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A comparative analysis of engineering options for adaptation to sea-level rise: a case study for a vulnerable beach in Shoalhaven NSW

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Abstract: Mollymook, Collingwood and Callala beaches and the communities living near them were identified as especially vulnerable to sea level rise by the Shoalhaven City Council. A number of possible engineering and management solutions have been identified for mitigating or eliminating the effects of expected flooding and erosion (e.g., sea wall, groyne, beach nourishment), based on guidelines developed by Engineers Australia. However, the question remains as to how to assess and compare the benefits (and not just the costs) of each option. While the cost of designing and implementing these options are reasonably easy to estimate, other environmental and aesthetic costs are more difficult to valuate. Even more challenging is quantifying in monetary terms the benefits of each option. Methods are available in the economic literature for estimating some of these parameters, however, their application requires data and resources that are not always available to local government.

In this study, we propose a pragmatic approach (relatively simple yet detailed) which combines a monetary-based probabilistic flood-damage estimation technique with an estimate of non-monetary consequences of an adaptation option using local knowledge and stakeholder consultation. These two types of information (monetary and non-monetary) are combined using multi-criteria decision analysis (MCDA) methods in order to generate a ranking of engineering adaptation options and assist in decision-making. We illustrate the method by applying to Callala beach in Shoalhaven. First, we calculate respective cost-benefit ratios of each option by simulating the likely effects of a flood event (with multiple probabilities of occurrence or return period) with and without proposed adaptation options, for different scenarios of sea level rise. Specifically, a flood model of Callala is developed using high resolution LiDAR Digital Elevation Model (DEM) data and tested for impacts under different sea level rise scenarios (using IPCC AR5 projections) and their corresponding exceedance probabilities (using Canute sea level rise calculator). Second, we estimate the potential damage to properties and infrastructures (cumulative over time) through flood damage function curves (quantifying the relationship between flood depth and potential damage cost of private properties and public infrastructure). Third, we estimate the non-monetary benefits of each option using a simplified approach, based on stakeholder consultation. Finally, we use two different multi-criteria decision analysis (MCDA) approaches (simple additive weight and outranking methods) for comparison of a number of engineering adaptation options (both hard and soft measures). Results show that, in general, a combination of beach nourishment & groynes is the most preferred option for Callala beach, across all decision analysis methods. Our analyses also show that hard measures such as sea walls tend to perform better in cost-benefit analyses where non-monetary factors such as community preferences, aesthetics and environmental factors are omitted. On the other hand, including these factors through MCDA methods seems to push sea walls down the rank.

Keywords: *Coastal, climate change adaptation, local government, engineering*

1. INTRODUCTION

The threat of projected changes to the world's climate has brought about profound revisions to science, policy and coastal zone management, around the globe. Australia, with approximately 85% of the population living within 50km of the coast and 710,000 addresses below 6m elevation, relies heavily on the coastal zone for livelihood (Watson 2011). The most recent Intergovernmental Panel on Climate Change (IPCC) report, AR5, outlines sea level rise scenarios ranging from a 0.55m to 1.25m increase by 2100 (IPCC 2014). In addition, an increase in the frequency and intensity of coastal storms is expected, with the potential for cyclones to affect regions of the Australian coast much further south than at present (Walsh and Katzfey 2000). Coastal councils are facing immense challenges to safeguard their communities, and the infrastructure systems that serve them, as they are likely to be impacted by sea level rise (SLR) and associated extreme events (e.g. tropical cyclones, storm surges). These can result in flooding, submergence, erosion and wetland change (Lin, Khoo et al. 2014).

Reducing vulnerability of coastal regions to these effects is hampered by a number of obstacles, including uncertainty in future projections of SLR, lack of availability of local-scale data and difficulties in collecting data, complexity of effects of SLR, lack of resources for implementing adaptation actions and poor institutional environment (Measham et al. 2011, Tonmoy and El-Zein 2013, Klein et al. 2014, El-Zein and Tonmoy 2015). Moreover, decision making on adaptation usually occurs in a context of which includes other, related problems such competing land occupancy demands, unemployment, infrastructure development and maintenance etc. (Hinkel et al. 2010). Therefore, it is critical to assess the full potential of cost and benefits of a given adaptation option, at the planning stage, in order to ensure that resources are well spent. However, there are very few clear methodologies or guidelines available to local government for analyzing the costs and more importantly benefits of an adaptation option (Lin et al. 2014, Tonmoy et al. 2014). An important difficulty is the need to combine monetary and non-monetary valuations of benefits and costs within a single decision-making framework. Specifically, two categories of benefits must be considered: a) an increase in the cultural, environmental, social and recreational values (non-market and non-monetary values); b) the reduction in the total potential damages occurring over the assessment period, as a result of putting an option in place (primarily monetary).

The goal of this paper is to propose a relatively simple, yet detailed, assessment methodology that combines monetary and non-monetary valuations in order to rank a set of local-scale adaptation options. First, we use probabilistic coastal storm inundation modelling to estimate damages in monetary terms. Second, we draw on local knowledge and stakeholder consultation to quantify non-monetary benefits of each option. Third, the two sets of information are combined within a multi-criteria decision analysis (MCDA) framework in order to generate a ranking of options. The methodology is illustrated by applying it to the case of Callala beach in Shoalhaven, New South Wales.

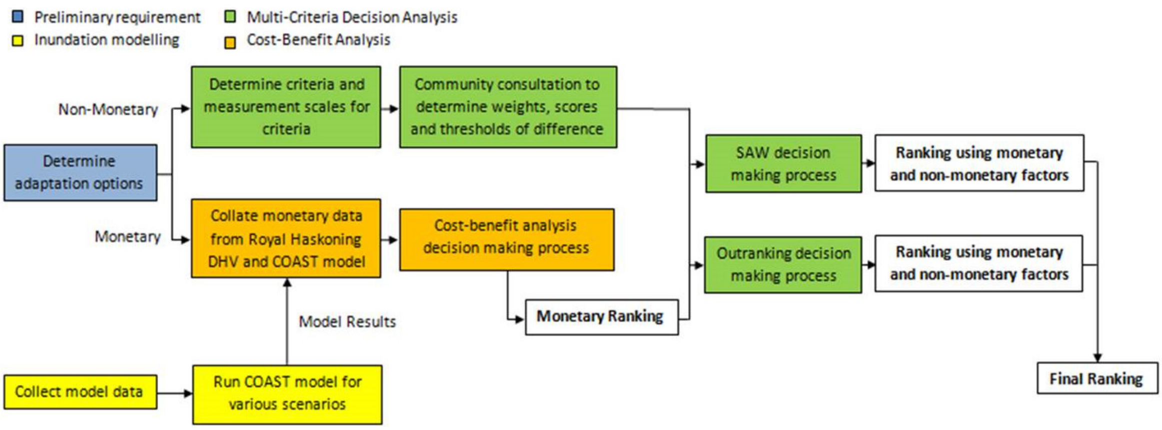

Figure 1. An approach for comparing engineering adaptation options.

2. METHODOLOGY

The method undertaken in this study comprises four main components (Figure 1):

a) inundation modelling to simulate storm surge impact under different SLR scenario with and without the adaptation options, b) estimation of potential damage cost as well as benefits of putting adaptation option in place (avoided damage cost) for each simulated inundation scenario using a depth versus damage function; followed by a cost-benefit analysis of each option under study, c) stakeholder consultation for eliciting local knowledge and preferences in order to estimate non-monetary benefits of each adaptation options and finally d) comparison of alternative engineering adaptation options (Table 2) using two different multi-criteria decision-making methods.

3. CONTEXT AND STUDY AREA

Callala Beach is located within Shoalhaven city council (SCC) on the south-eastern coast of Australia, approximately 180km south of Sydney (Figure 2). Callala beach has approximately 5km stretch of beach with a largest recorded tidal range of 1.88m. At mean sea level (MSL), the beach width is approximately 30m, though this can vary immensely during storms (DHV, 2013; Nielsen and Varley 2004). The demographics of Callala beach are dominated by young families and retirees. Relatively low income, an aging population and poor access to infrastructure contribute to the low adaptive capacity of the community (Tonmoy 2014). The region is a tourism hotspot, with sailing and canoeing as the primary activities, as well as mountain biking and fishing.

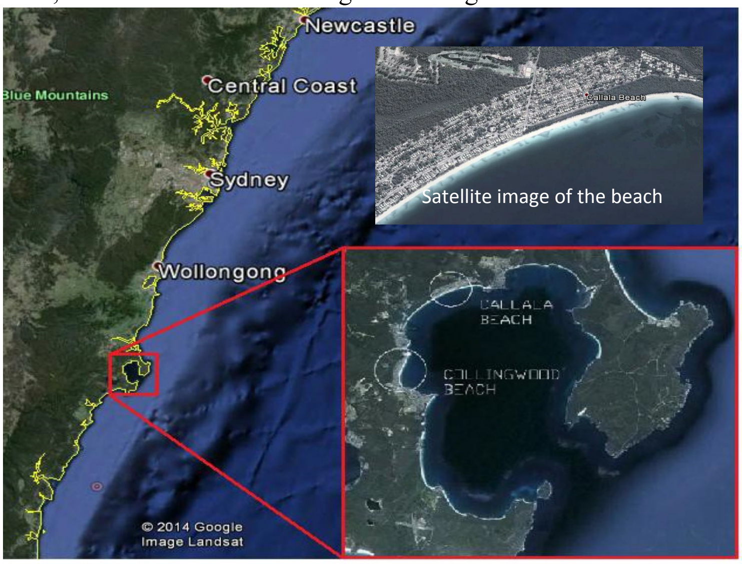

Figure 2. Callala beach.

In developing a long-term coastal zone management plan for the beach, Shoalhaven City Council commissioned studies (Adamantidis et al. 2009) that analyzed impacts of sea level rise along its coast (e.g., risk of damage to public and private property, socio-economic and institutional implications). Specific studies (DHV 2013) were then conducted, for Callala, with the aim of identifying possible engineering solutions that can mitigate or eliminate the effects of sea-level rise (e.g., sea wall, groyne, beach nourishment). Using the outcomes of these analyses, our study aims to conduct a first-pass comparison among the proposed solutions. It should be noted that council plan to conduct further detail study and in the process of engaging with community to develop an adaptive pathway for Callala's long-term erosion and inundation problems.

4. EROSION AND INUNDATION RISK AT CALLALA

Erosion: Historically, Callala beach has been prone to erosion, specifically during and after storm events from large south-east swells. For many years, the SCC has applied a restriction on property boundaries in the form of a setback from the sea to protect any development along Quay road. Erosion risk of the beach has been modelled in a previous study (Adamantidis et al. 2009) which has identified 81 and 107 at-risk properties, under 2050 and 2100 SLR scenarios, respectively. In addition, part of Quay road, an adjacent car park and a tennis club are at risk. Hence, estimation of long-term erosion damages to properties and infrastructure is conducted in this study using the modeling outcomes of Adamantidis et al. (2009).

Inundation: we develop a probabilistic storm surge inundation model for Callala beach using the Coastal Adaptation to Sea-Level Rise Tool (COAST), developed by Blue Marble Geographic in the USA (COAST 2013) . COAST uses a bathtub fill modelling approach. It is applied in this study to simulate the water depth for a range of storm events affecting Callala beach from 10 Annual Recurrence Interval, ARI (0.1% Annual Exceedance Probability, AEP) to 1000 ARI (0.001% AEP) under current (2014) sea level as well as 2050 and 2100 SLR scenario (all four RCPs). A description of the data required for these simulations is given in Table 2. Water level exceedance probability curves for Callala beach under different SLR scenario is generated from CANUTE SLR calculator (see Figure 3). Inundation modelling results show that Callala beach is at low risk of inundation damage over the next 100 years, assuming no new property development during this period. Results, however, indicate that if flooding is to occur at Callala Beach, the northern end of the beach would be at higher risk.

It is important to note that the influence of wave run up (the maximum vertical extent of wave uprush on a beach or structure above the still water level) and set-up (deviation from still water level as a function of beach slope and wave steepness) has not been included in these results. A previous study at Callala beach estimates an average and maximum wave run up of 1.5m and 3.52m, respectively (Adamantidis et al. 2009). Including these additional heights in the analysis suggests that the lowest properties in the northern parts of Callala Beach would be at risk of temporary inundation during extreme storm surge events (0.1% AEP). However, wave run-up and setup were not included in the following damage calculations. This is mainly because COAST uses a bathtub fill approach for inundation modelling and adding these separately generated values of wave setup and run-up on top of bathtub approach (in the absence of a detail hydrodynamic model) will create additional uncertainty in the analysis. Therefore, flood heights identified through bathtub inundation modeling have been used in the next step for estimating damages to properties and infrastructure using a depth-damage function which is then used as an input to cost-benefit analyses.

"Water observation from space (WOfS)" is a Geoscience Australia's product that analyses historical Landsat data to identify historical presence of water in a particular point in Australia. Comparing our results from COAST with WOfS, we have observed that parts of the Callala beach that COAST identified to be at risk of inundation have also been inundated in the past. This provides a preliminary form of qualitative validation for our inundation model.

5. OPTIONS COMPARED

DHV (2013) analyzed the construction cost and feasibility of a number of engineering options for protecting Callala beach from long-term coastal hazards. Their analysis was based on guidelines on adaptation of coastal zones in Australia, developed by Engineers Australia, Six of those options, as well as a "soft measure option" are included in our analyses (Table 1).

Table 1. Adaptation options identified by DHV 2013 for Callala beach and analysed in this study.

Adaptation Options	Description
Soft Intervention	Without investing in any hard options inform, educate and prepare the community for storm events, and help them to protect their properties. In reality this option would likely be required to accompany whichever adaptation option is implemented.
Seawall	This is a typical rock revetment. Preliminary design outlines two stages of development Precinct A: located along the entire length of Quay Road, approximately 1.4km of beach; and Precinct B: located along the entire length of Greenway Road, approximately 600m of beach. The estimated cost of Precinct A is $27.4 million, whilst Precinct B is $12.5million.
Beach Nourishment	A beach nourishment scheme along the entire 4.8km of beach. It requires nourishment of 13m from the dune crest to protect at risk properties. The construction and maintenance costs over the 50 year planning period are estimated to be $30million.
Beach Nourishment & Groynes	This option adds in a groyne near the western end of Quay Road, which reduces the length of beach nourishment to 2km. Nourishment of 13m from the dune crest is also required to protect at risk properties. The estimated construction and maintenance costs of this option are $12.5million and $13.5million respectively.
Beach Nourishment & Seawall	This option combines beach nourishment and a seawall. This was to help ensure that the beach would not completely disappear over time due to erosion in front of the seawall.
Beach Nourishment, Seawall & Groynes	This option combines the Seawall and Beach Nourishment & Groynes options
Nearshore Breakwater	This option includes six 200m long rock breakwaters, separated by 100m, located approximately 300m offshore. A rough estimate of $80-$90million was made for the construction of this option

6. COST-BENEFIT ANALYSIS (CBA)

The COAST model takes a given scenario (e.g. year 2100, 100Y storm event) and uses the model inputs to determine an inundation height. The depth of water at each property is then used alongside with a depth-damage function (water depth vs damage) to estimate the cost of potential damage to each property. Data specific to Callala was not available; therefore a Depth-damage functions (DDF) developed by Sargent (2013) was used. Sargent (2013) modified previous ANUFLOOD depth-damage functions to better represent the overall flood damage by including structural costs of repair. These curves are based on data collected in Ipswich during the Brisbane floods in 2011. On the other hand, damage to infrastructure is estimated using guidelines from the Department Environment, Climate Change and Water (DECCW; now the Office of Environment and Heritage) which suggests that damage cost of infrastructure (such as water, electricity and sewage) during a flood contributes to 15% of the total property damage cost. The other information used in CBA is the discount rate and the property appreciation rate. These allow future costs to be moved back to present day values. The discount rate is estimated to be approximately equal to the long-term inflation rate, with the target of 2-3% set by the Reserve Bank of Australia in 2014. A value of 2.5% is selected for the model. Cost of a given engineering option is estimated as the construction and maintenance cost of that option (for the study period), while benefits are defined as the avoided damage costs after implementing the engineering option.

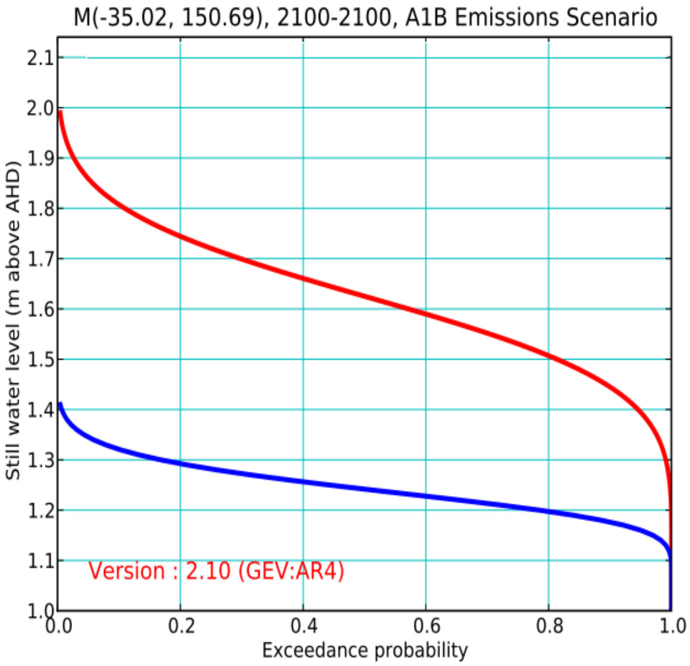

Figure 3. Water level exceedance curves for Callala Beach (generated using CANUTE tool).

7. MCDA METHODS FOR RANKING OF OPTIONS

Adaptation options are ranked using first, CBA and second, two different MCDA methods, Simple Additive Weight (SAW) based on Multi Attribute Utility Theory (MAUT) and ELECTRE-III based on an Outranking approach. As discussed before, MCDA methods are used in order to be able to combine monetary and non-monetary criteria. Both MCDA procedures used here are commonly applied in environmental appraisal of civil engineering projects. SAW is an additive process that uses utility values and weights to determine a global index for each option. This requires normalization of criteria values as they are usually of different scales and units. Such normalization assumes that bad performance in one criterion (e.g., environmental impact of an option) can be compensated for by good performance by another criterion, which forces the analyst to make assumptions about convertibility of criteria that may not be an accurate reflection of reality. On the other hand, outranking approaches such as ELECTRE-III, avoids this, by comparing each pair of alternatives against stakeholder preferences and thresholds, i.e. without normalizing criteria or forcing convertibility. For a detailed discussion of these two MCDA approaches, please refer to El-Zein and Tonmoy (2015).

Table 2. Data used in the analysis and their source.

Data Type	Format	Description/Use/Source
Land Elevation	Raster	Digital elevation model of the region, developed using LiDAR data and available through SCC
Asset Data	Shape-file	Cadastre data for roads and properties, and polyline shapefiles for water and sewer lines were available from SCC. This data did not contain asset values, so these values were added manually using data from Core Logic (previously known as RP Data). Property data for Callala Beach from RP Data was separated into three regions based on price:
Storm Surge Data	Exceedance curve	Storm surge level and average recurrence intervals, used to determine the likelihood of inundation and was derived using CANUTE SLR Calculator.
Eustatic SLR Data	Exceedance curve	Eustatic sea level rise (SLR) data was sourced from the IPCC 5th Report (2013), using a high scenario (0.98m in 2100) and maximum scenario (1.25m in 2100)
Base Water Level	Exceedance curve	Manly Hydraulics Laboratory (2012) report describing records at the Jervis Bay: Clyde River station (location: 291107E, 6111022N).
Local SLR Data	Exceedance curve	Local sea level rise probability curves, to determine the base water level before storm surge.
Depth-Damage Functions	Table	Tabulated data describing the relationship between inundation depth and percentage damage to structures. This is used to determine the cost of damage to assets. Data specific to Callala was not available, instead followed Sargent (2013)

8. STAKEHOLDER CONSULTATION AND SELECTION OF DECISION CRITERIA

Consultation with the SCC, through face-to-face meetings as well as online surveys is done in two phases: a) to develop decision criteria of comparison and b) to identify possible non-monetary impacts of a given engineering adaptation option and establish weights for each criterion, scores for each adaptation option and preference threshold values for conducting MCDA analyses that will be discussed in the following section.

9. RESULTS

Criteria Adopted: Two different MCDA methods are used for comparing the adaptation options. The use of MCDA allows the study to include non-monetary impacts of a given adaptation option along with the monetary impacts. In the 1st phase of the consultation with SCC, a set of decision criteria have been developed for this comparison (Table 3). Although the choice of the criteria is largely guided by the availability of data, the following three factors are also considered. a) Significance: whether the criterion is contextually important and is likely to be useful in establishing a preference order between some options; b) Measurability: ensuring that there is the capacity to provide reasonable measurement of the criteria based on available data/resources; c) Linear independence: the selection of criteria that do not significantly overlap.

Table 3. Decision criteria adopted in this study.

Category	Criteria	Scale
Governance	G1: Ease of implementation by council	Cardinal
	G2: Reduction of council liability for losses associated with sea level rise	Cardinal
Social /Community	C1: Access to vital infrastructure (during/following storm events)	Cardinal
	C2: Impact on the safety of beach users	Cardinal
	C3: Impact on public assets (particularly during/following storm events)	Cardinal
	C4: Minimizing community displacement	Numerical
	C5: Overall risk mitigation	Cardinal
Financial/Economic	F3: Maximizing the Benefit-Cost Ratio	Ratio
Direct Environmental	DE1: Impact on local natural ecological communities	Cardinal
Indirect Environmental	IE1: Impact on upstream/downstream natural ecological communities	Cardinal
Aesthetics /Amenity	A1: Impact on the pristine visual state of the beach	Cardinal
	A2: Maintaining beach width	Binary
	A3: Beach access (to the public)	Cardinal
Tourism	T1: Impact on recreational activities	Cardinal

For estimating the non-monetary impacts of implementing an option, a cardinal scale (mostly between 1 to 5, 1 showing the least and 5 the most negative impact) has been developed and SCC stakeholders have been consulted to assign a value based on local knowledge. As an example, sea walls have been implemented in SCC in the past and based on their observed impact on local ecology, stakeholders have been asked to assign a value on the cardinal scale for sea wall (DE1). Scores for some other criteria such as community displacement (C4) are estimated based on the number of houses impacted by flooding/erosion using an occupancy of 2.3 people per household (ABS 2011);

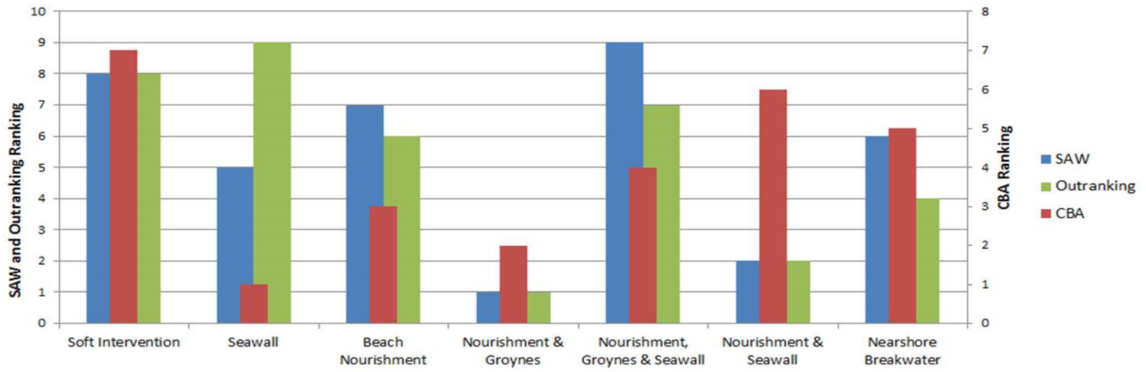

Figure 4. Ranking of options for 2050 scenario. A lower value on the vertical axis indicates better performance.

Ranking of Adaptation Options: Because of space restrictions, only rankings generated under 2050 SLR scenario are presented here (Figure 4). In general, results show that, the combination of beach nourishment & groynes is the most preferred option while a sea wall is the least preferred for Callala beach, particularly when MCDA procedures are used. On the other hand, the seawall option performed better in the cost-benefit procedures mainly due to absence of other non-monetary criteria against which seawall performs poorly. Rankings generated by SAW and ELECTRE III are generally similar except for seawalls which perform better

10. IMPLICATIONS OF RECENT POLICY CHANGE

The analysis of this study was conducted before Shoalhaven council adopted a new benchmark of SLR following suggestion from NSW state government's "Stage-1 reform of coastal policy". Stage-1 reform discarded the state wide 0.9m rise SLR benchmark and advised the councils to adopt benchmark that are more relevant to their local coastal topography. Following the policy change, the Council commissioned further studies and adopted of a benchmark of 0.36m rise by 2100.

11. LIMITATIONS AND CONCLUSIONS

Results obtained in this study are limited by: i) the comparison of options through time (2014, 2050 and 2100) assumes scores of non-monetary criteria do not change, which may not be the case in practice, ii) inundation modeling is conducted using a bathtub fill modelling approach rather than a more detailed and robust hydrodynamic model, iii) the number of participants in the stakeholders survey is quite small, finally iv) the reliance on data sourced from previous studies, causing their limitations and uncertainties to be present in this study. Nevertheless, our study has illustrated a pragmatic approach for comparing engineering adaptation options using CBA and two different MCDA approaches. The assessment approach used in this study allows an easy and quick way of including non-monetary impacts of an engineering adaptation option and can be used in a resource constrained local government settings, as a first-pass assessment. Its application in the context of Callala beach showed that hard measures such as sea walls tend to perform better in CBA where non-monetary factors such as community preferences, aesthetics and environmental factors are not included. On the other hand, including these factors through MCDA methods seems to push hard measures significantly down the ranks.

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REFERENCES

ABS (2011). "Cencus data: Year Book Australia."

Adamantidis, C., et al. (2009). Shoalhaven Coastal Hazard Study- Summary report- prepared by SMEC Australia for Shoalhaven City Council.

COAST (2013). "COAST (Coastal Adaptation to Sea Level Rise Tool) developed by Blue Marble Geographics. Available at https://www.bluemarblegeo.com/products/COAST.php accessed on 22nd July 2015."

DHV, R. H. (2013). Shoalhaven 'Authorised Locations' Coastal Erosion Remediation Options, Callala Beach. Prepared for Shoalhaven City Council.

El-Zein, A. and F. N. Tonmoy (2015). "Assessment of vulnerability to climate change using a multi-criteria outranking approach with application to heat stress in Sydney." Ecological Indicators **48**: 207-217.

Hinkel, J., et al. (2010). "Assessing risk of and adaptation to sea-level rise in the European Union: an application of DIVA." Mitigation and Adaptation Strategies for Global Change **15**: 703-719.

IPCC (2014). Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, United Kingdom and New York, NY, USA, Cambridge University Press.

Klein, R. J. T., et al. (2014). Adaptation opportunities, constraints, and limits. Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel of Climate Change. Cambridge, United Kingdom and New York, NY, USA, Cambridge University Press.

Lin, B. B., et al. (2014). "Assessing inundation damage and timing of adaptation: sea level rise and the complexities of land use in coastal communities." Mitigation and Adaptation Strategies for Global Change **19**(5): 551-568.

Measham, T. G., et al. (2011). "Adapting to climate change through local municipal planning: barriers and challenges." Mitigation and Adaptation Strategies for Global Change **16**(8): 889-909.

Nielsen, L. and I. Varley (2004). Shoalhaven Coastline Hazard Definition Study by SMEC Australia Pty Ltd.

Sargent, D. (2013). Updating Residential Flood Stage-Damage Curves based on Building Cost Data. From SIAQ Conference, Townville.

Tonmoy, F. (2014). Assessment of vulnerability to climate change: theoretical and methodological developments with applications to infrastructure and built environment. Civil Engineering, University of Sydney. **PhD Thesis**.

Tonmoy, F. N. and A. El-Zein (2013). Vulnerability of infrastructure to Sea Level Rise: A combined outranking and system-dynamics approach. European Safety and Reliability (ESREL-2013), CRC Press, pp 509. ISBN: 978-1-315-81559-6.

Tonmoy, F. N., et al. (2014). "Assessment of vulnerability to climate change using indicators: a meta-analysis of the literature." Wiley Interdisciplinary Reviews: Climate Change **5**(6): 775-792.

Walsh, K. J. and J. J. Katzfey (2000). "The impact of climate change on the poleward movement of tropical cyclone-like vortices in a regional climate model." Journal of Climate **13**(6): 1116-1132.

Watson, P. (2011). "Is there evidence yet of acceleration in mean sea level rise around mainland Australia?" Journal of Coastal Research **27**(2): 368-377.