MANGROVE AND SALTMARSH THREAT ANALYSIS IN A LARGE CITY: OPPORTUNITIES AND CHALLENGES FOR MANAGEMENT

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Abstract
Climate change adaptation options for natural systems are particularly challenging in high density urban settings. We model the vulnerability of estuarine vegetation (mangroves, saltmarshes and *Casuarina* forest) to SLR (SLR) in Australia's most populous city, Sydney, and conduct a detailed assessment of impacts and adaptation options for a densely urbanised estuary, the Cooks River. Our modelling demonstrates a range of opportunities for the preservation and, in some cases, expansion of estuarine vegetation area under SLR, though this is largely dependent on the degree of flexibility applied in the management of existing open space. Mangrove area increases under a high SLR scenario, more so than under a low SLR scenario, due to opportunities for landward colonisation. However, this would require estuarine vegetation expansion and land-use conversion of recreational, industrial or private land. Sediment nourishment emerges as a potentially cost-efficient means of preserving wetlands. The mix of wetland types is likely to change without active management, with higher proportion of mangrove and substantially less saltmarsh under all scenarios. Implementation of living shorelines, as opposed to hard defensive structures, could be incentivised. This could be achieved by planning concessions, 'payment for ecosystem services' such as managing 'blue carbon' values, and zoning controls that promote visual amenity and ecological adaptation.

Introduction
Climate change and its effects on sea level, ocean currents, storms, rainfall, run-off and hydrodynamics along coastal margins is of particular concern for managers tasked with protecting both natural and built assets. In Australia, where more than 85% of the population lives within 50 km of the coast (Trewin, 2004), climate change is and will continue to be a key threatening process. As cities are dominated by buildings and associated infrastructure, research attention has largely focussed on the effects of climate change on built assets. However, natural assets also have significant environmental, social and economic value (Barbier et al., 2011). The most recent estimate of the value of global ecosystem services indicated substantial economic value for functions such as climate regulation, nutrient cycling, erosion and sediment retention, and refuge for commercially important and non-commercially important fauna (Costanza et al., 2014). In addition, urban ecosystem services will differ from those occurring in regional areas primarily due to greater use by a larger population and their contribution to public health and quality of life for urban populations (Bolund and Hunhammar, 1999). Spatial land use planning has a significant influence on the delivery of ecosystem services in urban landscapes and planning for the effects of climate change on natural assets will be essential for the protection, maintenance and creation of urban ecosystem services.

Sydney, Australia's most populous city, provides a unique case study for exploring the effects of climate change on urban ecosystems and the services they provide. With a large population clustered along the coastline and estuarine shorelines, urban ecosystems are restricted in their distribution. This is particularly the case for intertidal ecosystems, such as mangrove and saltmarsh, for which natural distribution is already restricted to the upper half of the tidal range, approximately between mean sea level at the seaward margin and highest astronomical tide at the landward margin (Rogers et al., 2017). Like other urban areas, the distribution of mangrove and saltmarsh is contained within the margins of urban sprawl, with significant losses associated with land-cover conversion from wetland to other land uses. In addition developments at wetland margins restrict landward expansion of wetlands, progressively constraining the space available for estuarine vegetation and termed ‘coastal squeeze’ (Doody, 2004; Pontee, 2013). However, unlike other Australian cities, the distribution of mangrove and saltmarsh is further constrained by factors inherited from the geology of the Sydney Basin. In this regard, sediment delivery during the Quaternary period to the deeply incised drowned river valleys of the Sydney Basin (Roy et al., 2001) was not high enough for formation of expansive depositional environments suitable for the establishment of large mangrove forests and saltmarsh plains (Saintilan and Rogers, 2013). Consequently, mangrove and saltmarsh development within Sydney Harbour, Port Hacking and the Hawkesbury River is restricted to narrow margins along these drowned river valley estuaries or within small fluvial delta regions, where bedrock depth is shallow and hydrodynamic energy is low enough to facilitate sediment deposition and vegetation establishment.

The mangrove and saltmarsh extent in the Sydney region is also a highly reduced remnant of its pre-European extent. It is difficult to estimate the original area of mangrove and saltmarsh across the region, but significant developments up until the 1970’s resulted in the conversion of large areas of mangrove and saltmarsh for commercial, residential and recreational facilities. Examination of early plans and documents (McLoughlin, 1987, 2000a; McLoughlin, 2000b) has suggested that sedimentation associated with land clearing for development provided fresh habitat for mangroves head-ward of their pre-20th century extent in the Lane Cove and Parramatta Rivers. Comparison of historic and aerial photography has established a consistent increase in mangrove extent and subsequent saltmarsh decline in intertidal flats across the region (Saintilan and Williams, 1999). The cause of mangrove encroachment into saltmarsh across southeast Australia is being investigated and is consistent with a global trend of mangrove proliferation at poleward limits of mangrove range (Saintilan et al., 2014). Best available science for the southeast Australian region suggests changes in relative sea level are likely to have been an important driver (Rogers et al., 2006).

Mangroves and saltmarshes are responsive to climate change due to their position within narrow zones defined by tidal regime and mean sea level and their sensitivity to changes in atmospheric carbon dioxide, temperature and rainfall (McKee et al., 2012). Many of the changes evident over the past few decades are consistent with response to climate change and associated SLR (Cahoon et al., 2006; Rogers et al., 2005b; Woodroffe et al., 2016). A stepwise approach to assess opportunities and challenges for estuarine vegetation management in the Sydney region was undertaken. This included a first-pass broad-scale assessment of mangrove and saltmarsh vulnerability for the Sydney Coastal Councils Group region using the vulnerability framework advocated in the third assessment report of the Intergovernmental Panel on Climate Change (IPCC). Medium-resolution assessment of mangrove and saltmarsh vulnerability to SLR was then conducted for the Cooks River catchment. This was undertaken using a readily available spatial model (Clough et al., 2010; Craft et al., 2009) that could be used to provide an indication of the extent of estuarine vegetation under a range of SLR, management and land-use scenarios. SLR adaptation approaches for coastal shorelines, including mangrove and saltmarsh, were subsequently considered; and we identified specific adaptation needs of mangrove and saltmarsh in the Sydney region. Adaptation options and the locations where such options might be implemented were recommended, and the principles and practices related to these adaptation options are discussed.

Methods

Study site

The city of Sydney is situated around the infilled drowned river valleys of Sydney Harbour, the Georges River, the Cooks River, the Hawkesbury River and Port Hacking. Mangrove and saltmarsh development is typically restricted to shorelines and fluvial deltas on tributaries where bedrock depth is shallow and hydrodynamic energy facilitates the accumulation of sediments over time (Figure 1a). The study focussed on estuarine vegetation (mangrove, saltmarsh and *Casuarina*) occurring within the local government areas of the Sydney Coastal Councils Group, a regional organisation of councils (SCCG) (Figure 1b). To identify potential pathways for expansion of estuarine vegetation along estuaries, the study area included all estuarine vegetation associated with the SCCG as well as low-lying land associated with the Wolli Creek. This study focussed on low-lying sediments that have accumulated over the Quaternary period and upon which mangrove and saltmarsh develop (Figure 1c).

Medium resolution assessment was data intensive and therefore restricted to a small spatial extent. The Cooks River, the most highly urbanised estuary of the Sydney region, was chosen as the focus study site for further modelling (Figure 1d). The Cooks River is a mature, wave-dominated estuary, which enters the large coastal embayment of Botany Bay. Characteristic of wave-dominated estuaries, the estuary entrance has been infilled with sediment over time forming a coastal barrier that restricts both flood and ebb-tides into the estuary and results in measureable tidal attenuation along the estuary. Our reasoning for using this study site was that if climate change adaptation for estuarine vegetation is achievable in the Cooks River, it could potentially be accommodated elsewhere in Australia.

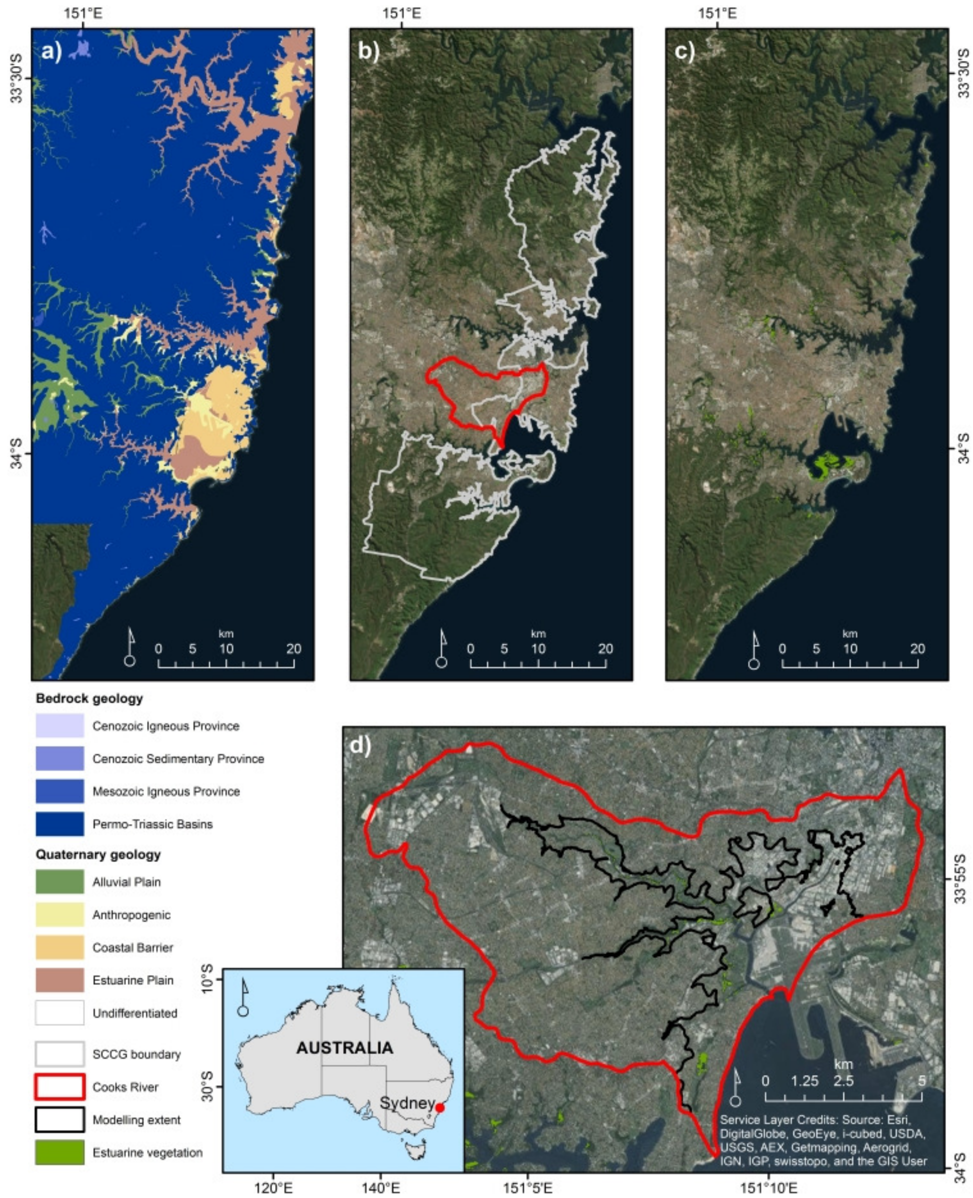

Figure 1: The study site location and features of the study site, including a) bedrock and Quaternary geology of the Sydney Basin, b) extent of the Sydney Coastal Councils Group regional organisation of councils and the Cooks River study area, and c) extent of estuarine vegetation within the Sydney Basin.

Broad-scale Vulnerability Assessment

The broad-scale vulnerability assessment focussed on biophysical aspects and builds upon a previously established approach (Rogers and Woodroffe, 2016). The initial assessment used a raster-based approach within GIS using the ArcGIS spatial analyst extension. Input datasets were used as proxy indicators of estuarine vegetation exposure, sensitivity and adaptive capacity. These included:

- *Shuttle Radar Topography Mission-derived 1 second Digital Elevation Model (SRTM-DEM)*. Used to exposure of coastal landforms to the effects of inundation and erosion. The SRTM-DEM is a raster surface with a cell size of approximately 30 m and elevation to the nearest metre.
- *Coastal Quaternary geology mapping.* Used to characterise the sensitivity of coastal landforms to inundation and erosion. The NSW Coastal Quaternary Geology (Troedson et al., 2004), was recently revised to incorporate the Sydney metropolitan area (Troedson, 2015) and constitutes a significant increase in the coverage of coastal Quaternary geology mapping of NSW. This mapping differentiates lithified (bedrock) from unlithified Quaternary sediments that are more sensitive to erosion. Quaternary sediments can be further classified on the basis of the depositional environment in which they were deposited.

– *Sydney's salty vegetation mapping*. Used to characterise the adaptive capacity of coastal ecosystems to inundation and erosion. This dataset was originally prepared by OEH (2013) and a subset of 53 vegetation communities were selected by the Working Group of the SCCG Sydney's Salty Communities program following a series of workshops with member councils within the Sydney Coastal Councils Group. Vegetation communities pertinent for this assessment and which incorporated mangrove, saltmarsh and *Casuarina* forests included i) Coastal swamp paperbark-swamp oak scrub, ii) Estuarine swamp oak forest, iii) Estuarine saltmarsh, iv) Estuarine reedland, and v) Estuarine mangrove forest.

Composite choropleth maps were prepared that provided a relative indication of the vulnerability of estuarine vegetation in the study region to i) inundation and ii) erosion. To generate these maps, input raster surfaces were processed according to the geomorphological and ecological criteria detailed in Table 1. The extract function was used to select 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. The composite choropleth maps characterising inundation and erosion vulnerability were generated by adding raster surfaces that characterised the exposure, sensitivity and adaptive capacity of cells using the raster calculator tool. A final raster surface of the vulnerability of cells to both inundation and erosion was compiled by adding the original cell scores for inundation and erosion using the raster calculator tool to create an integrated raster surface. To assist with reporting of vulnerability, cell scores were reclassified into five classes ranging from low to high vulnerability.

As the approach considered both ecological and geomorphological factors contributing to the vulnerability of mangrove and saltmarsh, the assessment broadly applied to depositional areas, as defined by Quaternary geology mapping, and was not limited to areas that currently support mangrove and saltmarsh. The initial assessment therefore did not account for the occurrence of built-up areas or incompatible land-uses. It also did not account for the effect that SLR may have on the future distribution of mangrove and saltmarsh. Consequently, the assessment was constrained using masking techniques in ARCGIS to exclude any built-up areas or areas of incompatible land-use. The analysis also specifically considered estuarine vegetation distribution being constrained on the basis of a) current estuarine vegetation distribution, and b) possible future distributions of mangrove and saltmarsh associated with SLR on the basis of *90cm water level projections* data layer derived for the study area (McInnes et al. 2012).

Table 1: Input data sets, explanation of data need and cell characterisation (label and description) for raster layers of inundation and erosion exposure, sensitivity and adaptive capacity. Cell scores were assigned to raster surfaces on the basis of the indictors and their relationship to various components of vulnerability.

Effect	Component	Input data	Explanation	Cell label	Cell description
Inundation (I)	Exposure (IE)	Elevation (SRTM-DEM)	Lower elevations more exposed to inundation by proximity, higher elevation less exposed. Based on bath-fill approaches that have been widely used as an indicator of vulnerability (e.g. DCC, 2009). Rogers et al. (2012) demonstrates why bath-fill approaches do not constitute a high resolution, quantitative assessment.	High (3)	Elevation: 0-1 m
				Mod. (2)	Elevation: 1-2 m
				Low (1)	Elevation: 2-5 m
				Nil (0)	Elevation: > 5 m
	Sensitivity (IS)	Quaternary geology; Slope (SRTM-DEM derived)	Low slopes indicative of Quaternary sediment accumulation, which creates ideal habitat for estuarine vegetation. Low slopes indicative of greater sediment deposition and wetland development, and less sensitivity to sediment movement. This is synonymous with mature estuaries exhibiting greater mangrove and saltmarsh development than immature estuaries (Roy et al., 2001), though applied at a smaller spatial scale.	High (3)	Quaternary geology + Slope>5°
				Mod. (2)	Quaternary geology + Slope 2-5°
				Low (1)	Quaternary geology + Slope <2°
				Nil (0)	Bedrock geology
	Adaptive capacity (IAC)	Vegetation (Sydney's Salty Veg)	Mangrove (typically at lower elevations) is less sensitive to inundation changes due to improved capacity to build elevation through accretion and plant productivity, than saltmarsh. Based on relationships between elevation gain and vegetation within southeastern Australia (Rogers et al., 2005a; Rogers et al., 2006). Adjoining upland vegetation sensitive to salinity changes (Greenwood and MacFarlane, 2006).	Low (3)	Coastal Swamp Paperbark-Swamp Oak Scrub, Estuarine Swamp Oak Forest
				Mod. (2)	Saltmarsh, Estuarine reedland
				High (1)	Mangrove
				Nil (0)	Other Veg
Erosion (E1)	Exposure (EE)	Elevation	Lower elevations more exposed to erosive wave action.	High (3)	Elevation: 0-1 m or Marine sed's
				Mod. (2)	Elevation: 1-2 m
				Low (1)	Elevation: 2-5 m
				Nil (0)	Elevation: > 5 m
	Sensitivity (ES)	Quaternary geology	Quaternary sediments more sensitive to erosion, particularly fine material associated with fluvial deposits, than bedrock geology.	High (3)	Fluvial sediments
				Mod. (2)	Estuarine sediments
				Low (1)	Marine sediments (undiff, anthro)
				Nil (0)	Bedrock geology
	Adaptive capacity (EAC)	Vegetation	Mangrove has greater capacity to buffer wave action and accumulate sediments than saltmarsh (Kelleway et al., 2017).	Low (3)	Coastal Swamp Paperbark-Swamp Oak Scrub , Estuarine Swamp Oak Forest
				Mod. (2)	Saltmarsh, Estuarine reedland
				High (1)	Mangrove
				Nil (0)	Other Vegetation

Medium-resolution assessment of the Cooks River

The medium-resolution assessment of mangrove and saltmarsh vulnerability to SLR was undertaken using the Sea Level Affecting Marshes Model (SLAMM). SLAMM is a widely used mangrove and saltmarsh focused spatial landscape model that simulates six primary processes affecting the survival of estuarine vegetation with long term SLR, namely inundation, erosion, overwash, saturation, salinity and accretion. The model is used primarily to simulate the changes in wetland boundaries and shoreline modifications with increasing sea level through the inundation and accretion functions (Clough et al., 2014; Galbraith et al., 2002; Linhoss et al., 2014).

As mangrove and saltmarsh communities lie within narrow elevation ranges associated with tidal inundation, it is important to consider tidal attenuation when modelling the effect of SLR on the Cooks River. The parameterisation of tidal range within SLAMM, which is conceptualised as a flat surface with no slope, however, does not sufficiently capture the tidal effects throughout the estuary (Mogensen and Rogers, in review). This can be improved by discrete parameterisation of tidal range in SLAMM, thereby partially accounting for the effect of tidal attenuation on vegetation distribution. To do this, a continuous tidal range surface was created, following the method of OEH (2014). From the resulting surface, subsites were delineated based on 0.1 m variations in tidal range along the Cooks River (Figure 2) and a discrete, mean tidal range value was calculated from each subsite to be utilised within SLAMM.

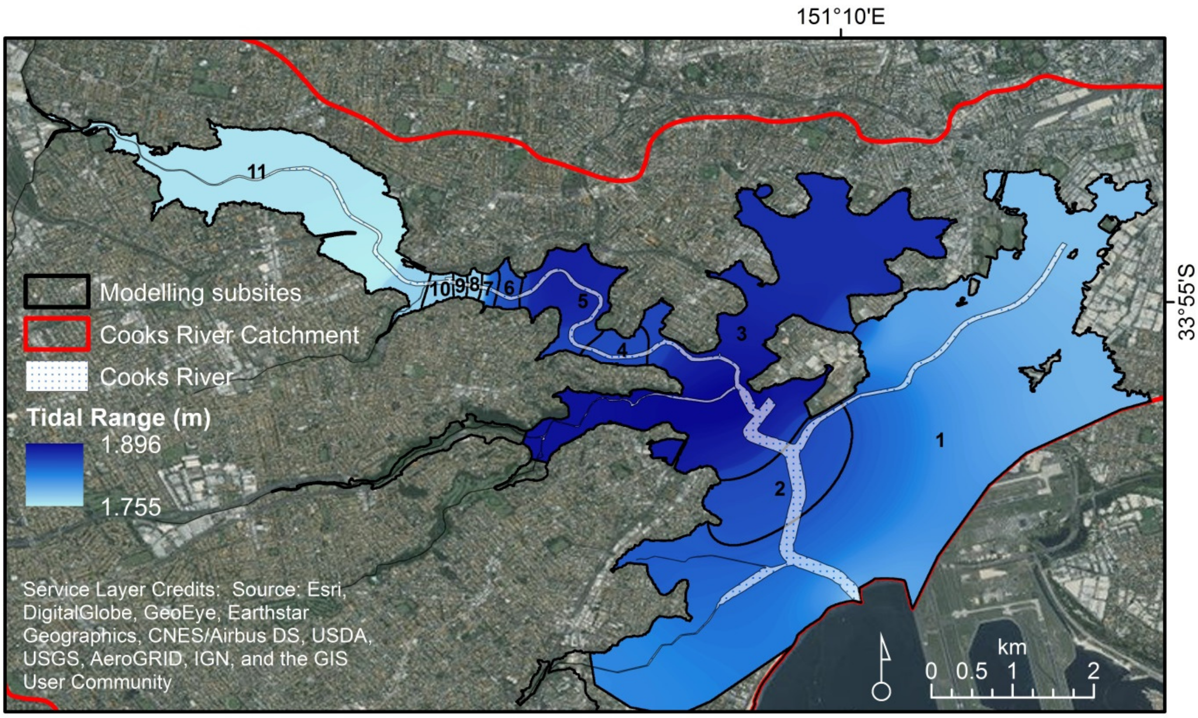

Figure 2: Modelled tidal range surface and derived subsites used within SLAMM. Outer line represents the modelling extent of the Cooks River study site.

SLAMM requires information regarding elevation, slope, vegetation communities, elevation boundaries of these communities, accretion rates for the wetland vegetation and an historic trend in SLR. Topographic data in the form of Lidar (light detection and ranging) point files and derived digital elevation models (DEM) were the primary input data for SLAMM. The Lidar survey of the Cooks River region was flown in 2013 and the derived DEM utilised in this study has a horizontal spatial resolution of 5 m and reported vertical RMSE of 1 m. A slope surface was derived from the 5m DEM and utilised within the model.

Vegetation input into SLAMM is based on categories of the US National Wetlands Inventory (Cowardin et al., 1979). Analogous vegetation classes and spatial distribution of the vegetation classes were derived from digital mapping of the *Native Vegetation Communities of the Sydney Metropolitan Area* (OEH, 2013). Vegetation classes are reported here as tidal flat, mangrove, saltmarsh, reedland, *Casuarina* for convenience. Developed areas were defined as built-up areas, including urban, industrial and commercial zones. These areas were delineated from the *Standard Instrument Local Environmental Plan - Land Zoning (LZN)* (DPE, 2013) and *Inner Sydney Regional Cadastral Survey* 2012 acquired from the Sydney Coastal Councils Group. Areas within the study site not classified as vegetation or developed were deemed to be undeveloped areas. Within SLAMM, each vegetation class is assigned a certain elevation range within which it will typically occur. For this study, elevation ranges for each vegetation and land use category were assigned with respect to the tidal range, where the unit of measurement for elevation was the half tide unit (half of the tidal range set for a particular site), in order to account for the variation in tidal range and, thus, vegetation distribution with respect to elevation throughout the study site. Elevation ranges were determined based upon analysis of the 5m DEM and derived slope surface with respect to the vegetation distribution at 2013. Further refinement of elevation boundaries was conducted during model calibration to ensure model error (the difference between modelled and observed vegetation distributions) at 2013 was no greater than 10%.

Accretion rates of wetland vegetation can be modelled in a variety of ways in SLAMM. Within this study, the accretion module was implemented and rates of surface elevation change were used as they incorporated subsurface processes of autocompaction. The accretion module was parameterised on the basis of empirical relationships derived from Surface Elevation Table-Marker Horizons (SET-MH) from a site of similar characteristics, Homebush Bay (Rogers et al., 2005a). For mangrove and saltmarsh, these were modelled in relation to elevation, with a minimum of 0.1 mm/yr grading to 0.21 mm/yr in saltmarsh, and a minimum of 0.21 mm/yr grading to 2.63 mm/year in mangrove (Bowie, 2015).

Tidal data spanning the time period 1990-2013 were analysed and mean SLR determined for the study site, estimated to be 2.8 mm/yr. This value was consistent with the global mean SLR for the period 1993- 2010 published by the IPCC (IPCC, 2013) and was utilised as the historic SLR within SLAMM.

Once parameterised and calibrated for the study site, SLAMM was implemented to examine vulnerability of saltmarsh and mangrove under three SLR scenarios (Stocker et al., 2013: low (RCP 2.6), intermediate (RCP 4.5) and high (RCP 8.5). These SLR scenarios were time-adjusted to fit the modelling period, resulting in a projected rise of 0.322 m, 0.592 m and 1.022 m respectively to 2100 compared to 1990 sea-level. Modelling was first conducted to simulate a scenario in which built-up areas were maintained over time (i.e. developed areas protected and simulates coastal squeeze effects), prohibiting movement of vegetation to higher elevations designated as built-up areas. Keeping all parameters constant, an additional three SLR scenarios (low, intermediate and high) were simulated in which built-up areas were permitted to convert to a vegetation class over time (i.e. developed areas unprotected and coastal squeeze effects minimised). This was examined using ArcGIS (v.10.4.1) by determining the difference in modelled vegetation extent at 2100 when developed areas were maintained and when vegetation was permitted to occupy designated built-up areas. Spatial and statistical data on the conversion of vegetation and land use classes between the initial year of modelling, 2013, and 2100 was also conducted (i.e. change detection analysis). From such information, patterns of vegetation change and, by extension, the effects of SLR on a variety of vegetation communities were able to be examined.

Results

Broad-scale Vulnerability Assessment

The assessment of erosion, inundation and vulnerability is subject to assumptions about flexibility in land-use conversion and future pathways for changes in vegetation distribution. The spatial distribution of estuarine vegetation vulnerability based on assessments assuming no changes in land-use and with vegetation distribution constrained to current extents, and possible future vegetation distribution presuming 90cm SLR, are illustrated in Figure 3 for the Botany Bay region. The proportion of wetland exhibiting moderately high to high vulnerability was less than 13% of existing vegetation area and less than 8% of the potential future vegetation area when accounting for SLR (Table 2). The proportion of wetland area assigned moderately high to high vulnerability based on potential future vegetation area was lower as landward areas that convert from other land-use to wetland will exhibit lower vulnerability due to their higher elevation, thereby resulting in a larger proportion of the future wetland area having moderate to low vulnerability. However, the absolute area identified as moderately high to high vulnerability increased by more the 50% when SLR was incorporated in the assessment. Overall, it is probable that wetland area may increase substantially with SLR providing land-use conversion is facilitated, and much of this increase is associated with areas of lower vulnerability.

Table 2: Area (ha) and proportion of total area (%) with low to high vulnerability. Estimates are based on the current distribution of estuarine vegetation, and possible vegetation distribution under a 90cm SLR projection scenario.

Vulnerability Class	Cell Score	Estuarine vegetation		Estuarine vegetation with 90cm SLR projection	
		Area (%)	**Area (ha)**	**Area (%)**	**Area (ha)**
Low	1-3	52.45	3.29	267.66	6.07
Moderately low	4-7	682.34	42.79	2044.66	46.36
Moderate	8-11	658.91	41.32	1787.75	40.54
Moderately high	12-15	191.61	12.02	300.70	6.82
High	16-18	9.18	0.58	9.35	0.21
	Totals	**1594**	**100**	**4410**	**100**

Medium- resolution assessment of the Cooks River

When allowing for an assumption that developed land was able to convert to wetland classes where possible (i.e. coastal squeeze effects were minimised) approximately 199 ha of developed land was projected to convert to *Casuarina*, mangrove or freshwater wetland under a high SLR scenario (Figure 4, Table 3). This contrasts with the area of developed land projected to convert under a low SLR scenario, which was in the order of 18 ha and primarily composed of *Casuarina*. The overall pattern was the conversion of higher tidal range vegetation classes to lower tidal range vegetation classes or open water, with this pattern exacerbated under a high SLR scenario. Under a low SLR scenario, there was projected to be virtually no loss of mangrove extent, and significant gains through the conversion of undeveloped land and *Casuarina* to mangrove. Saltmarsh area changed little, while *Casuarina* exhibited the largest change in area with 70 ha converting to mangrove under a low SLR scenario. Under a high SLR scenario the model projected conversion of 9 ha of mangrove habitat to lower intertidal tidal flat. Significant gains in mangrove extent were modelled to occur through the conversion of developed land (148 ha), undeveloped land (134 ha) and *Casuarina* (6 ha) to mangrove. However, reductions in saltmarsh extent were greater under a high SLR scenario, declining to 16 ha, with 2.5 ha converting to tidal flat. Tidal flat increased in area by 33 ha with significant conversions from mangrove (9 ha), *Casuarina* (7 ha) and undeveloped land (13.36 ha) to tidal flat under a high SLR scenario.

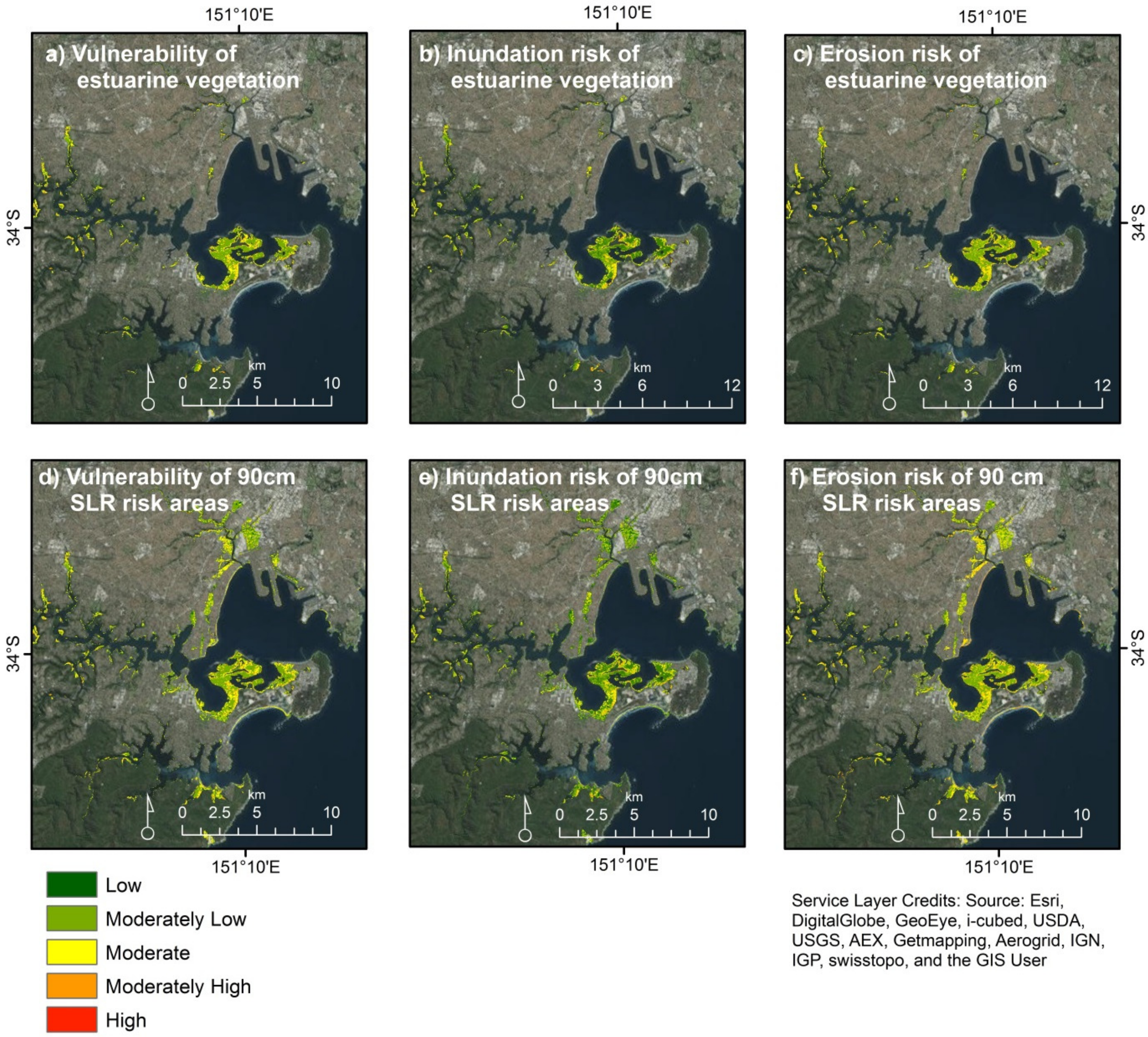

Figure 3: a) Vulnerability assessment, b) inundation and c) erosion assessment of estuarine vegetation at Botany Bay, and with a 90cm SLR projection zone included.

When the planning assumption excluded the conversion of developed land to other classes the overall outcome for wetland vegetation was a reduction in wetland area (Figure 4 a-b). For example, under a low SLR scenario the model projected a mangrove area of 51 ha, contrasting with an area of 77 ha when conversion of developed land to wetland vegetation was allowed; under a high SLR scenario, these differences were exacerbated with only 130 ha of mangrove projected when developed land was protected from conversion compared to 292 ha when conversion of developed land to wetland vegetation classes was allowed. There was little difference in the outcome for saltmarsh between the model projection with or without conversion of developed land to vegetation classes, however the differences were substantial for *Casuarina* under both a high SLR scenario (27 ha without developed land conversion, 78 ha with conversion of developed land), and low SLR scenario (7.6 ha without developed land conversion, 46 ha with conversion of developed land).

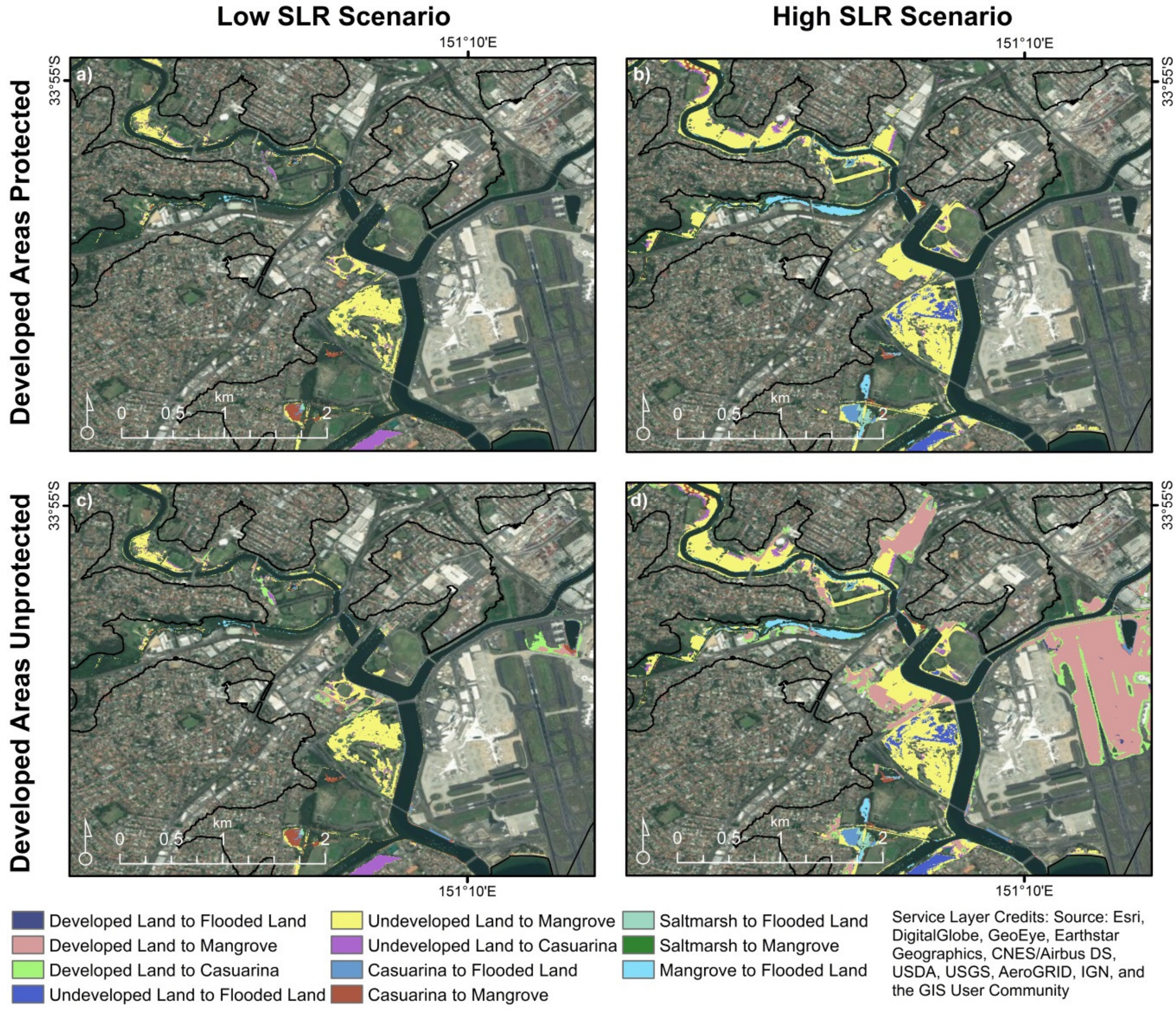

Figure 4: Change detection analysis comparing current vegetation distribution (2013) with projected vegetation distribution (2100) under: a) low SLR scenario with developed land protected from land use changes; b) high SLR scenario with developed land protected from land use changes; c) low SLR scenario with developed land able to convert to other land uses; and d) high SLR scenario with developed land able to convert to other land uses.

Table 3: Change in area (ha) of vegetation classes from 2013 (columns) to 2100 (rows) based on planning assumptions that developed land is either protected or unprotected from land cover conversion, and high and low SLR scenarios.

		Vegetation Class		Developed Land	Undeveloped Land	*Casuarina*	Saltmarsh	Mangrove	Tidal Flat	Estuarine Water
				2013						
Develop Areas Unprotected	Low SLR Scenario (RCP 2.6)	Developed Land	2100	1975.39	0	0	0	0	0	0
		Undeveloped Land		0	509.51	0	0	0	0	0
		Casuarina		9.87	13.35	20.65	0	0	0	0
		Saltmarsh		0	0	0	18.71	0	0	0
		Mangrove		8.50	45.91	8.51	0.17	16.12	0	0
		Tidal Flat		0	0.17	2.08	0.22	0.83	0.20	0
		Estuarine Water		0	0	0.36	0	0	0.01	120.03
	High SLR Scenario (RCP 8.5)	Developed Land		1793.90	0	0	0	0	0	0
		Undeveloped Land		0	413.48	0	0	0	0	0
		Casuarina		50.25	7.74	17.07	0	0	0	0
		Saltmarsh		0	0	0	15.95	0	0	0
		Mangrove		147.61	133.74	5.90	0.60	7.42	0	0
		Tidal Flat		0.58	13.36	6.77	2.51	9.16	0.01	0
		Estuarine Water		0.10	0.03	1.85	0.03	0.40	0.21	120.03
Develop Areas Protected	Low SLR Scenario (RCP 2.6)	Developed Land		1993.77	0	3.09	0	0.52	0.02	0
		Undeveloped Land		0	509.51	0	0	0	0	0
		Casuarina		0	13.35	20.65	0	0	0	0
		Saltmarsh		0	0	0	18.71	0	0	0
		Mangrove		0	45.91	6.52	0.17	15.67	0	0
		Tidal Flat		0	0.17	1.32	0.22	0.79	0.20	0
		Estuarine Water		0	0	0.03	0	0	0	120.03
	High SLR Scenario (RCP 8.5)	Developed Land		1993.77	0.00	3.09	0	0.52	0.02	0
		Undeveloped Land		0	413.48	0.00	0	0	0	0
		Casuarina		0	7.74	17.07	0	0	0	0
		Saltmarsh		0	0.00	0.00	15.95	0	0	0
		Mangrove		0	133.74	5.29	0.60	7.23	0	0
		Tidal Flat		0	13.36	5.31	2.51	8.84	0	0
		Estuarine Water		0	0.03	0.84	0.03	0.39	0.20	120.03

Discussion

The first pass assessment provided a useful means of identifying areas that may convert to coastal wetland, particularly under future conditions of SLR, and established that the Cooks River, one of the most heavily urbanised estuaries, offers significant opportunities for estuarine vegetation adaptation to SLR, though the medium resolution analysis indicated that some vegetation communities fare better than others. When developed areas were unprotected, allowing for landward encroachment across a range of current land-uses (i.e. assuming no barriers emplaced), mangrove extent increased under all scenarios and was primarily limited to lower reaches of the Cooks River (Figure 4). The best outcomes for mangrove extent were achieved under the highest SLR scenario with developed areas unprotected, under these conditions mangrove was projected to increase by approximately 800% from a starting extent of 16 (ha). Conversely, saltmarsh extent diminished under the high SLR scenarios and was restricted to the upper portions of tributaries. Saltmarsh extent was projected to decline between approximately 2-17% from a baseline extent of up to 32 ha.

Actual outcomes for estuarine vegetation will therefore be profoundly influenced by land-use planning decisions. For example, the model projected conversion of part of Sydney Airport to mangrove under a high SLR scenario or a complex of mangrove and *Casuarina* under a low-SLR scenario; however both are likely to be prevented due to activities to safeguard infrastructure. In Sydney Harbour and its tributaries, seawalls armour in excess of 50% of the shoreline (Bulleri and Chapman, 2010) that would prevent landward migration. In other circumstances, however, there may be opportunities for the creation of "living shorelines" (Currin et al., 2010), which promote mangrove and saltmarsh extent and SLR adaptation. To date, the living shorelines approach has not been widely utilised in Australia, despite benefits for coastal resilience as well as other ecosystem benefits, such as nursery habitat to threatened, commercially and recreationally important species, and carbon sequestration and storage (Davis et al., 2015; Gittman et al., 2015). Provided environmental factors such as geomorphology, hydrology and biogeochemical conditions are appropriate, mangrove and saltmarsh species generally have a strong capacity to vegetate an intertidal area without active planting methods. Establishing new tidal wetlands or rehabilitating existing areas of estuarine vegetation has the resilience building benefit of binding sediments to limit erosion and enhances sediment trapping capacity by attenuating wave action, whilst also providing a sink for greenhouse gases (Duarte et al., 2013).

The promotion of living shorelines is supported by recent policy developments. In November 2016, the Greater Sydney Commission released a draft amendment to the Greater Sydney Regional Plan entitled 'Towards our Greater Sydney 2056' (Greater Sydney Commission, 2016). The draft identified three major centres with both central Sydney and Parramatta within the estuarine zone and six distinct planning districts with four of these – North, Central, South and West Central – containing the vast majority of Sydney's estuaries. Sustainability priorities are focussed on maintaining landscapes, protecting waterways, protecting and enhancing biodiversity, building up our resilience against climate change and creating a 'Green Grid' across Greater Sydney. Two central tenets of the 'Green Grid' approach are to integrate management of the coast and the land; and improve public access to waterway foreshores, wetlands and riparian corridors.

The Central District Plan makes a special mention of maximising benefits to the public from the innovative use of golf courses, setting the action to *identify opportunities for shared golf courses and open space*. Where golf courses abut waterways, opportunities exist to improve integration with the natural environment, including estuarine vegetation, into the design of these areas in the future. The spatial distribution of areas projected in this study to support large extents of mangrove correspond to the current distribution of sporting fields and golf clubs, including Marrickville Golf Club and Kogarah Golf Club, where the tidal range of the Cooks River is typically higher than elsewhere, and would therefore create more accommodation space for estuarine vegetation (Figure 2). The utilisation of existing open spaces may provide the most feasible opportunities for supporting the establishment of estuarine vegetation in the future. Opportunities may also exist to utilise 'surplus' industrial lands, purchase private land, or develop agreements with private landholders for the purpose of conversion to estuarine vegetation.

Modelling outputs indicated that the best ecosystem outcomes were achieved when wetlands were positioned higher within the tidal frame. High elevation intertidal wetlands possess 'elevation capital' (Cahoon and Guntenspergen, 2010; Lovelock et al., 2015), which provides for a longer period of time over which a deficit between elevation gain, achieved through accretion and plant productivity, and SLR can be tolerated. This is particularly important for saltmarsh which exhibits a very narrow elevation range and is vulnerable to encroachment by mangrove at lower elevations (Saintilan and Rogers, 2013) and *Casuarina* at higher elevations. Improving elevation capital and maintaining optimal positions within the tidal frame can be enhanced by applying thin layers of sediment to wetland surfaces that are typically sourced from dredge spoil (Ford et al., 1999; La Peyre et al., 2009). This technique has yet to be applied in Australia, but is commonly used throughout the USA to improve wetland resilience. In urban areas, excavated sediment from building works may provide a low-cost and relatively contaminant-free source of sediment nourishment. Sediment derived from building sites offers additional advantages as the industrial history of Sydney's estuaries (particularly the upper Parramatta River, Cooks River and sections of the Georges River) means that estuarine sediments are likely to be contaminated. Opportunities for sand nourishment using offshore marine sand resources have been scoped and offer an additional sediment source (AECOM, 2010). Sediment nourishment may be particularly relevant where there are limited opportunities for estuarine vegetation expansion to higher elevations, either due to topographic or land use constraints. For example, within Wolli Creek, the steep terrain and infrastructure constraints (e.g. train line and high-density housing) may make sediment nourishment the most viable, cost effective option for preservation of estuarine vegetation ecosystem services. The strategy may also be effective in preserving the saltmarshes within the steeply incised Middle Harbour and Land Cove Rivers. As there is little evidence to indicate that mangrove removal will enhance saltmarsh resilience, active management through sediment nourishment may be the only viable option where SLAMM modelling indicated high potential for mangrove expansion to higher elevations in Cooks River and Wolli Creek, but not for saltmarsh.

Rezoning of foreshore and low lying areas could be used to increase the horizontal space for wetland migration and to establish living shorelines. While this may reduce the footprint available for development, this will predominantly be in areas of already high inundation and flooding risk. Further, an effective living shoreline will act as buffer to SLR for surrounding development areas. Development of living shorelines will also increase the extent of open green space, which is currently lacking in the area and could be integrated with plans to increase foreshore access and amenities. Tools to enable living shoreline creation may include land buy-back and/or land exchange (Rogers et al., 2016). Other incentives for private stakeholders may include floor space bonuses, whereby developers may negotiate additional planning provisions, such as an increase to number of levels allowed in their development consent, in return for provisions which improve environmental or community benefits related to the project. Growing global interest in the utilisation of market-based schemes to facilitate tidal wetland establishment, restoration and conservation could be explored (Rogers et al., 2016). This is largely founded upon the emerging knowledge that 'blue carbon' ecosystems, namely mangrove, saltmarsh and seagrass areas, may be stores of significant preserved carbon stocks, mostly in their soils and below-ground biomass, and may accumulate carbon at a faster rate than most terrestrial ecosystems (McLeod et al., 2011).

Conclusions

This assessment has identified two overarching adaptation priorities: management strategies which accommodate wetland vegetation migration under SLR and; strategies which specifically preserve and accommodate saltmarsh. Modelling demonstrated that saltmarsh is particularly vulnerable in the Sydney region, with previous research also identifying links between changes in relative sea level and the expansion of mangrove into saltmarshes. Specific consideration of saltmarsh conservation and actions to improve resilience are therefore appropriate. Based on the identified adaptation priorities, we have identified four potential adaptation options : i) eliminate or reduce non-climate stressors to enhance the resilience of existing ecosystems; ii) protect existing estuarine vegetation through engineering activities, including modification of existing structures where appropriate; iii) maintain the position of estuarine vegetation within shifting tidal prisms as the sea rises through thin-layer sediment nourishment; and iv) plan for living shoreline establishment and migration. Importantly, these adaptation options require further investigation to establish their efficacy and cost effectiveness, and should be underpinned by mechanisms to monitoring and evaluate adaptation outcomes.

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