INVESTIGATING THE RESPONSE OF ESTUARIES TO CLIMATE CHANGE

K Rogers[1], CD Woodroffe[1], N Saintilan[1,2], J Dodson[3], I Ghetti[4], D van Bracht[5]
[1]University of Wollongong, Wollongong, NSW
[2]NSW Office of Environment and Heritage
[3]Australian Nuclear Science and Technology Organisation
[4]Shoalhaven City Council
[5]Bega Valley Shire Council

Abstract

Despite the threat of sea-level rise to estuarine shorelines and surrounding ecosystems, settlements and infrastructure, there have been very few assessments of the vulnerability of estuaries. Systematic attempts have been hampered by the diversity of estuarine geomorphology, and the complexity of shoreline responses to sea-level rise, human disturbance and natural and anthropogenic influences. The relationship between rates of sediment supply and rates of sea-level rise is central to understanding the geomorphic response of estuaries to climate change. Analyses of coastal sea-level rise impacts have focused on open ocean sandy coasts and commonly employ ‘the Bruun Rule’; a simple heuristic which predicts erosion of the beach and deposition of sand in shallow water according to an 'equilibrium profile' that migrates landwards as the sea rises. Increasingly, research reveals that the sedimentary response of shorelines to climate change and sea-level rise is complex and the Bruun Rule is frequently inappropriate as rates of sediment supply and erosion vary spatially and temporally. Analyses of sediment surplus or deficits from a shoreline, commonly referred to as sediment budgets, provide a useful means of determining the response of estuarine shorelines to climate change. The aim of this project is to quantify sediment budgets, sedimentation and sediment sources for selected estuaries in southeastern Australia; and in doing so; develop a framework for assessing the response of estuaries to sea-level rise. This framework is broadly applied as a first pass assessment of the vulnerability of estuaries to sea-level rise; and is validated using a range of techniques to quantify sediment contributions and sources to selected estuarine shorelines. The outcomes of this project will assist with modelling the response of estuaries to climate change; and will guide the implementation of management actions that facilitate adaptation of estuaries, ecosystems and communities to climate change.

Introduction

Sea level is rising and is anticipated to accelerate this century as a consequence of global warming (Church et al., 2013). This threatens estuarine shorelines and surrounding ecosystems, settlements and infrastructure. There have been very few assessments of the vulnerability of estuaries; systematic attempts have been hampered by the diversity of estuarine geomorphology, and the complexity of shoreline responses to sea-level rise, human disturbance and natural and anthropogenic influences. The majority of studies on the impacts of sea-level rise on shorelines have focused on open-ocean sandy coasts. Most have adopted a simple heuristic called the 'Bruun Rule' (Bruun, 1962) which predicts erosion of the shoreline and deposition of sediment in shallow water maintaining an 'equilibrium profile' that migrates landwards as the sea rises. However, research is increasingly revealing that the sedimentary response of shorelines to climate change and sea-level rise is convoluted; the simple Bruun Rule relationship rarely holds true (Cooper and Pilkey, 2004, Ranasinghe et al., 2012). This is because sediment delivery is largely controlled by hydrodynamics, which varies spatially and temporally within estuaries. The relationship between rates of sediment supply and rates of sea-level rise is central to understanding the geomorphic response of shorelines to climate change; and consideration of a shoreline's sediment budget, that is whether there is surplus or deficit of sediment from a shoreline over a period of time (Rosati, 2005), is useful for conceptualising the geomorphic response of a shoreline.

The concept of a sediment budget is even more critical for estuaries because each estuary represents a sink that is progressively infilled with sediment and organic carbon supplied by fluvial, wave and tidal processes. Whereas beaches are composed of sand, estuarine shorelines may be rocky, sandy or muddy, and each of these substrate types will behave differently as the sea rises. A range of other factors that don't affect open coast beaches may influence the response of estuarine shorelines to sea-level rise. Sediment delivery is largely controlled by hydrodynamics with strong relationships established between tidal range (Kirwan and Guntenspergen, 2010, Rogers et al., 2006), suspended sediment concentrations (Kirwan et al., 2010), elevation (Pethick, 1981, Rogers et al., 2005) and friction (Bouma et al., 2007, Howe et al., 2009). Fluvial flows (Sklar and Browder, 1998, Day et al., 2011) and catchment modification (Lee et al., 2006) influence the supply of catchment sourced sediments and organic material to estuaries. Barrier sediment budgets (Hennecke, 2004), wave action and tide power (Harris et al., 2002) influence the delivery of marine sediments (largely sand) to estuaries. Vegetation on shorelines, such as mangrove and saltmarsh, has a multifaceted influence in sedimentation by baffling tidal flow, binding sediments in the root zone (Howe et al., 2009, Bouma et al., 2007) and contributing organic matter *in situ* (McKee, 2011, Nyman et al., 2006).

Despite this diversity in estuarine shorelines, estuaries have evolved under relatively similar conditions of sea-level rise over the Holocene, and their current differences largely reflect their sediment budgets or the variable rates of infill of estuaries in response to sea-level rise over the Holocene. Extrapolation of this history of sediment infill to current conditions of sea-level rise may provide a useful indication of the likely response to projected sea-level rise in the 21st century. In this paper we present a geomorphic framework, based on the Holocene history of estuaries as sediment sinks. This framework can be used to assist with identifying estuarine shorelines and coastal landscapes that may be vulnerable to climate change. We integrate this geomorphic framework with a framework for vulnerability assessment and spatially apply the integrated framework in a geographic information system (GIS) to systematically qualify the vulnerability of coastal landscapes to climate change on the south coast of NSW.

Geomorphic framework of estuary response to sea-level rise

The estuaries of southern NSW originated in incised bedrock (or drowned river) valleys on a wave-dominated coastline. In association with the most recent post-glacial marine transgression (~7000 ka), sea levels rose and wave energy transgressed inland. The overriding influence of wave energy on the coastline meant that sand barriers and spits developed along the coastline, with barriers being bounded by estuary entrances and geomorphic features that are resistant to erosion from wave energy, such as headlands and rocky outcrops. These barriers at the entrance of bedrock valleys constrict flow between the estuary and the open ocean, and contribute to the dissipation of wave energy into estuaries, decreasing the hydrodynamic energy of estuarine waters. The resulting low energy environment within estuaries creates hydrodynamic conditions ideal for the deposition of sediment delivered to the estuary from the catchment or from waves or tides that penetrate the estuary.

Estuaries, in effect behave as a ‘sink’ for sediment. The volume of sediment that an estuary sink can potentially hold is commonly termed ‘accommodation space’ and is dependent upon the shape of the bedrock valley and the elevation of hydrological influence, which equates to highest astronomical tide and correlates with mean sea level. Deeper valleys have more accommodation space than shallow valleys, while broad valleys have more accommodation space than narrow valleys.

Over the Holocene, sediment has been delivered from catchments and marine sources to the estuary and has, to varying degrees, infilled the ‘total accommodation space’; resulting in a progressive decrease in accommodation space available for sediment deposition. Consequently, the ‘available accommodation space’ is not only dependent upon sea level, and shape of the bedrock valley, but is also dependent upon the Holocene history of sediment delivery to the estuary. This evolution of accommodation space has been characterised broadly for both wave, river and tide dominated estuaries (Boyd et al., 1992, Dalrymple et al., 1992, Harris and Heap, 2003, Harris et al., 2002), and more specifically for the estuaries of southeastern Australia by Roy (Roy, 1984, Roy et al., 2001). In these classifications, the degree of infill corresponds to the maturity of an estuary, whereby mature estuaries have less available accommodation space than immature estuaries. The association between mean sea level, geomorphology and accommodation space is demonstrated in figure 1.

Sea-level rise acts to reverse estuary maturity and increases the areal extent of open water and intertidal areas within estuaries, thereby creating new accommodation space for the deposition of marine sands and terrestrial colluvial deposits, muds and silts. The geomorphic response of estuaries to sea-level rise, evident through increased accommodation space, will vary in accordance with a number of factors, as detailed in figure 1. At the simplest level of assessment, the primary indicators of the geomorphic response of an estuary to sea-level rise are the degree and rate of sea-level rise, bedrock valley shape, and the degree of estuary infill with sediment (estuary maturity). Estuary zonation provides an indication of the exposure of an estuary to different climate change drivers.

Estuary maturity

The stage of infill is an artefact of sediment budgets occurring over the Holocene; accordingly, mature estuaries have strongly positive sediment budgets, while immature estuaries have weakly positive sediment budgets. Should these antecedent conditions continue in the future, mature estuaries may continue to infill at rates that approach equilibrium with the rate of increase in accommodation space (i.e. sea-level rise);

conversely, sediment delivery to immature estuaries may lag the rate of increase in accommodation space. Extensive marine transgressive deposits that extend further landward in some estuaries in southern Australia support the hypothesis that rates of sediment supply to barriers may lag rates of sea-level rise (Sloss *et al.* 2005). These deposits provide evidence that lower estuaries have behaved more like marine embayments during the mid Holocene, with the estuary only becoming confined when rates of sediment supply exceeded rates of sea-level rise. In addition, estuary maturity can also denote possible areas impacted by sea-level rise. Low-lying depositional environments are poorly developed in immature estuaries and tend to be confined to the fluvial delta and flood-tide delta regions, while low-lying alluvial plains are extensive on the margins of mature estuaries. Consequently, settlements, infrastructure and agriculture that favour the environmental conditions on alluvial plains (e.g. flat topography and nutrient rich alluvial soils) are vulnerable to inundation and flooding.

Shape of the bedrock valley

Accommodation space provided by sea-level rise is proportional to the shape of the bedrock valley with greater accommodation space created in broad, shallow valleys compared to narrow confined valleys. In the absence of enhanced sediment budgets, alluvial plains and estuarine plains in broad valleys will be more sensitive to inundation from sea-level rise, flooding and storm surge than shallow incised valleys.

Estuary zonation

Estuary zonation will inform the exposure of depositional environments to climate drivers, and consequently the exposure of associated ecosystems, settlements and infrastructure. The marine zone, which includes the barrier, tidal creeks and flats, tidal deltas and back barrier sand flats, will preferentially be exposed to marine climate drivers such as wave climate and sea level, while the fluvial and alluvial zones, which includes floodplains, levees, distributary channels and the flood-tide delta, will preferentially be exposed to terrestrial climate drivers such as rainfall/runoff. Exposure of the estuarine zone to climate drivers will be partly mediated by estuary maturity and the shape of the bedrock valley.

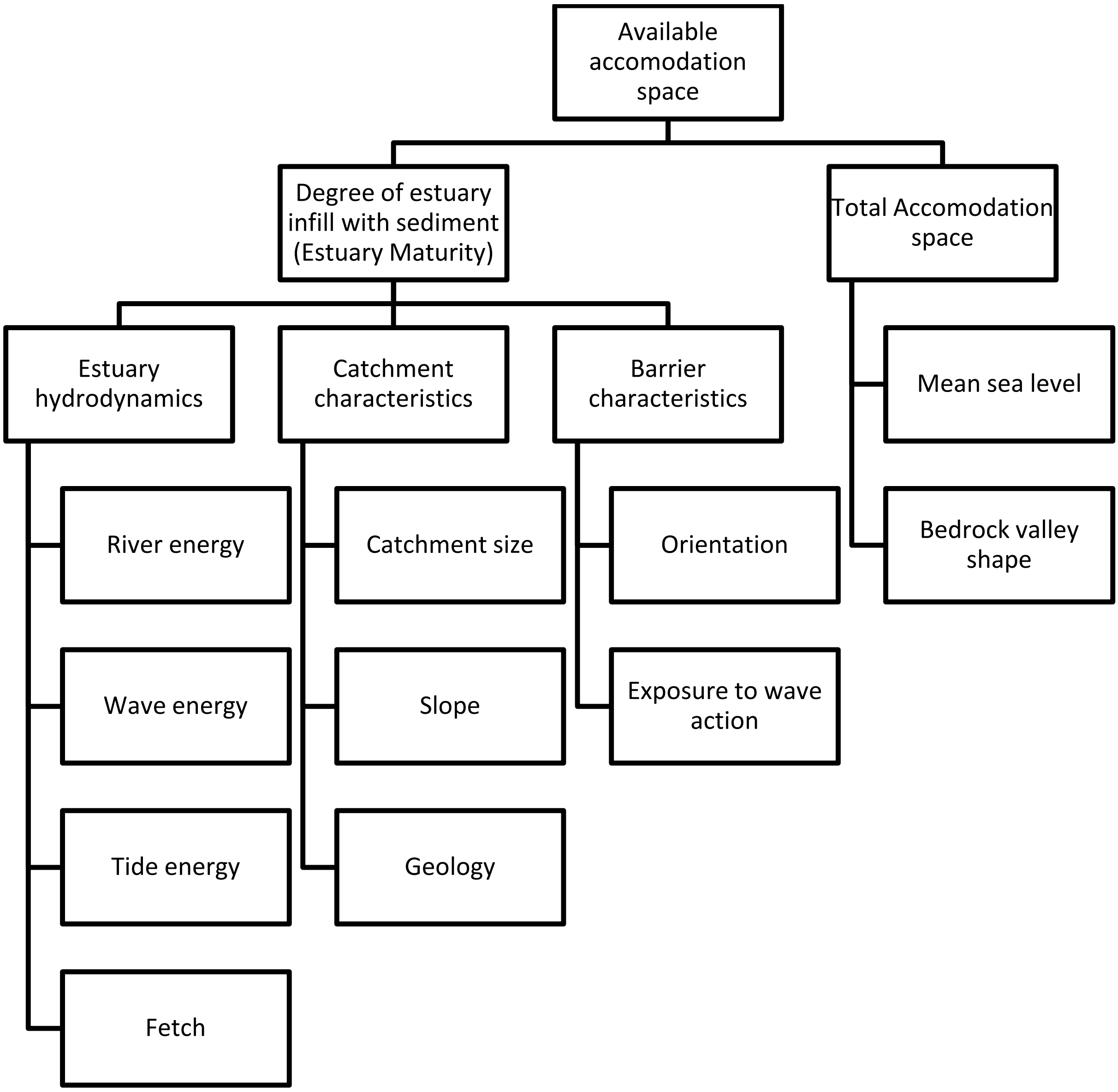

Figure 1: Conceptual model of the factors influencing the geomorphic response of estuaries to sea-level rise.

Framework for vulnerability assessment

Vulnerability is a term which has in the past been used to describe resilience, marginality, susceptibility, adaptability, exposure, sensitivity, risk, coping capacity and a range of other concepts (Füssel and Klein, 2006). The Fourth Assessment Report of Working Group II of the Intergovernmental Panel on Climate Change (IPCC) defined vulnerability as 'a function of the character, magnitude, and rate of climate change and variation to which a system is exposed, its sensitivity, and its adaptive capacity' (Parry et al., 2007). The Fifth Assessment Report defines vulnerability in terms of contextual (or starting point) vulnerability and outcome (end point) vulnerability (Agard et al. 2014). In the context of this study we have adopted an outcome vulnerability approach, as discussed by O'Brien et al. (2007), which defines vulnerability on the basis of residual consequences that remain after adaptation has taken place, and have aimed to capture the exposure, sensitivity and adaptive capacity of landforms associated with estuaries, as per the vulnerability definition in the Fourth Assessment Report (Parry et al., 2007) (Figure 2).

To aid simplicity the approach included some caveats:

- The approach focussed solely on biophysical components of vulnerability as there have been few assessments that have successfully integrated geomorphology and socio-economic indicators of vulnerability. Socio economic indicators of vulnerability could be incorporated through a post-hoc analysis of socio-economic indicators that employed a similar grid-based GIS approach.
- The approach focussed on the effects of hazards and climate change on inundation and erosion of land adjacent to estuarine waters. Other stressors that may affect estuaries that are not considered here include water temperature, acidification and water quality.
- Exposure is defined as ‘the character, magnitude and rate of change in climate drivers operating on a system’ (Parry et al., 2007) and is typically incorporated within coastal vulnerability indices (CVI) by characterising the spatial variability in exposure of a coastline to coastal processes, such as sea-level rise and wave height. Due to the constricted nature of estuaries and their intricate, sinuous and highly embayed shorelines, the amplitude of these processes can vary significantly over relatively short distances, both within and between estuaries. Characterising the spatial variability in coastal processes within estuaries is difficult and would require development and application of sophisticated modelling techniques. For this reason we have characterised exposure on the basis of proximity to climate change drivers, with marine zones preferentially exposed to sea-level rise, and alluvial and fluvial zones preferentially exposed to catchment derived flooding.
- Sensitivity is defined as ‘the degree to which a system is affected by climate variability or change’ (Parry et al., 2007) and for this assessment was defined on the basis of the landscapes sensitivity to erosion and inundation.
- Adaptive capacity is defined as ‘the ability of a system to adjust to climate change’ (Parry et al., 2007) and in this study was characterised on the basis of autonomous adaptation and did not include other adaptation mechanisms, such as planned adaptation. Autonomous adaptation (also called spontaneous adaptation) is defined on the basis of intent and contrasts with planned adaptation as it is not a conscious response to climatic stimuli and is a response triggered by changes within a system. In this study autonomous adaptation largely constitutes building land elevation through natural processes of accretion or plant productivity; and contrasts with planned adaptation such as increasing floor heights, creating living shorelines, or establishing sea walls and buffers.

Integration of Geomorphic and Vulnerability Frameworks

Estuarine geomorphology provides a useful foundation from which to assess the vulnerability of estuaries to climate change. As estuaries are defined by mixing of marine and freshwater flows, we focused on the influence of climate change on marine and fluvial processes, henceforth termed marine drivers and fluvial drivers and their influence on inundation and erosion of land associated with estuaries.

Vulnerability was characterised on the basis of exposure, sensitivity and adaptive capacity, whereby:

- Exposure was largely extrapolated from the elevation of the landscape because lower elevations exhibit greater exposure to drivers; and the position of depositional units, whereby marine units exhibited greater exposure to marine drivers of storm surge and wave activity and fluvial/alluvial units exhibited greater exposure to fluvial drivers of rainfall/runoff and flooding. The slope of land adjoining estuaries was relevant when considering the influence of marine and fluvial drivers on erosion; steep slopes limit run-up from storm surge, but also exhibit greater runoff.

- Sensitivity to inundation was considered to be relatively consistent across the coastal zone of southern NSW. However, we considered sensitivity to erosion to be dependent upon the capacity of the material to resist erosion. In this regard, unlithified Quaternary sediments were considered to be more sensitive to erosion.
- Adaptive capacity was complex to define, but relates to estuary maturity. Specifically, we propose that mature estuaries exhibit a history of sediment budgets exceeding accommodation space created by sea-level rise over the Holocene and therefore may have a greater capacity to adjust to sea-level rise. Accordingly, we identified supratidal environments, based on a history of sedimentation over the Holocene, as areas that may have capacity to build elevation at rates that exceed rates of sea-level rise.

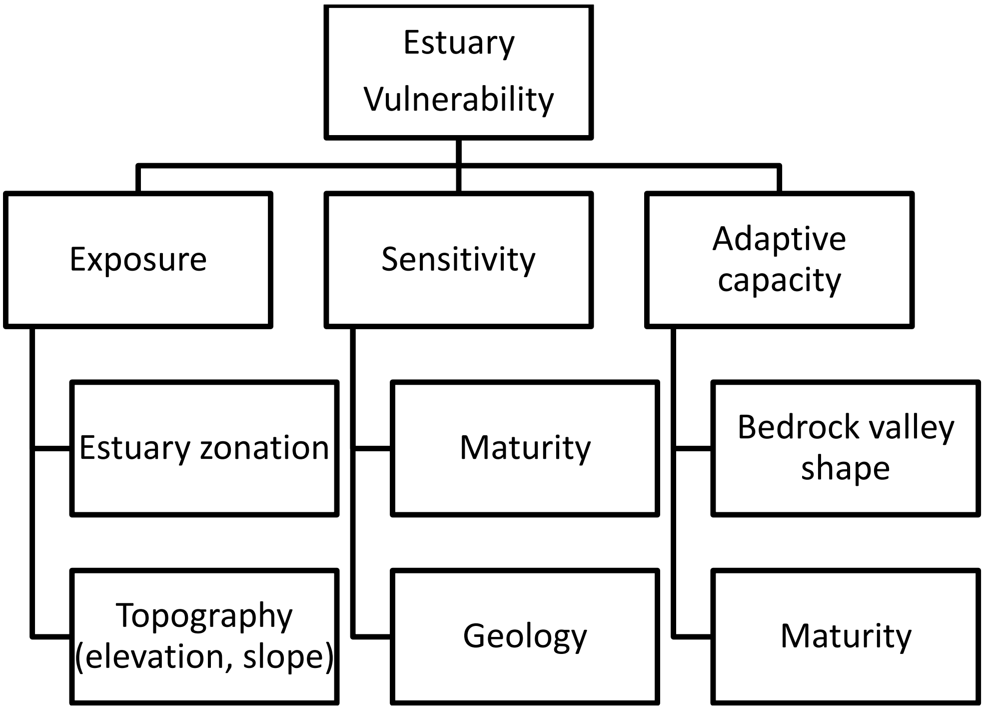

Figure 2: Conceptual framework for assessing vulnerability, as per the definition of Parry et al. (2007).

Integrated Framework Application

Study area

The South Coast of NSW spans the Sydney Basin and Lachlan Fold Belt (Figure 3). The coastline consists of a series of embayments which are flanked by headlands, dividing the coast into discrete coastal compartments (Davies, 1974). Each compartment has experienced a similar history of climate and sea-level change. The coastline is wave dominated and the prevailing wave direction from the south east promotes processes of long-shore drift in a northerly direction.

The coastal zone is marked to the west by the Southern Tablelands and Southern Highlands. Due to the proximity of these highlands to the coastline small catchments dominate the region and headlands coincide with watersheds (Bishop and Cowell, 1997); only six catchments (Shoalhaven, Clyde, Moruya, Tuross, Bega and Towamba

Rivers) drain an area exceeding 1000 km^2 and having total annual flows greater than 130 000 ML.

Roper et al. (2011) identify 102 estuarine waterbodies (defined on the basis of their width on maps at 1:25 000 resolution) in southern NSW between the Illawarra (Hargraves Creek: 34.23°S, 150.99°E) and NSW-Victorian border (Nadgee Lake: 37.47°S, 149.97°E). Entrances to estuaries are generally positioned near headlands at the northern or southern end of compartments, where they are afforded some protection from wave action and the build-up of marine sands at entrances is limited. However, marine processes delivering sediment to estuary entrances have facilitated the development of many intermittent estuaries, commonly termed Intermittently Closed/Open Lakes and Lagoons or ICOLLs (Haines et al., 2006), where exchange with the ocean is periodically limited by the development of a complete barrier across the estuary entrance.

Methods

The spatial extent of the analysis was limited by the extent of existing spatial data sets used in the assessment. The Coastal Quaternary geology and bedrock mapping, which was prepared by the NSW Department of Mineral Resources as part of the Southern Comprehensive Coastal Assessment of NSW (Troedson et al., 2004), was the primary dataset used for the analysis.. This dataset focussed on onshore areas and subaqueous areas associated with enclosed coastal waterways. The spatial extent of the dataset was limited in the south by the NSW-Victoria border and the north by the extent of the Kiama 1:100 000 map sheet; this map sheet intersects Lake Illawarra and only includes approximately half of its catchment area. The extent of Quaternary geology mapping is illustrated in Figure 3.

We employed a raster-based approach within GIS using the ARCGIS Spatial Analyst extension. Input data sets were used as proxy indicators of estuary exposure, sensitivity and adaptive capacity. These consisted of Quaternary geology and bedrock mapping, which was prepared by the NSW Department of Mineral resources as part of the Comprehensive Coastal Assessment (Troedson et al., 2004); and Shuttle Radar Topography Mission-derived 1 second Digital Elevation Model (SRTM-DEM). The SRTM-DEM is a raster surface with a cell size of approximately 30 m and elevation to the nearest metre. The cell position and size of this surface was used as the template for converting the vector layers of Quaternary and bedrock geology to raster surfaces. The Slope function in ARCGIS was used to characterize the slope of cells within the SRTM-DEM; the slope of cells is therefore a function of the spatial resolution. All analyses were limited to the spatial extent of the Quaternary geology mapping (Figure 3).

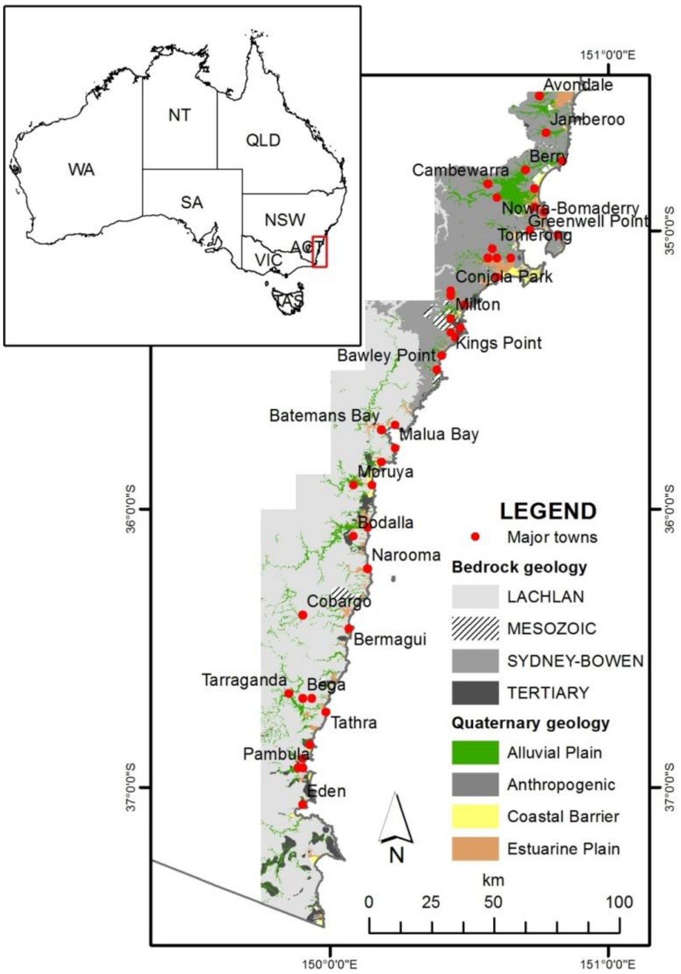

Figure 3: Location of study area and Quaternary and bedrock geology in the study area.

Four composite choropleth raster maps were prepared that provided a relative indication of the vulnerability of estuaries to marine and fluvial drivers causing inundation and erosion. To generate these maps, input raster surfaces were processed according to geomorphic criteria detailed in Table 1. The extract function was used to extract relevant cells from the input datasets. These cells were then reclassified and assigned a value of 1-3 depending on whether the extracted cells were indicative of high, moderate or low exposure, sensitivity or adaptive capacity. Due to the spatial scale of the analysis, three cell values (high, moderate, and low) were employed to simplify the processing of raster surfaces and to ensure that equal weighting was given to each component of vulnerability (i.e. exposure, sensitivity and adaptive capacity). The four composite raster maps were compiled by adding raster surfaces that characterised the exposure, sensitivity and adaptive capacity of the coastal zone together using the raster calculator tool. Cell scores in these surfaces ranged between 3 and 9; with low scores indicating low vulnerability to a driver (i.e. marine or fluvial) and effect (i.e. erosion or inundation), and high scores indicating higher vulnerability to a driver and effects.

A final raster surface of the vulnerability of cells to all drivers and effects was compiled by adding the cell scores for each of the four composite raster surfaces. Cell scores ranged between 12 and 36; low scores were indicative of low vulnerability.

Table 1: Approach to assessing vulnerability to climate drivers causing erosion and inundation within estuaries. Components of vulnerability were divided on the basis of marine or fluvial drivers and erosion and inundation effects. Indicators for the different vulnerability components were established and input data sets that spatially represent these indicators were identified. Cell scores were assigned to raster surfaces on the basis of the indicators and their relationship to the various components of vulnerability. Choropleth maps for each vulnerability component were developed on the basis of cell scores.

Drivers & Effect		Component	Indicator	Input data set	Explanation	Cell Label (Score)	Cell score and description
Marine	Erosion	Exposure	Deposit type; Slope; Elevation	Quaternary geology; DEM	– Lower elevations exhibit greater exposure to wave action – Greater exposure to wave action closer to shoreline – Steep slopes limit wave run-up – Marine drivers exhibit history of operating near coastal and estuarine Quaternary deposits.	High (3)	– Distance < 500 m + Elevation < 5 m + Slope < 10°
						Moderate (2)	– Distance < 5 km + Elevation < 5m; or – Distance < 500 m + Elevation < 5 m + Slope > 10°; or – Coastal/estuarine unit + Elevation < 5 m.
						Low (1)	– Coastal/Estuarine unit + Elevation > 5m
		Sensitivity	Geology	Bedrock & Quaternary geology	– Hard bedrock geology less sensitive to erosion than Quaternary deposits	High (3)	– Quaternary deposits
						Low (1)	– Bedrock geology
		Adaptive capacity	Maturity	Quaternary geology; DEM	– Supratidal environments (2-5 m elevation), and to a lesser extent intertidal environments(< 2 m), exhibit past capacity to resist erosion and build elevation – Higher elevations (5-10)m unlikely to be exposed to marine and terrestrial hydrological processes that build elevation	High (1)	– Elevation > 5 m and Elevation < 10 m
						Moderate (2)	– Elevation < 2 m
						Low (3)	– Elevation > 2 m and Elevation < 5 m
	Inundation	Exposure	Deposit type; Elevation	Quaternary geology; DEM	– Marine deposits (lesser extent estuarine deposits) exhibit greater exposure to marine drivers then estuarine and alluvial units, sequentially – Low elevations exhibit greater exposure to marine drivers	High (3)	– Coastal unit + Elevation < 5 m
						Moderate (2)	– Estuarine unit + Elevation < 5m
						Low (1)	– Coastal/Estuarine unit +Elevation>5m; or – Alluvial unit + elevation < 5 m
		Sensitivity	Equal sensitivity				
		Adaptive capacity	Maturity	Quaternary geology; DEM	– Supratidal environments (2-5 m elevation), and to a lesser extent intertidal environments(< 2 m), exhibit recent capacity to resist erosion and build elevation – Higher elevations (5-10)m unlikely to be exposed to marine and terrestrial hydrological processes that build elevation	Low (3)	– Elevation > 5 m and Elevation < 10 m
						Moderate (2)	– Elevation < 2 m
						High (1)	– Elevation > 2 m and Elevation < 5 m

Drivers & Effect		Component	Indicator	Input data set	Explanation	Cell Label (Score)	Cell score and description
Fluvial	Erosion	Exposure	Deposit type; Slope; Elevation;	Quaternary geology; DEM	– Fluvial deposits (lesser extent estuarine deposits) exhibit greater exposure to fluvial drivers – Steep slopes exhibit greater runoff – Low elevations exhibit greater exposure to fluvial drivers	High (3)	– Alluvial unit + Elevation < 5 m – + Slope > 2°
						Moderate (2)	– Alluvial/Estuarine unit + Elevation < 5m
						Low (1)	– Quaternary deposits + Elevation > 5m; or – Coastal unit + Elevation < 5 m
		Sensitivity	Geology	Bedrock & Quaternary geology	– Hard bedrock geology less sensitive to erosion than quaternary deposits	High (3)	– Quaternary deposits
						Low (1)	– Bedrock geology
		Adaptive capacity	Maturity	Quaternary geology; DEM	– Intertidal units have the greatest capacity to build elevation – High elevation Quaternary deposits, particularly alluvial and estuarine units, have the lowest capacity to build elevation due to limited opportunities to deliver sediment.	High (1)	– Elevation < 2 m
						Moderate (2)	– Elevation > 2 m and < 5 m
						Low (3)	– Alluvial/Estuarine unit + Elevation > 5 m
	Inundation	Exposure	Deposit type Slope Elevation	Quaternary geology; DEM	– Marine and estuarine deposits exhibit greater exposure to wave activity and storm surge – Steep slopes exhibit less run-up – Low elevations exhibit greater exposure to wave activity and storm surge	High (3)	– Fluvial + Elevation < 5 m
						Moderate (2)	– Estuarine + Elevation < 5m
						Low (1)	– Fluvial/Estuarine + Elevation > 5m
		Sensitivity	Equal sensitivity				
		Adaptive capacity	Maturity	Quaternary geology; DEM	– Supratidal environments (lesser extent intertidal environments) exhibit past capacity to build elevation	Low (3)	– Elevation < 2 m
						Moderate (2)	– Elevation > 2 m and < 5 m
						High (1)	– Elevation > 5 m

Spatial analysis results

Total vulnerability

The combined effect of marine and terrestrial drivers on erosion and inundation within estuaries in southern NSW can be substantial. The need to consider the effect of marine and terrestrial drivers on estuarine geomorphology is particularly evident for the Shoalhaven River estuary, which exhibited the highest vulnerability of the catchments in this study to marine erosion, marine inundation, fluvial erosion and fluvial inundation in the study area (Figure 4a). In actuality, due to the geomorphology of the Shoalhaven River it only needs to be exposed to either a large marine or terrestrial event for vulnerability to inundation or erosion to be evident (Figure 4b-e). Planned adaptation actions may need to be undertaken to heighten the adaptive capacity of the estuary and limit the exposure of the estuary and nearby floodplains to climate drivers.

Estuaries with the largest catchments typically exhibited the greatest degree of vulnerability (Figure 5). In particular, estuaries with catchment areas exceeding 100 000 ha were commonly found to have vulnerability areas exceeding 2000 ha; these include the estuaries of Bega River, Clyde River, Moruya River, Tuross Lake and Shoalhaven River. However, there were some exceptions to this relationship. Other factors that were found to influence the total area of vulnerability within a catchment include:

- The degree of maturity: This is the case for the Minnamurra River, which exhibited significant vulnerability despite its limited catchment size. Minnamurra River is a mature estuary with almost complete infill of the narrow bedrock valley with marine and alluvial sediments; infilling to this degree creates extensive floodplains that are particularly prone to inundation.
- The shape of the bedrock valley: This is the case for Lake Illawarra. While Lake Illawarra is relatively immature (Roy et al.) and has a relatively small catchment, the catchment is almost entirely within the coastal plain, lying east of the Illawarra escarpment. The estuary bedrock valley is broad, and infill is largely limited to the barrier at the entrance and alluvial infill in the foothills of the Illawarra escarpment, which has created an expansive floodplain in the West Dapto region. The lake is relatively immature as the proportion of infill is low; however the area of the alluvial floodplains is substantial and has been prone to flooding; the frequency of severe flooding in the region is elevated merely by the size of the estuary within a narrow coastal region (Nanson and Hean 1985). The effect of bedrock valley shape on estuarine evolution has been identified by Sloss et al. (2006), but extension of this concept to vulnerability to climate change has not been quantitatively tested.
- The orientation of the entrance (and other entrance features): This is the case for St Georges Basin, where much of the vulnerable area is associated with the extensive coastal barrier deposits at the entrance of the estuary, which formed during the Holocene when marine sands obstructed the entrance of the antecedent Pleistocene valley (Sloss et al., 2011). The Bhewerre barrier, as it is known, is described as ‘the largest and most complex single barrier system in the region’ (Thom, 1987), a factor that was facilitated by the orientation of the estuary entrance and nearby headlands to the prevailing wave direction in the south southeast. The barrier is greater than 2 km width (up to 3.5 km) and 7 km long. Dune development is significant; long-walled transgressive dunes are largely vegetated and extend to heights over 60 m and an active dune is located along the present coastline. While the Bhewerre Barrier has mostly been designated as low vulnerability due to its height largely exceeding 5 m; most of the cells on the barrier were given a low score, rather than no score, due to the accumulation of coastal/estuarine deposits.

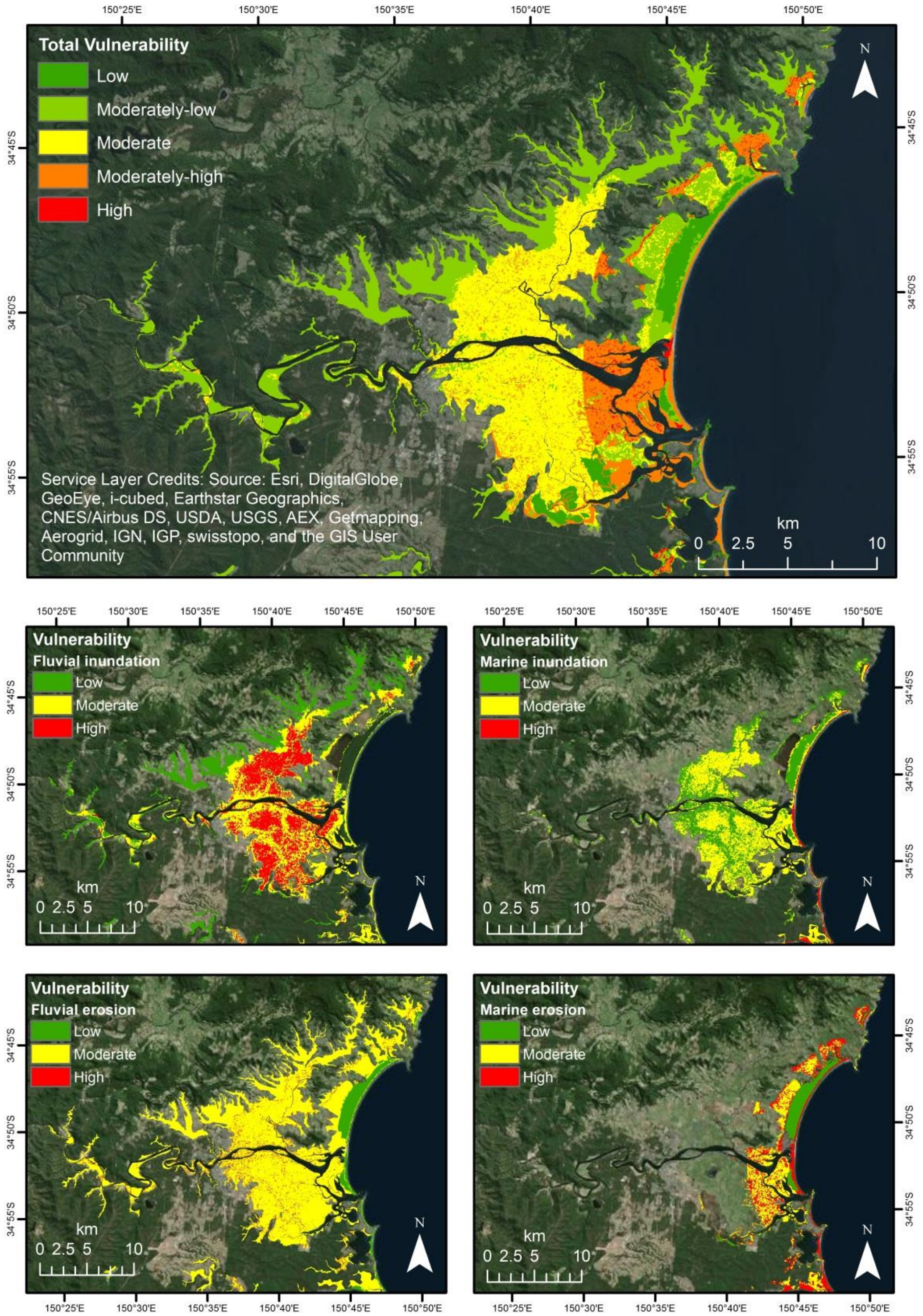

Figure 4: The vulnerability of the Shoalhaven River estuary to coastal and flood hazards, and climate change: a) total vulnerability, and vulnerability to b) fluvial inundation, c) marine inundation, d) fluvial erosion and e) marine erosion.

While the area identified as vulnerable for estuaries with large catchments relates to maturity, shape of the bedrock valley and orientation of the entrance, these factors are less important for smaller catchments. We undertook a simple analysis of the relationship between elevation and area of vulnerability in the region to identify a predictor of vulnerable area across the entire study region (Table 2). The mean elevation of all cells identified as having some level of vulnerability (i.e. low-high) was 15.23 m. A highly significant relationship was evident between the extent of vulnerable areas within catchments and the extent of area below the identified mean elevation of 15 m within catchments (r^2 = 0.9850, $p<0.0001$, Figure 6a). Approximately 93% of the vulnerable cells had a moderately low vulnerability score (i.e. score = 2), and largely constituted foothill alluvial deposits that may be prone to fluvial erosion and inundation associated with storms and high rainfall events. Cells with moderately high to high scores (i.e. score = 4 or 5), constituting 2.6% of all vulnerable cells, had a median elevation of 1.04 and 3.53 m, respectively. Collectively these cells had a mean elevation of 2 m and were largely characterised as low elevation deposits within the coastal floodplain. A significant, though less robust, relationship was evident between the extent of areas with high to moderately high vulnerability and the extent of area below the identified mean elevation of 2 m (Figure 6b).

The Shoalhaven estuary (Figure 5) exhibits the highest degree of vulnerability to coastal hazards and climate change within the region which is primarily a function of the shape of the bedrock valley within the vicinity of the Shoalhaven estuary and the degree of maturity of the estuary. Umitsu et al. (2001) proposed that at the commencement of the last marine transgression, the Shoalhaven floodplain was a large, broad bedrock valley that became confined by an entrance barrier. Levees throughout the floodplain mark previous channels within the delta as it migrated east over the Holocene and as sediment infilled a vast lake that extended from Nowra to the beach ridges of Seven Mile Beach and Comerong Island. Today, the estuarine area of the Shoalhaven River has an extensive floodplain of approximately 15 km width and 20 km length (~300 km^2); and has been classified by Roy et al. (2001) as a mature, completely infilled barrier estuary.

Interestingly, the coastal bedrock valley of the Shoalhaven River and Lake Illawarra are remarkably similar in size, however the evolution of the two estuaries is contrasted, due in large part to the greater delivery of sediment to the estuary from the larger catchment of the Shoalhaven River (7086 km^2), as opposed to the sediment delivered from the smaller, coastal-confined catchment of Lake Illawarra (239 km^2). As a consequence of the contrasted catchment sizes and associated evolutionary histories, the proportion of the Lake Illawarra catchment that is estuary is substantial (35.8 km^2 estuary area; estuary to catchment proportion of 15%) compared to the Shoalhaven River (31.9 km^2 estuary area, estuary to catchment proportion of 0.45%). The outcome of this is that the Lake Illawarra estuary will absorb much of the threat associated with climate change, while the saucer-shaped coastal floodplains of the Shoalhaven River will act as a transitional store for fluvial and marine inundation under future climate change scenarios. The expansive floodplains of the Shoalhaven river are now extensively drained and support a dairy industry as well as a number of smaller communities. While the exposure of this floodplain to the various climate drivers and effects is variable, the distribution of land use across the landscape is also variable and consequently ensures that minimising exposure to climate drivers and increasing the adaptive capacity of the landscape will be complex and will require an integrated approach that accounts for the variance in vulnerability and landuse across the floodplain.

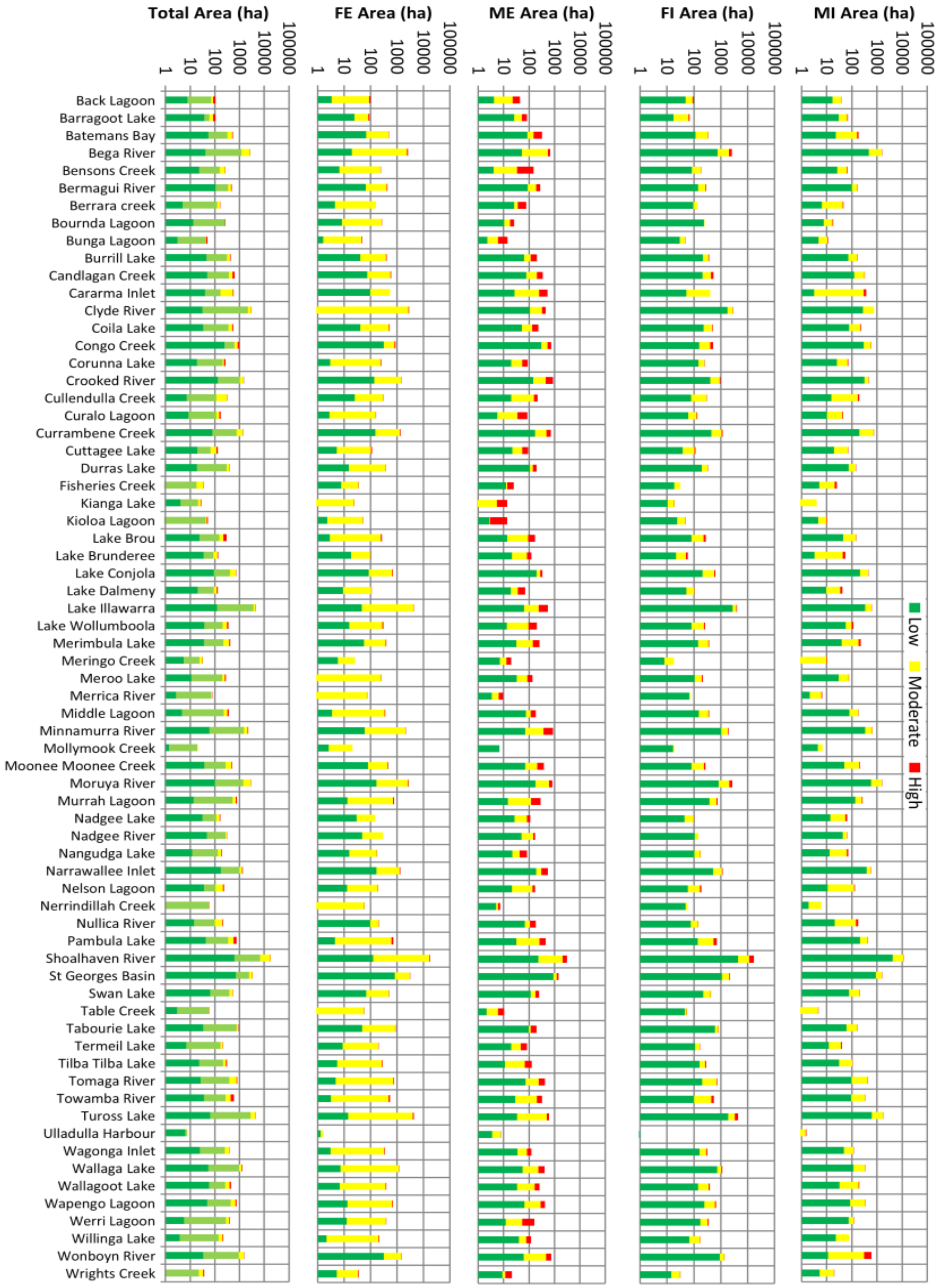

Figure 5: The vulnerable area (ha) within estuaries within the study area: a) total vulnerability, and vulnerability to b) fluvial erosion (FE), c) coastal erosion (CE), d) fluvial inundation (FI) and e) coastal inundation (CI).

Table 2: Area and elevation statistics (mean (x̄), minimum (Min), maximum (Max) and standard deviation (σ)) for the different vulnerability classes in the study region.

Vulnerability class	Area (ha)	Elevation (m)			
		x̄	Min	Max	σ
Low	11578	25.4	-10.7	166.4	31.1
Mod-low	38802	23.1	-14.0	618.2	33.7
Moderate	13806	2.6	-12.3	5.0	1.5
Mod-high	15377	1.8	-15.5	10.0	2.4
High	3198	2.0	-12.7	5.0	2.2
Mod-low and Low	50379	23.6	-14.0	618.2	33.1
Moderate, Mod-high, High	32381	2.2	-15.5	10.0	2.1
Total	82760	15.2	-15.4	618	27.9

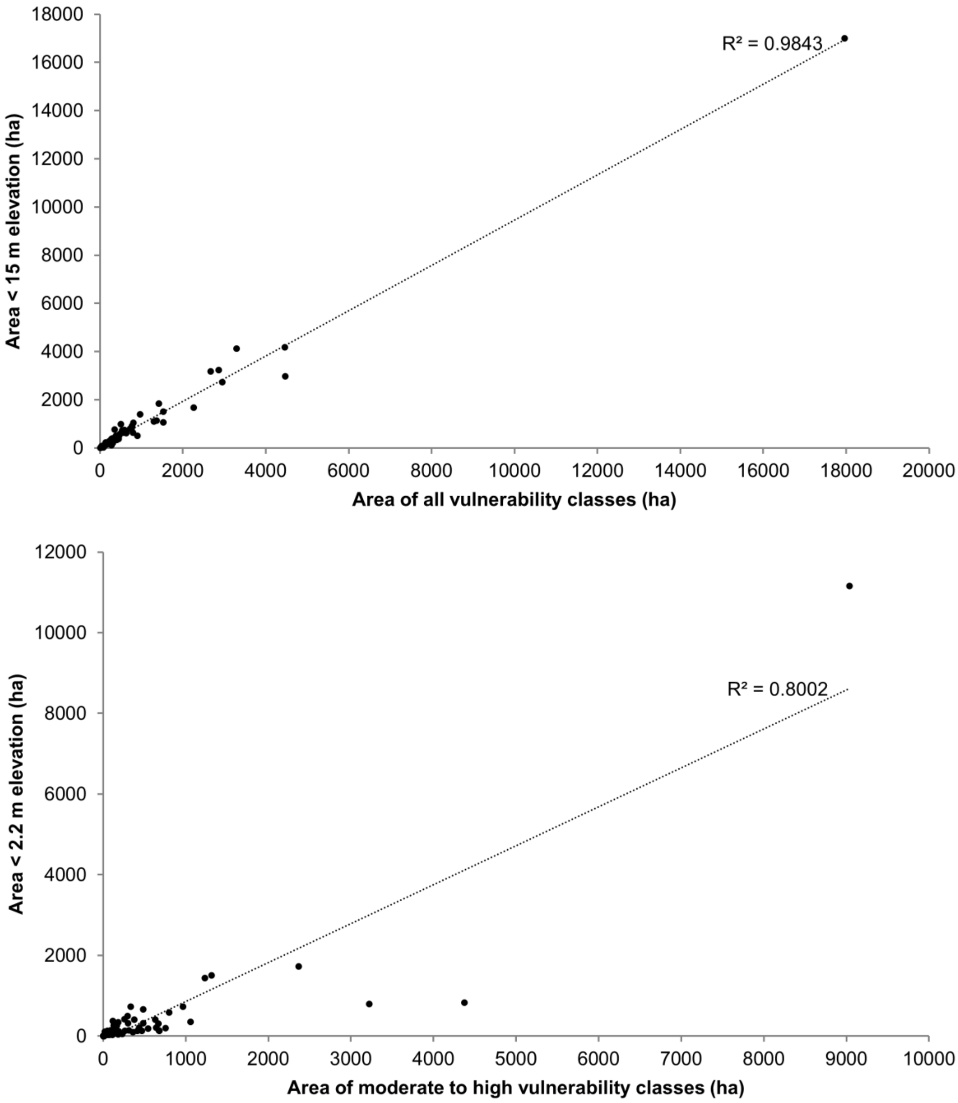

Figure 6: Relationships between a) area of all vulnerability classes and area with elevation less than 15 m within catchments; and b) area of moderate, moderate-high and high vulnerability classes and and area with elevation less than 2.2 m within catchments.

Drivers and Effects

High vulnerability to coastal erosion was evident in most catchments (Figure 5b), although this was largely limited to barriers (beaches) at estuary entrances and did not have a wide distribution across the estuarine floodplain; where much of the coastal agriculture and industry, settlements and infrastructure are located. The beaches of the region are iconic and a highly valued feature for both residents and tourists; the effect of climate change will influence the morphology of these beaches and alter the services provided by these beaches (Stive et al., 2009, Barbier et al., 2011). Attracting greater attention is the vulnerability of assets (buildings and infrastructure) situated on these coastal barriers and attention should now be directed to quantitatively projecting the effect of climate change on these systems so as to identify the most appropriate adaptation option (Woodroffe et al., 2012). In a positive move forward, coastal zone planning studies, such as the Wollongong Coastal Zone Study and Coastal Management Plan (Cardno LawsonTreloar, 2010, BMT WBM, 2012), are now integrating analyses of coastal erosion with flood studies to quantify the likely impact of climate change on buildings and infrastructure in the coastal zone.

High vulnerability to fluvial inundation (Figure 5e) was significant for some estuaries; particularly those with larger catchments, such as Bega River, Lake Illawarra, Minnamurra River, Moruya River, Shoalhaven River and Tuross Lake. Matched pairs t-test indicated that while the difference between the values was not significant ($p=0.2143$), the area identified as highly vulnerable to fluvial inundation more commonly exceeded the area vulnerable to marine erosion. This will have significant ramifications for settlements, industry and infrastructure associated with these environments.

The effects of marine inundation typically influenced a smaller areal extent, although some exceptions were evident. Of particular interest is Wonboyn River, where the orientation of the estuary entrance to the southeast has facilitated the progradation of an extensive, low profile barrier at the estuary entrance; creating a feature that is particularly vulnerable to washover and inundation. The Shoalhaven River also has extensive areas that may be exposed to washover and inundation during large marine events; this is an artefact of the large Seven Mile Beach ridge plain situated at the estuary entrance. The erosion effects of fluvial events are not projected to be significant and appear to be limited in extent to channels and areas with steep slopes.

Conclusions

Estuaries are exposed to both marine and terrestrial drivers and the combination of these effects amplifies climate change influences within estuaries and their adjacent floodplains. The approach employed in this study integrates a conceptual framework of the geomorphic response of estuaries to Holocene sea-level rise with a framework for assessing vulnerability to climate change. This approach constitutes a first-pass assessment of estuary vulnerability to climate change and provides a relative indication of the vulnerability of land, represented by raster cells of approximately 30 m x 30 m, to various drivers and effects related to coastal hazards and climate change. It does not provide a definitive indication of areas that will be impacted by climate change, or the degree of impact that will occur; rather it is a qualitative analysis that can be used to guide the prioritisation of vulnerable areas for further assessment. For areas that have been prioritised for further vulnerability assessment, we advocate the use of high resolution spatial modelling that employs empirical data to provide an indication of the degree of vulnerability and the probability of occurrence, such as the methods of Rogers et al. (2005, 2006).

The coastline of southern NSW is characterised by numerous settlement types ranging from coastal cities with populations exceeding 100 000 to small, remote coastal hamlets with populations less than 15 000 (Gurran et al., 2006); the majority of these settlements are associated with an estuary. This analysis also highlighted the need to direct planning and management attention in southern NSW towards these estuarine shorelines and surrounding floodplains where the impacts of coastal and flood hazards are likely to have greater effect on communities. In the study region, this was particularly evident for the Shoalhaven estuary, which exhibited the greater degree of vulnerability.

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