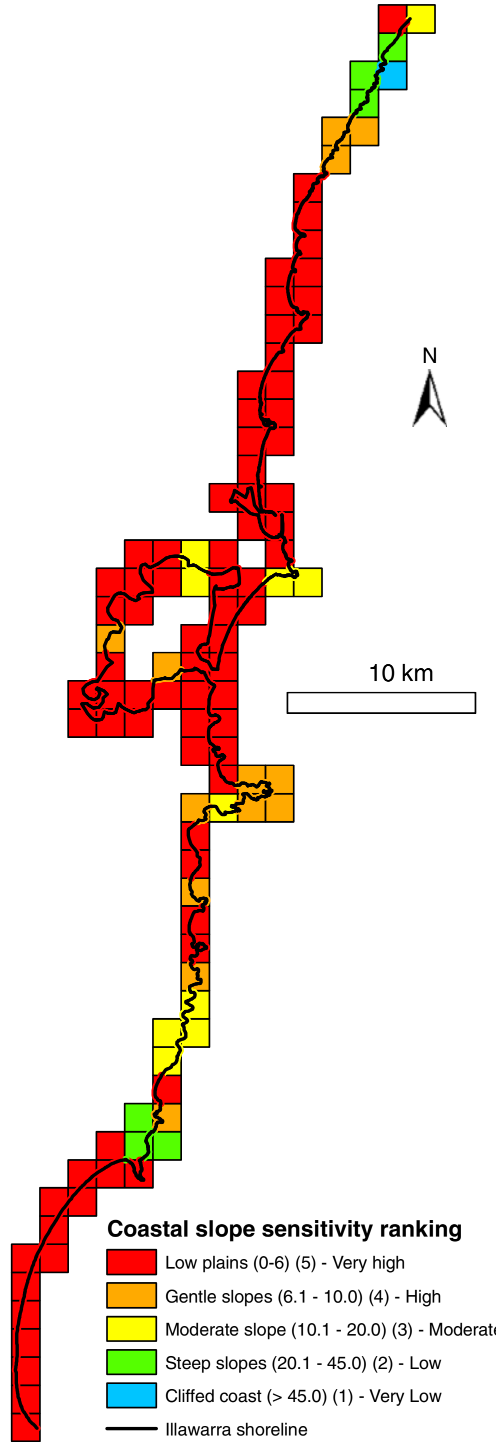

Fig. 3 The relative ranking of the coastal slope variable for the Illawarra coast

trends are preserved in the morphologic and stratigraphic record, and that they provide insight into present-day and future coastal changes.

The classification of barriers adopted for the Illawarra coast recognises five types namely: (1) prograded, (2) stationary, (3) receded, (4) mainland beach, and (5) episodic

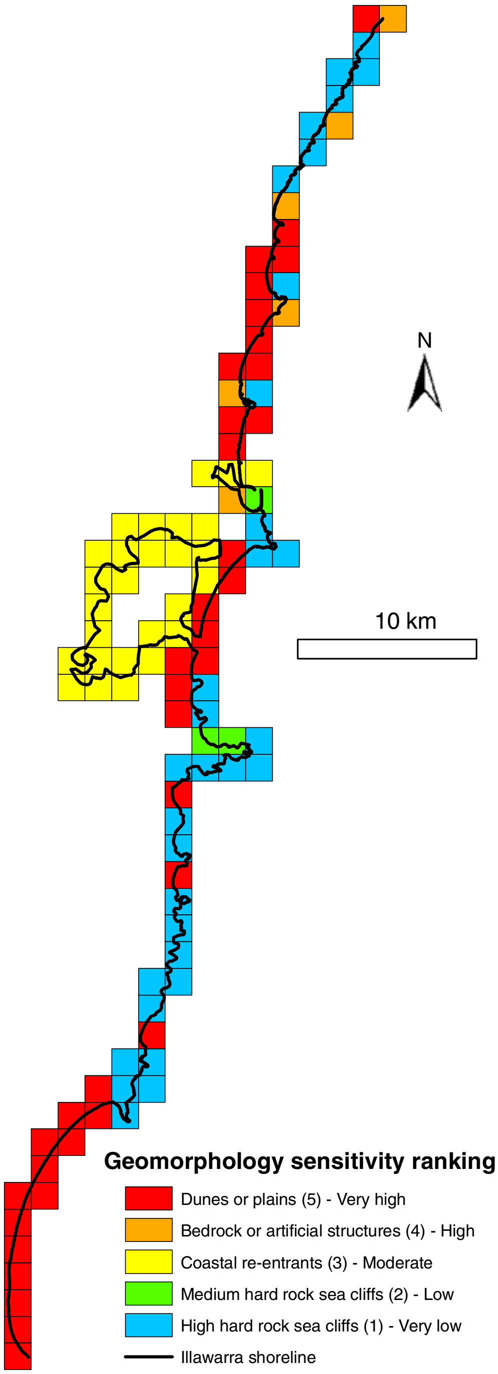

Fig. 4 The relative ranking of the geomorphology variable for the Illawarra coast

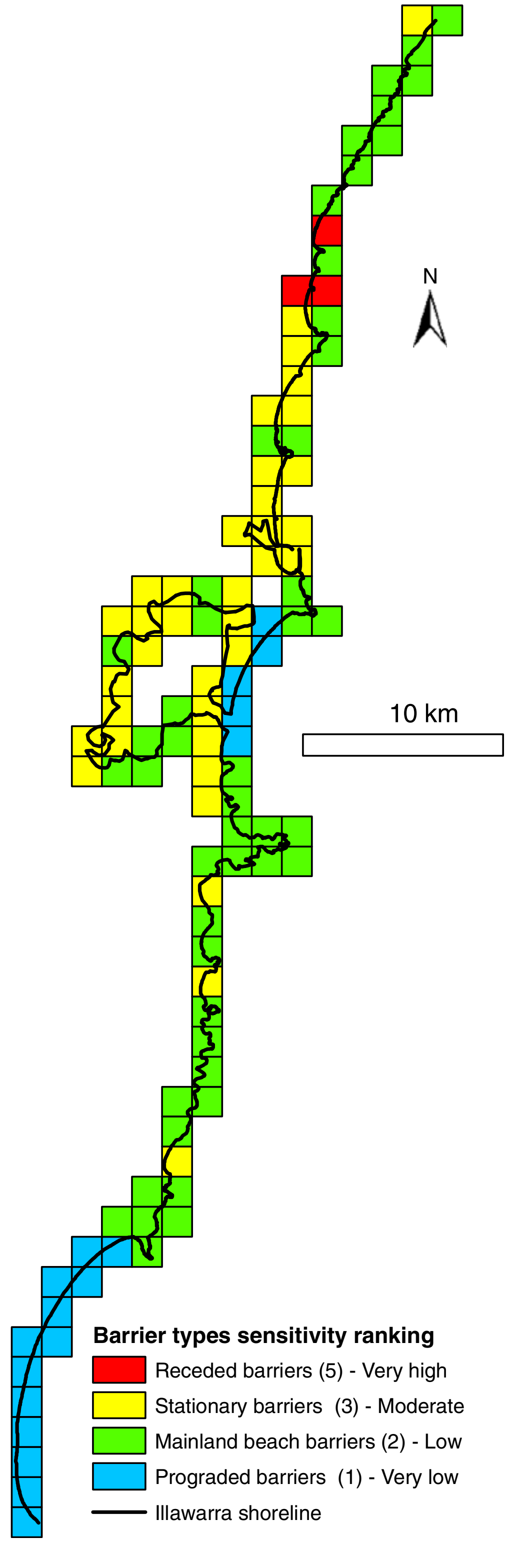

Fig. 5 The relative ranking of the barrier types variable for the Illawarra coast

transgressive dune barriers (Chapman et al. 1982). Receded barriers are thin marine sand deposits that overlie, and appear to have been reworked across, estuarine or back-barrier sediments which outcrop on the shoreface (Chapman et al. 1982). This barrier type has been described on several beaches on the Illawarra coast such as Bulli Beach where muds deposited beneath mangroves have been encountered exposed on the beachface (Jones et al. 1979). This type of barrier would appear particularly prone to future recession and has been assigned the most sensitive rank (5). By contrast transgressive dune barriers, found elsewhere in NSW, are not well represented on this stretch of coast. The

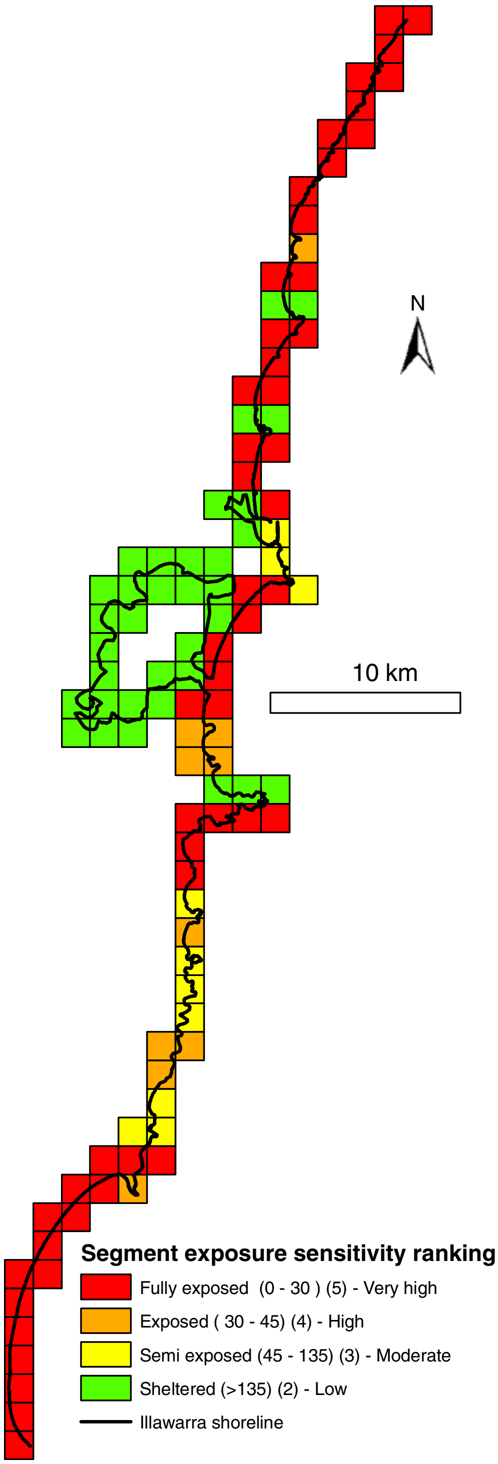

Fig. 6 The relative ranking of the shoreline exposure variable for the Illawarra coast

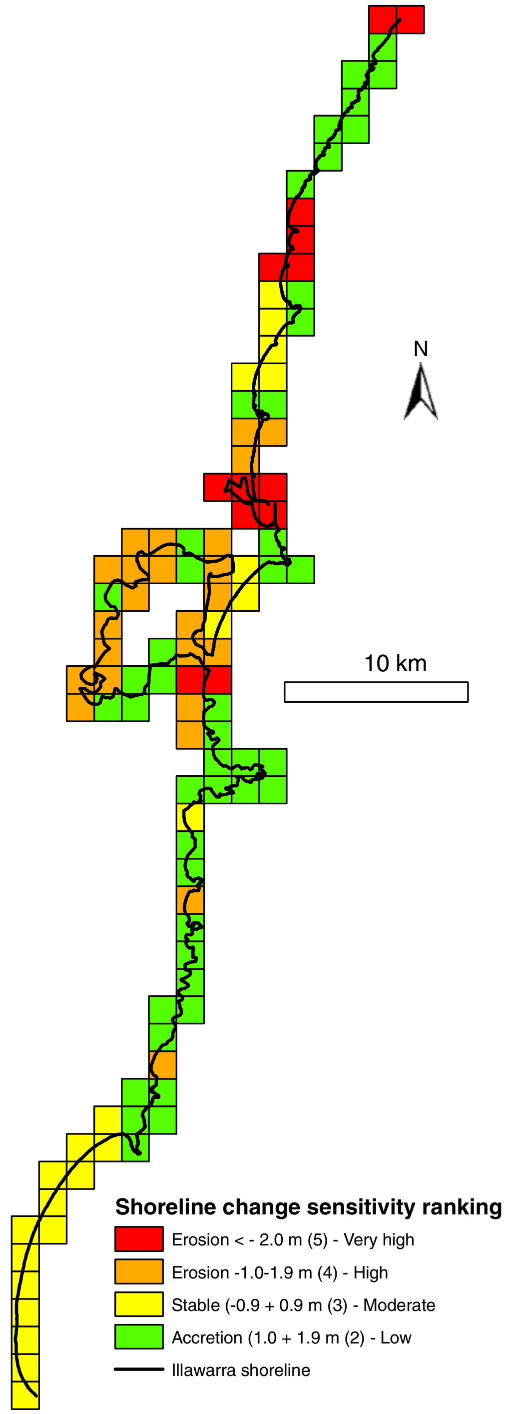

Fig. 7 The relative ranking of the shoreline change variable for the Illawarra coast

northern section of Perkins Beach has an extensive dune behind it, although one that has undergone disturbance in the past with sand mining. Stationary barriers are dominated by a single prominent dune ridge (Thom 1983). They tend to form where there is a limited sediment supply (Hesp and Short 1999) with little evidence of progradation over the past 5,000 to 6,000 years, and may experience erosion in the future so have been assigned a rank of 3.

Mainland beach barriers are thin beach deposits (averaging 5 m thick) that abut against a bedrock coastline (Chapman et al. 1982). These are essentially rocky shores and were mapped as having a low sensitivity ranking (2).

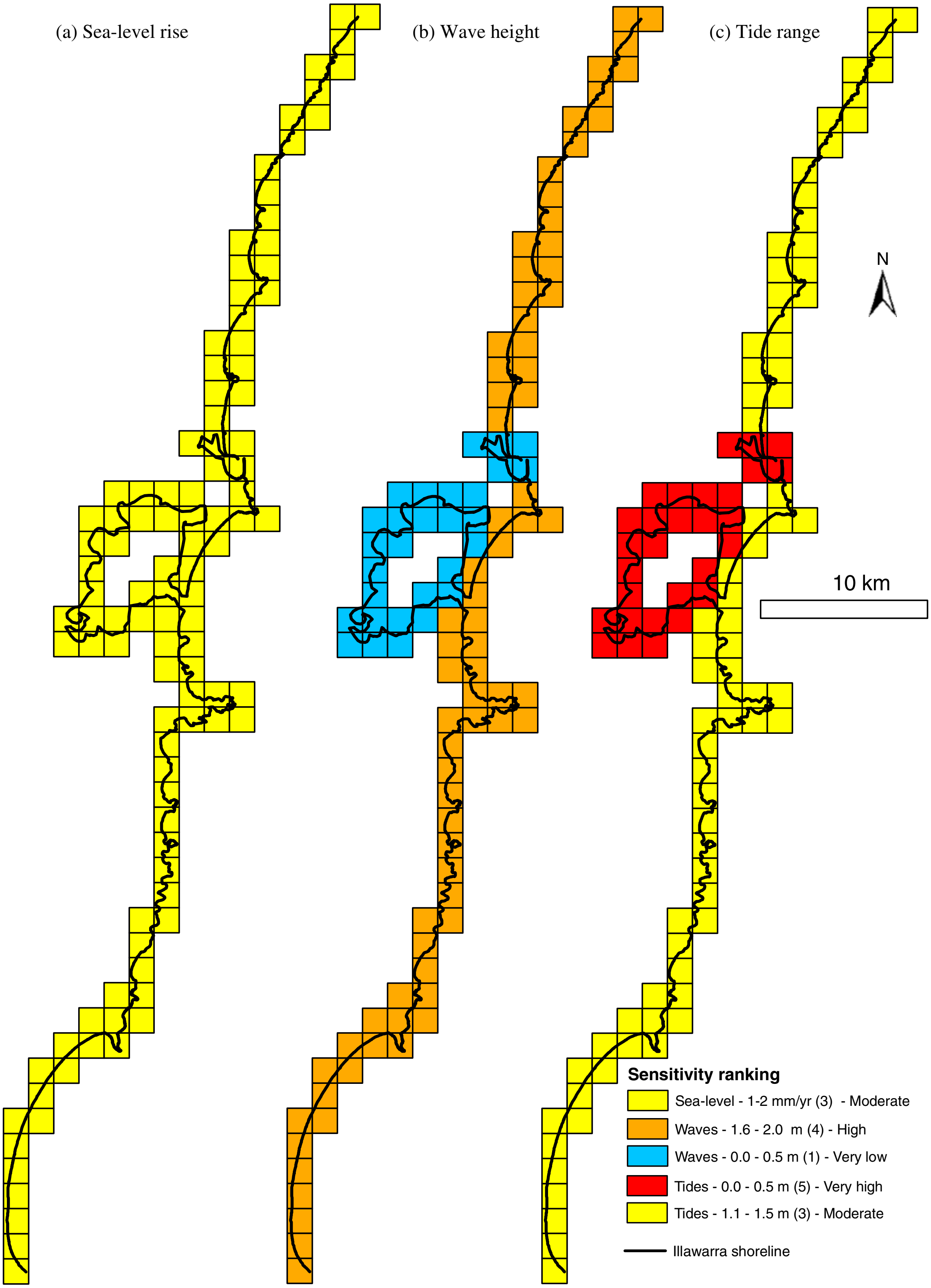

Fig. 8 Process variables reclassified in terms of sensitivities along the Illawarra coast. (**a**) Relative sea-level rise showing moderate sensitivity for all the 105 grid cells. (**b**) Mean wave height divided into waves of between 1.6 m and 2.0 m occurring in the open ocean coast and waves of between 0.0 m and 0.5 m occurs within Lake Illawarra and Tom Thumb lagoon. (**c**) Mean tide range similarly distinguishing open coast and re-entrants

Prograded barriers have built seawards over the mid to late Holocene and are characterised by multiple beach ridges, sometimes preserving a relict foredune on their crest, such as the sequence of ridges that occur landwards of Seven Mile Beach. Barrier progradation is regarded as an indication of a positive sediment budget, the beach ridges behind Seven Mile Beach having formed as a result of sand supply mainly from the Shoalhaven River (Thom et al. 1978). If sections of the coast are still receiving inputs of additional sediment they may be less susceptible to recession as a consequence of sea-level rise than those barriers that have a finite sediment volume, or have demonstrated a history of retreat. Mapping of the coastline in terms of barrier type variable (Fig. 5) resulted in 48 cells classified as mainland beach barriers (45.7%), 36 cells as stationary barriers (34.3%), 18 grids as prograded barriers (17.1%) and three cells as receded barriers (2.9%).

Shoreline exposure

Shoreline exposure is a new variable referring to the orientation of shores relative to wave direction; it has not been previously considered in the derivation of a CSI. It is included because the exposure of a coastline to the dominant wave direction influences its susceptibility. It is thus a physical variable but one that captures an element of one of the process variables. Waves have a lesser effect on a sheltered beach compared to an exposed coast, composed of the same rock type. Shoreline exposure is a qualitative measure of the degree to which a particular shoreline segment is exposed to whatever wave energy impinges on the broader coast of which it is a part, over a period of time and is not a quantitative measure of the amount of wave energy received by a shoreline (Sharples 2006). Shoreline exposure was measured in positive degrees from 0 to 359.9 clockwise from the north (e.g., a southeast-facing beach has a direction of 135°). The orientation of a particular shore to the wave direction, and presence or absence of features such as sheltering headlands and islands, makes certain shoreline segments more exposed to waves than others.

Before the shoreline exposure could be mapped, data from a directional waverider buoy off the coast of Sydney, 80 km to the north, was analysed and a rose diagram developed for the Illawarra area. The assumption was that the data obtained from the Sydney station would be representative of the waves in the study area (the waverider buoy at Port Kembla does not capture directional data). The wave direction at Sydney has been measured for a period of 12.8 years from March 1992 to December 2004 resulting in 86,595 records (Kulmar et al. 2005). From this dataset it was established that the dominant wave direction along the Illawarra coast is from the south-southeast (SSE), accounting for 31% of waves reaching the shore followed by waves from the south (S) accounting for 19%, while waves from the southeast (SE) account for 16% (Kulmar et al. 2005). The shoreline exposure was therefore measured in relation to the most dominant SSE wave direction throughout the year. Using a rose diagram for the Illawarra coast, aerial photographs and field observations, each coastal cell was assigned a category and a rank depending on its orientation relative to the dominant wave direction. Sensitivity classes for the coast derived from the shoreline exposure variable are shown in Table 1. In terms of shoreline exposure, Fig. 6 indicates that 51 cells are mapped as fully exposed segments to the dominant wave direction from the SSE (48.6%), 34 cells as sheltered segments (32.4%); semi-exposed and exposed segments had ten cells each and account for 9.5% of the shoreline.

Shoreline change

Beaches in eastern Australia experience substantial erosion as a consequence of storms. The morphodynamics of these beaches has been studied in detail (Short and Woodroffe 2009), and variation across a spectrum of beach states from reflective to dissipative is understood in relation to antecedent and incident wave energy (Short 2006). Repeat beach surveys over three decades at key sites at Narrabeen to the north and Moruya to the south indicate recovery of beaches over several years following major storm cut (McLean and Shen 2006; Short and Woodroffe 2009). Beach behaviour involves considerable volumes of sand that may accrete on the beach during periods of relatively calm conditions, but can be eroded from the beachface and deposited in the nearshore as a consequence of higher energy conditions.

Under these circumstances, recognition of a distinct trend in shoreline position appears more complex than seems to have been the case in previous studies that have produced an index incorporating shoreline change. Shoreline change is a difficult parameter to determine, because erosion is episodic and aerial photographs provide only a synoptic overview in time. Shoreline evolution can be variable over a wide range of different temporal and/or spatial scales. Detailed assessments of the rates of shoreline change were obtained for 11 Illawarra beaches as part of a broader study using aerial photographs to determine fluctuations in the position of the shoreline based on HWL and vegetation line indicators (Abuodha 2009). As opposed to being eroded, some shorelines along the Illawarra coast appeared to have undergone net accretion. The shift of the shoreline position inferred between the earliest and latest aerial photograph has been used to derive rates of shoreline change for surveyed beaches, and that trend extrapolated to the entire Illawarra coast, assuming similar trends for beaches that were not measured based on their backshore as a guide. The classification of rates of shoreline change is shown in Table 1. Figure 7 indicates that 45 cells were mapped as eroding at between −1.0 m/yr and −1.9 m/yr (42.9%), 24 cells were mapped as accreting at between 1.0 m/yr and 1.9 m/yr (22.9%), 23 cells were mapped as stable with shoreline change rates of ±0.9 m/yr (21.9%) and 13 cells were mapped as eroding at greater than 2.0 m/yr.

Relative sea-level rise

Whereas most of the structural variables were mapped from aerial photographs or field survey, sensitivity rankings for the process variables (Table 1; Fig. 8), were obtained from waverider buoy or tide gauge records. The relative sea-level rise trend adopted for the Illawarra was 1.2 mm/yr based on tidal records at Fort Denison in Sydney over a period of 82 years (Church et al. 2006). A significantly faster rate of 3.1 mm/yr has been observed at the Port Kembla tide gauge, a high resolution Seaframe tide gauge operated since July 1991 (National Tidal Centre 2008). These rates are broadly similar to the global mean rate determined from tide gauges for the past several decades, and the more rapid rate indicated by satellite altimetry for the decade or decade and a half for which that is available, respectively. The relative sea-level rise variable has been assigned a mid-value rank (Fig. 8a); all 105 cells have been assigned the same value (3), whether on the open ocean coast or within coastal re-entrants. If a higher value were considered more appropriate then all cells would be affected equally in the case of this variable, which appears to differentiate no variation within this study area.

Mean wave height

Wave action can result in erosion and is a significant factor modifying the shoreline, so is an important variable to include in a CSI. The NSW open coast is a wave-dominated coast. Waves arriving on the NSW coast have a mean deepwater wave height of 1.6 m and a period of 10 s (Short 2006). Wave heights within coastal re-entrants range from 0.0 to 0.5 m indicating that these more sheltered areas should be assigned a lesser ranking (Table 1; Fig. 8b). Mapping the coastline in terms of mean wave height (Fig. 8b) resulted in 76 cells on the open ocean coast mapped as experiencing waves of between 1.6 m and 2.0 m (72.4%), and 29 cells within re-entrants mapped as experiencing waves of between 0.0 m and 0.5 m (27.6%) occurring within Lake Illawarra and Tom Thumb lagoon.

Mean tide range

The coast of NSW has a microtidal range (i.e., less than 2 m); the Illawarra coast experiences a spring tide range of 1.6 m and a neap tide of 0.7 m (Short 2006). However, the tidal range for the coastal re-entrants is less. Water level variations within Lake Illawarra attributed to tides are only around 0.05 m but may vary up to a maximum of 0.12 m following permanent opening of the lake's entrance with construction of training walls, and associated scour of the inlet. It should be noted that ranking coasts in relation to tidal range has been viewed differently by different researchers. We have adopted a view that the higher the tidal range, the lower the sensitivity based on the following perspective advocated by several workers in previous studies (Thieler and Hammar-Klose 1999; Pendleton et al. 2004). The reasoning is based primarily on potential influence of storms or other extreme water levels and the extent to which they are likely to impact above the highest tidal levels. On a macrotidal coastline, there is only a small chance of a storm occurring at high tide. Thus, for a region with a five metre tidal range, a storm having a two metre surge height could occur without exceeding the elevation of highest tide if it occurred during neap tides. On a microtidal coastline, however, unusual extreme water-level highs are always likely to exceed high tide levels and these coasts are therefore always at greater risk of inundation from storms (Thieler and Hammar-Klose 1999). Although the mean tide range is ranked in five different classes in Table 1, sections of the Illawarra coast experience only two of those categories (Fig. 8c), with 76 cells on the open ocean coast mapped with tides of between 1.1 m and 1.5 m (72.4 %) and 29 cells within Lake Illawarra and Tom Thumb lagoon mapped as experiencing tides of between 0.0 m and 0.5 m (27.6 %).

Coastal sensitivity index (CSI)

The value of the coastal sensitivity index (CSI) for each of the cells was determined using the square root of the product of the ranked variables divided by the number of variables as shown in the equations in Table 2. Four different iterations were undertaken to derive a CSI based on different combinations of the variables. The first iteration involved the six variables which have been most frequently adopted in the CVI that has been used widely by the USGS, and which can be regarded as the conventional variables. These are coastal slope (b), geomorphology (c), shoreline change (f), relative sea-level rise (g), mean wave height (h), and mean tide range (j). This conventional set of six variables, used by a range of authors, is denoted as CSI6.

A second iteration used all 9 variables, and was applied to the Illawarra coast to determine how much more discriminatory power, if any, the incorporation of additional variables would provide. This is denoted as CSI9 (Table 2). Two further iterations involve eight variables, in each of these one of the nine variables was omitted. The first, CSI8a, incorporated the 6 conventional variables together with the two additional variables that were introduced in this study (barrier type (d) and shoreline exposure (e)); the excluded variable in this case was rock type (a) which has been left out in more recent compilations of CVI in the US and elsewhere. The second, CSI8b, incorporated all the variables except shoreline change (f) on the grounds, argued above, that this is not so much a physical attribute of the section of shoreline under study but rather a manifestation or outcome of the interaction between process and structure. Excluding the shoreline change variable from calculation of the index provided the opportunity to explore whether observed shoreline change trends could be used to assess the validity of the index.

The data for each coastal cell was processed in ArcGIS (with a unique ID), assigning specific rankings in the attribute table of the 'shapefile' for each variable. In this study, we selected an unweighted product model, thereby making no a priori assumption about the importance of each variable in the overall calculation of the index. In this way, each variable was viewed as potentially making an equal contribution to the overall sensitivity of the Illawarra coast. The resulting output of CSI index values have been divided into quartiles, such that the discrete index values of cells are ranked in terms of their magnitude and the lowest quarter (the 25th percentile) are displayed as least sensitive, those below the median displayed as moderately sensitive, with the high and very high classes distinguished at the 75th percentile. This is comparable to the approach adopted for portrayal of the CVI (Pendleton et al. 2004). There are alternative ways to choose the index values at which to place boundaries (Diez et al. 2007; Gornitz 1991; Doukakis 2005) and it is important to realise that the choice of divisions for sensitivity levels of a coastline to sea-level rise can lead to quite different impressions of the degree of vulnerability (Nageswara Rao et al. 2008, p. 203). In this study, quartiles were used to slice the data on the basis of the magnitude of calculated indices for all the cells to highlight different relative sensitivities along the coast; an approach which is consistent with the that applied on the US coast (Thieler and Hammar-Klose 1999). This displays the relative sensitivity of the sections of coast examined, implying that roughly a quarter of the coast is very highly sensitive, highly sensitive, moderately sensitive and of low sensitivity. These classes apply only within the area studied, but cannot be extrapolated to, or compared with, other areas of coast which may have involved a different ranking scheme for the variables. This can be seen, for example, in consideration of the tidal range variable; many shorelines in northern Australia are marcotidal and fall beyond the range of values adopted in this study—a consistent set of classes would need to be used in any study which compared these very different coasts.

Results and discussion

The four different iterations of the CSI produced different indices for the set of 105 cells, but as can be seen in Fig. 9 yielded broadly similar patterns in terms of the relative sensitivity of the Illawarra coast. The index values produced by the conventional CSI6 ranged from the lowest value of 3.5 for a cell at the northern end where the escarpment intersects the shoreline and forms cliffs, to the highest value of 27.4 that was reported for six cells. The addition of further variables produced higher values for the indices. When all 9 variables were used in CSI9 the values ranged from the lowest of 13.9 to the highest of 250. The broad distribution is very similar to that produced by CSI6; although the cell registering the lowest sensitivity is a different one; the cells with the highest value also recorded high values with CSI6. CSI9 yielded 35 discretely different index values, more than those indices based on fewer variables. This indicates an increase in the discriminatory power associated with using more variables, but it is primarily a mathematical consequence of using the product of ranked variables.

Adding barrier types and shoreline exposure to CSI6 resulted in eight variables used in CSI8a with index values ranging from the lowest of 9.5 to the highest of 118.6. These eight variables produced 33 discrete index values, almost as many as the full nine variables. Iteration CSI8b ranged from the lowest value of 10.4 to a highest of 118.6 indicating that this high value is produced because of the similarity of variable ranks and not because of any specific feature of the variable itself (both the omitted values had the same rank, 5, for the cell(s) considered most sensitive). The two cells with the highest sensitivity value for all four iterations occur on Bulli Beach, a beach on the receded barrier (Jones et al. 1979), and were the only cells that scored a ranking of 5 for all 6 of the physical variables.

As is apparent from Fig. 9, the different CSIs produce a very similar assessment of the distribution of relative sensitivity along the Illawarra coast. The conventional CSI6 indicates a trend from the least sensitive cliffed shorelines to the highly sensitive beaches backed by low plains. When comparing the sensitivity classes into which cells were placed, 77 of the cells (73%) were similar between the CSI6 and CSI9 iterations. The most similar of the iterations were CSI9 and CSI8a, for which 101 of the 105 cells (95%) occurred in the same sensitivity class, implying that the omission of the rock type variable did

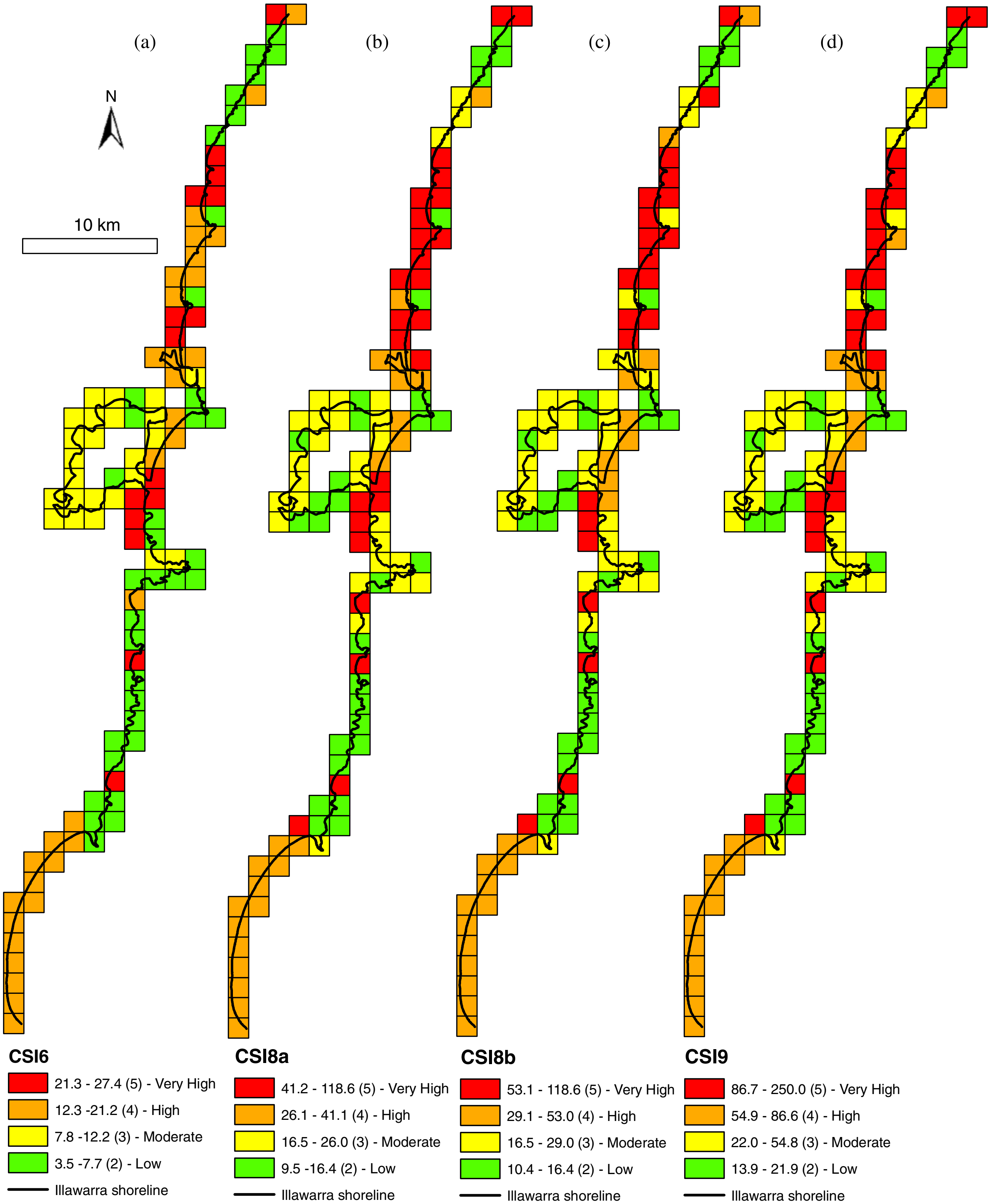

Fig. 9 Four iterations of CSI divided into quartiles, categories indicating sensitivities along the Illawarra coast

not significantly alter the pattern of apparent susceptibility. CSI8b shared 89% of sensitivity classes with CSI9 and 87% with CSI8a. Comparison of rank order between iterations further confirmed the broad similarity of the pattern, and several of the discrepancies related to issues associated with how a quartile boundary was defined rather than significant re-ordering of cells.

Although it is frequently used in many applications of the CVI, the shoreline change variable is unlike other variables in that it is more an indication of coastal response to processes such as sea-level rise and storm surges (and in some cases sediment depletion or diversion) rather than physical characteristics. Therefore, it was purposefully omitted in CSI8b in order that a comparison could be made between the sensitivity index and the direction of apparent shoreline change, to see whether this might provide independent validation of the sensitivity index. A comparison of the rankings of the CSI8b index (Fig. 9) and the initial mapping of shoreline change presented in Fig. 7 indicates very little similarity between the two. Only 36 out of the 105 cells fell within the same class, predominantly within the low sensitivity class. This reflects the wide range of trends in shoreline behaviour on sandy beaches which may erode or accrete. The NSW coast has been observed to show rapid shoreline erosional events during storms, alternating with periods of slower, but near continuous accretion of new foredune when wave conditions are calm (McLean and Shen 2006). From 1974 to 1976, several east-coast cyclones originating in the Tasman Sea resulted in extensive coastal erosion along the coast of southeastern Australia (Bryant and Kidd 1975). Long-term studies on foredune development started in 1972 at Moruya Beach (200 km south of the study area) have shown that the beaches, although initially eroded, are able to recover as backshores develop into foredune (McLean and Shen 2006). The volumes of sand eroded and transferred between beachface and nearshore by occasional storms and replenished during subsequent calmer periods is equivalent to, or more than, the beach retreat that would be anticipated over decades or centuries of gradual retreat in response to sea-level rise (Hennecke et al. 2004). It has also been shown that sand can move from one end of a beach to the other, a process known as beach rotation, as a consequence of differing wind patterns within El Niño and La Niña phases linked with the Southern Oscillation Index (Ranasinghe et al. 2004).

Reconstructions of beach behaviour are also inadequately captured using a limited number of aerial photographs. Rates of shoreline change for this study were determined from only six time periods within 45 years (1961–2006), and other events that have changed the shape of the shoreline were not captured within these six time periods. Another reason for shoreline change being a poor indicator of coastal sensitivity for the Illawarra coast is because shoreline change rates were only measured for 11 out of the beaches, under-representing patterns of shoreline change along the Illawarra coast. On long sandy barrier island coasts, such as in the eastern US, it may be easier to detect a trend of shoreline retreat, and historical rates of change are likely to yield a credible foundation for forecasting future recession. By contrast, for the coast of eastern Australia shoreline change is a poor indicator of a coast's sensitivity (as measured by CSI), and perhaps therefore it may also be a poor indicator of future rates of change.

If the pattern of observed shoreline change cannot be used to indicate current susceptibility or future vulnerability, then the validity of the sensitivity index rests on the relative ranking of the variables. Coastal cells ranked with very high sensitivity are mainly composed of Quaternary sediments and occur along the open ocean sandy shores, particularly those backed by low plains, but also those backed by dunes. Receded barriers, such as at Bulli Beach, appear very susceptible where they are fully exposed to the dominant wave direction (SSE). Such coasts have undergone recession over recent millennia and may be subject to further landward retreat during storm surges. Figure 10a represents an example of a coast that maps in the very high sensitivity class, and shows a scarp cut into the dune face by a recent winter storm. On the other hand, coastal segments with low sensitivity are mainly composed of resistant rocks with steep to moderate slopes, while others are sheltered from the dominant wave direction (SSE). Many of the rocky coasts, such as that shown in Fig. 10b can be regarded as a low sensitivity coast.

The grid template and portrayal of sensitivity using cells provide a clear visual display of the relative indices, but there are situations where individual cells occur across significantly contrasting shorelines. For example, some cells cover both Perkins Beach which is exposed to the open ocean and a section of the sheltered Lake Illawarra estuarine embayment. Alternative techniques have been used to illustrate shoreline sensitivity data in other studies, including segmenting a polyline representing the shoreline, using schematic lines displaced seaward of the shoreline, or adopting a polygon map. Each of these also has constraints, particularly in places where the shoreline is convoluted, as in the case of the Lake Illawarra described above, resulting in a loss of detail, confusion and misrepresentation of the results.

The cell-based template provides a visual representation which may enable coastal planners and managers to appreciate the contrasts between the most sensitive and the least sensitive areas within their study area. This can assist in prioritizing efforts to enhance the natural resilience of the coast, or invest in adaptation measures such as

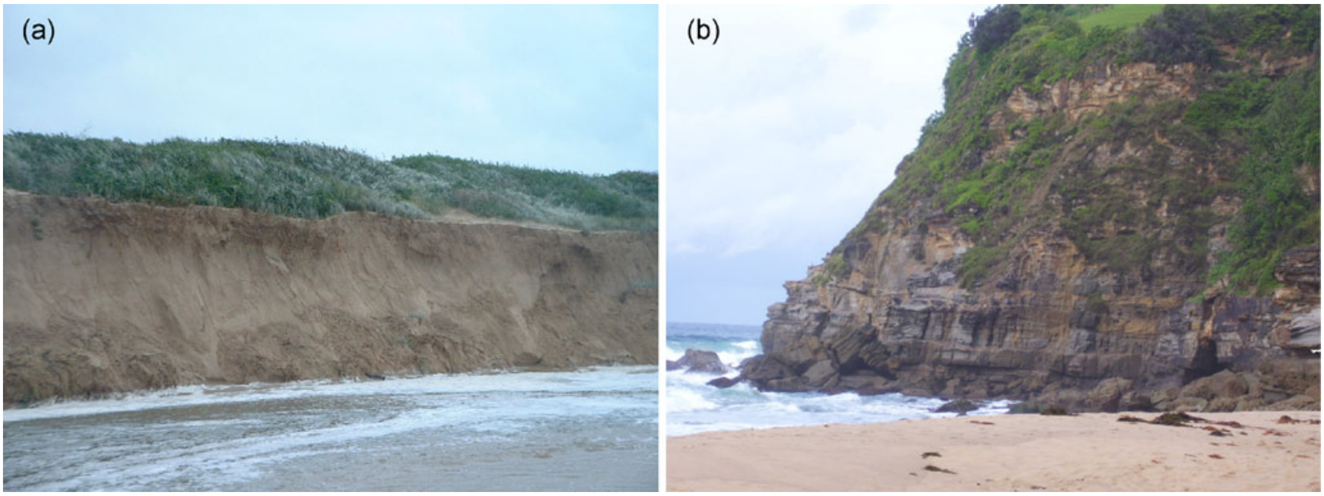

Fig. 10 (**a**) An example of a very high sensitivity shoreline on the Illawarra coast composed of unlithified sand and occurring on an open coast exposed to the dominant wave direction. (**b**) An example of a low sensitivity coast composed of resistant rocks with a steep slope and semi-exposed to the dominant wave direction

revegetating dunes. The CSI index is based only on physical variables; integration with further social, cultural and economic factors may enable a broader assessment of the vulnerability of sections of the coast and the communities who live there.

Conclusion

This study is the first attempt to apply a coastal sensitivity index to a section of the Australian coast following a methodology developed for coasts of the US and then applied more widely. Variables representing different structural characteristics and coastal processes that can influence the sensitivity of a coastal zone to the impacts of coastal hazards and sea-level rise were ranked for cells along the embayed headland-and-beach Illawarra coast in southern New South Wales. In addition to conventional variables, two additional variables, barrier type, which captures millennial scale trends of progradation and erosion, and shoreline exposure, which represents the exposure to wave processes, were included to increase the discriminatory power of the index. Four iterations were undertaken and in each iteration the indices, derived from the product of the ranked variables, have been displayed in four sensitivity classes (quartiles): very high, high, moderate and low sensitivities. The greatest number of index values occurred when all 9 variables were included (CSI9), slightly increasing the discriminatory power of the index. When the shoreline change variable was omitted the pattern was little different, but shoreline change was not found to correlate well with sensitivity, presumably as a consequence of the complex erosional and accretionary behaviour along this coast which precludes forecasting the direction or rate of shoreline change. It appears that rate of shoreline change is not a suitable variable to use for testing or validating the indices, because this coast is influenced by large storm events and experiences spatial and temporal variations in erosion or accretion rather than a dominant trend of either. The CSI provides a first-order indication of relative sensitivity, discriminating s range of shorelines from resistant rocky cliffs to the highly sensitive beaches backed by erodible plains or dunes. Integration with further socio-economic data might extend this sensitivity analysis to give a broader indication of the relative vulnerability of coasts and the communities associated with them within a coastal study region.

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