Exploring valuation methods for climate adaptation options, with particular reference to Australian coastal councils

Final Report

Chi Truong, Stefan Trück, Peter Davies (Macquarie University)
and Supriya Mathew (Charles Darwin University)

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Table of Contents

Introduction

Valuation of adaptation options is crucial to appropriate adaptation decision-making. A range of valuation methods are available, including cost-benefit analysis, cost effectiveness analysis, cost utility analysis and multi-criteria analysis. A complete cost–benefit analysis requires the valuation of all project impacts, whether they are marketed or non-marketed goods. A number of valuation techniques can be used to evaluate non-marketed goods' direct use and non-use values (option value, quasi option value, bequest value, existence value), with the tangibility decreasing from 'use' to 'non-use' values. Monetary estimates of the non-use values may be obtained using revealed preference methods like travel cost methods and stated preference methods such as, e.g., willingness to pay and willingness to accept. It is difficult for local government stakeholders to understand the contexts in which various valuation methods should be applied. In this report, as a guide for local government decision makers, we showcase three case study examples where different valuation methods have been applied.

We provide a literature review on various valuation methods in Chapter 1. A block diagram of various valuation methods with sign posts indicating when to apply each of the methods is developed to guide stakeholders. In Chapter 2, we present; i) a multi-criteria analysis that incorporates the impacts of social costs, flexibility value and intangible impacts of adaptation options, ii) a real option framework that incorporates the impact of sea level rise uncertainty in adaptation decision-making, iii) a cost benefit analysis that incorporates the historic value of land.

These frameworks are applied to three coastal case study locations (Shoalhaven in New South Wales, Mandurah in Western Australia and Port Macquarie in New South Wales) that are dealing with the management of coastal erosion.

Chapter 1. Literature review of project valuation for coastal adaptation

In this chapter, we provide an overview of valuation methods that can be used for evaluation of adaptation projects in coastal areas. This includes cost benefit analysis, cost effective analysis, cost utility analysis and multi-criteria analysis. In the second section, we examine in detail cost benefit analysis and multi-criteria analysis methods that are used in the provided case studies in Chapter 2. In particular, we examine the determination of discount rates, methods to estimate non-market values (revealed preference method, stated preference method, statistical methods, benefit transfer methods), approaches to optimally time investment, linear utility multi-criteria analysis, PROMETHEE II multi-criteria analysis and methods applied to elicit criteria weights. In the last section of this chapter we review studies that evaluate coastal adaptation projects to highlight issues that are important in this area of research. These include cost benefit studies as well as optimal timing studies.

1 Overview of valuation methods

Valuation methods that are commonly used in project valuation and can be used to evaluate coastal adaptation include Cost Benefit Analysis (CBA), Cost Effective Analysis (CEA), Cost Utility Analysis (CUA) and Multi-Criteria Analysis (MCA) (Persson, 2010).

CBA is used when it is possible to value all costs and benefits associated with a considered policy or project in monetary terms. The policy or the project is recommended when the benefits exceed the costs. CBA has been a dominant valuation method in general, and a much used method in coastal adaptation in particular. For example, Mendelsohn and Olmstead (2009) use CBA to determine whether Singapore should construct a seawall to protect against flooding due to sea level rise while Turner et al. (2007) conduct a CBA on whether the UK should implement retreat.

When the benefits of different policies or options cannot be valued in monetary terms, but can be measured in alternative output units, for example tonnes of carbon sequestered, then CEA can be used. In CEA, the option that has the minimum cost per unit of output is selected. Wintle et al. (2011) provide an example of using CEA to find the least costly adaptation option to conserve a given area of habitat for species that are vulnerable to climate change.

When benefits are measured in more than one output unit and all costs are measured in monetary units, then CUA can be used to select the option that helps to achieve a desired level of utility at the least cost. For example, Marinoni et al. (2011) uses CUA to find the portfolio of intervention sites for treating water pollution in a river catchment that maximises the community’s utility subject to a budget constraint. Outputs in their model include various water quality measures, as well as ecological outputs. Marinoni et al. (2011) calculate the utility scores for each intervention measure using a MCA and use these scores together with their costs to obtain a benefit cost ratio. The benefit cost ratio then provides a measure that reflects how much benefit is obtained for each dollar spent, or how effectively expenditure is allocated.

When benefits are measured in more than one output units and not all costs are measured in monetary units, MCA can be used. MCA involves determining the performance of alternative policies or options against selected criteria and the weight attached to each criterion. The option that has the highest weighted score is selected.

Some guidance on method selection is provided in Figure 1. CBA is often preferred since it is typically based on actual data and therefore more objective (compared to MCA) and can handle optimisation. CBA is, however, only applicable when all costs and benefits can be monetised. When other criteria such as social and distributional effects are also important, or when benefits cannot be quantified and valued (such as the benefits of preserving biodiversity), then MCA may be a preferred valuation method. However, note that the selection of methods need not be mutually exclusive. For example, the outcomes of CBA can be incorporated into MCA to make a hybrid analysis.

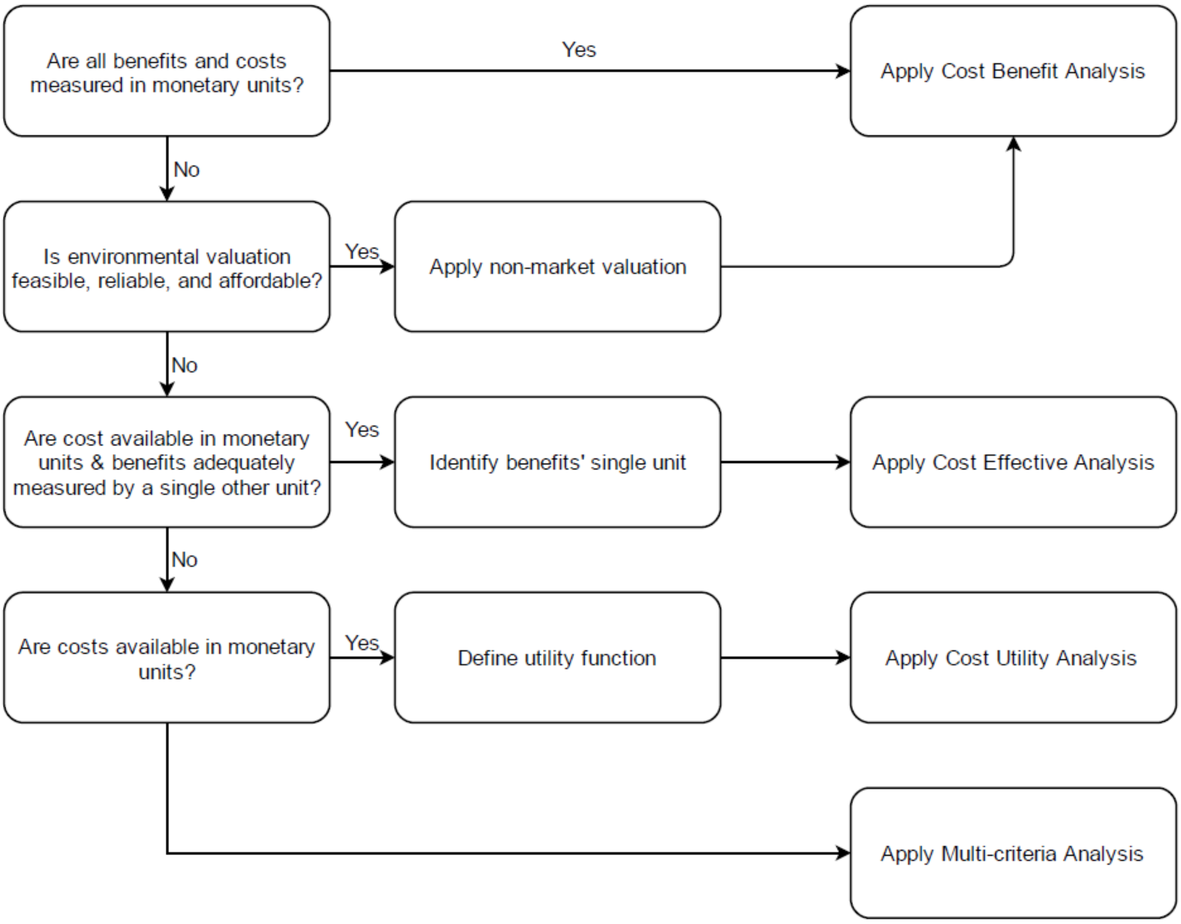

Figure 1 Selecting appropriate tools to evaluate climate change adaptation options (Hajkowicz, 2008)

All the above approaches involve stakeholders at a number of different points within the appraisal process. Stakeholders could, for example, be involved in setting management objectives, or in the determination of values. Deciding how stakeholders should be involved may influence the choice of the valuation approach (Gamper and Turcanu, 2007).

CBA is recognised as the main decision tool for adaptation in coastal areas in many countries. The UK and Holland governments have developed a CBA model for funding prioritisation between projects (Persson, 2010). The UK government guidance on CBA emphasises the need to use a decreasing discount rate over a long run time horizon and to include as many benefits and costs (market and non-market) as is feasible with a money metric and existing knowledge (Turner et al., 2007). In the US, CBA is a primary tool for regulatory impact analysis. Circular A-4 issued by Office of Information and Regulatory Affairs (2016) outlines analytical considerations and best practices for regulatory CBA, including development of baselines, methods for obtaining costs and benefits, choice of discount rates, and treatments of uncertainty.

In contrast, MCA is rarely required by law. It is, however, indirectly required through the environmental impact assessments, where conflicts, equity and distributional issues need to be recognised (Gamper and Turcanu, 2007). The potential of MCA is highlighted in situations involving multiple value systems and objectives, which cannot be easily quantified (e.g. environmental issues), even less, translated in monetary terms due to their intangible nature (e.g. social, cultural or psychological issues). MCA also can structure and facilitate stakeholders' involvement in the decision processes. The analysis, the questions raised and the reasoning in the process of a MCA can have a positive impact on the decision process such that preferences are revealed and can be considered by the final decision maker. The added value of MCA for public decision making lies in its ability to reveal preferences in a more direct and practical way than other decision support tools. Affected stakeholder groups are asked, as a minimum, to ascribe their preferred options and criteria respective weights, and might even be involved in creating these from an early stage of the decision making process (Gamper and Turcanu, 2007).

2 Review of Relevant Methods

2.1 Discount rate

Investment projects usually have investment costs that occur at or near the investment time and benefits that spread over a long time period. Due to time preference of money— i.e. people often prefer to have money now rather than in a future time— one dollar that is obtained in a future period is worth less than a dollar that is obtained now. To make investment benefits that occur at future times comparable with investment costs that occur at the initial time point, an appropriate discount rate needs to be identified to convert all cash flows of the project to the present values. Once this is done, project costs can be deducted from project benefits to obtain the net present value (NPV) of the project. The NPV rule is that if the NPV of the project is positive then the project is a worthwhile investment.

The discount rate has a significant impact on the NPV of adaptation projects, and therefore on the valuation results. The choice of an appropriate discount rate for long lasting projects is, however, highly controversial in the literature. Some studies such as Stern (2007) and Garnaut et al. (2008) suggest that for projects that span more than one generation, the discount rate should reflect not only the consumption-saving preference of the current generation, but also that of future generations to ensure intergenerational equity. They propose to use an optimal growth rate model to determine the discount rate. Determining discount rates based on optimal growth rate models, however, requires a social value judgement about intergenerational equality, which may be subjective and difficult. Other studies including Newell and Pizer (2003), Nordhaus (2007) and Quiggin (2008) suggest to determine the discount rate based on the observed market interest rates. The literature review of studies on adaptation to reduce catastrophic risk shows that the assumed discount rates vary across these studies and are usually not explicitly justified (Truong and Trück, 2016). An exception is the study by Michael (2007) which uses discount rates provided by Newell and Pizer (2003).

Truong and Trück (2016) adopt the approach proposed by Newell and Pizer (2003) to determine the appropriate discount rate for investment valuation in Australia. This approach estimates the discount rate using data on the prices of long term government bonds. Since the prices of government bonds vary stochastically over time, risk free interest rates are also stochastic. Therefore, the authors estimate the stochastic interest rate model proposed by Cox et al. (1985) using long term Australian government bond data. They found that Australian interest rate has a quite low persistent coefficient, and the estimated certainty equivalent discount rate converges quickly to a long run level of 4.5%.

2.2 Estimation of non-market values

Cost benefit analysis is often conducted based on a total economic value model, where the value of environmental goods and services can be categorised as use values and non-use values. Use values include the value obtained from actual usage or consumption of the environmental good. Non-use values are the values that arise from improving the well-being of people, even though no environmental good is consumed.

Use values can include direct values, such as timber harvest, and indirect use values such as clean air from trees. Direct values can be divided into consumptive such as timber harvest or non-consumptive such as forest visual amenity (Tapsuwan et al., 2009).

Non-use values may be existence, bequest or option values. The existence value is the value that people place on knowing that something is there, such as knowing that a rare species still exists. The bequest value is the value that is gained from being able to conserve something for future generations. The option value is the value that an individual is willing to pay to ensure that a resource is available to them in the future.

In general, use values are easier to estimate since the values are reflected in the market place. For example, the value of timber can be measured by the dollar amount for which the timber can be sold. The value of a beach can be measured by the amount that people pay to visit the beach. Non-use values are more difficult to measure due to the lack of a market for such services. For example, it is difficult to determine the benefit in dollar terms of preserving a wildlife species (Tapsuwan et al., 2009).

A number of techniques have been developed to estimate use and non-use values of environmental goods in the absence of explicit markets. These methods belong to two broad classes: behavioural (revealed preference) and attitudinal (stated preference) methods. Revealed preference methods aim to find the value people place on a good from observed behaviour in markets for related goods while stated preference methods ask consumers how much they value environmental goods and services in carefully structured surveys (Mendelsohn and Olmstead, 2009).

Two main revealed preference methods are the travel cost method and the hedonic pricing method. The travel cost method estimates the recreational value of an environmental good such as wetland and beach based on the costs that people incur to travel to the recreational site. Hedonic pricing methods use the market price of related goods to infer the value of an environmental resource. For example, the price of a house depends on the intrinsic characteristics of the house (number of bedrooms, number of bathroom, land area) as well as the environmental amenity such as beach view. Hedonic property models collect data on the prices of home sales and housing characteristics, and then estimate the marginal implicit prices of the characteristics of interest.

Two main methods of stated preference are contingent valuation and choice modelling. In contingent valuation, people are asked about their willingness to pay to prevent the loss of an environmental asset, or their willingness to accept (a compensation) to let go or lose the environmental asset. Choice modelling is similar to contingent valuation, but the environmental good in question is described in terms of its attributes and the levels of the attributes and respondents are required to choose between various attribute packages.

Thus, the willingness to pay or to accept can be broken down into the willingness to pay/accept for each attribute.

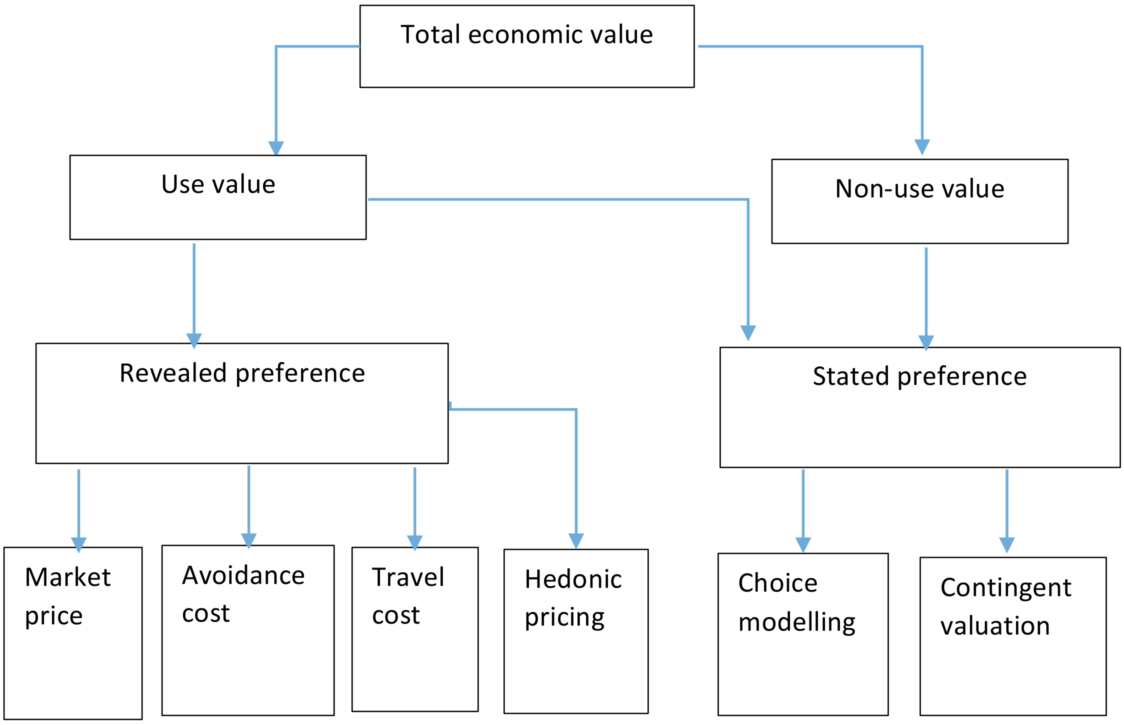

Figure 2. Valuation techniques for use and non-use values (Bateman et al., 2002)

For revealed preference methods—because experiments are not randomised—the methodologies must control undesired variation using a combination of carefully choosing experiments and controlling for remaining problems with statistical techniques. Stated preference methods have the appealing feature that they can be used to value any environmental good or services as long as the good can be described. However, in practice, survey methods are more difficult than they appear. What people say they would do, and what they actually do, may differ. Thus, economists generally rely primarily on revealed preference methods to estimate use value and reserve stated preference methods for non-use value and to assess peoples' value for states of the world that do not exist (e.g. estimating the value of a piped water connection where there currently is none) (Mendelsohn and Olmstead, 2009).

2.2.1 Revealed Preference Methods

Travel cost and hedonic pricing are the two main revealed preference methods. Travel cost models are among the most widely applied valuation methods and have become a very useful tool for estimating recreational demand. These methods, however, are vulnerable to the possibility that important factors have been omitted, which could bias the results. In addition, actual travel cost or some portion of it may be unobservable. One key unobserved cost is the opportunity cost of travel time. Wage rates may be assigned to value time, but empirical evidence suggests that people enjoy traveling, suggesting a lower value (Cesario, 1976). Another important issue concerns multi-purpose trips. For trips with multiple purposes, an individual recreation site represents only a portion of the trip's value. If the analyst excludes multipurpose trips from the sample, so that all trips are single purpose, it will bias downward the site's value. Assigning proportional values to each destination or purpose is unfortunately arbitrary (Mendelsohn and Olmstead, 2009).

Many of the assumptions of travel cost models can be dealt with through sensitivity analysis. Researchers can make a range of assumptions about the opportunity cost of time, which travel expenditures to include and what portion of costs for a multipurpose trip should be attributed to an individual site. They can then observe how the recreational value of a site changes with these changes in assumption (Mendelsohn and Olmstead, 2009).

Hedonic pricing models infer the marginal value of an environmental amenity from observed market values such as house prices. Hedonic models have been used to estimate the economic value of air quality, proximity to wetlands and open space and 'disamenities' such as hazardous waste sites and airport noise. Also hedonic models have some limitations. It is assumed that buyers and sellers have good information on the characteristics of all housing alternatives. Thus, the models are appropriate only for estimating the value of observable or known amenities and disamenities. Second, the models assume that people are mobile enough and that current prices reflect their preferences (Mendelsohn and Olmstead, 2009).

Unobserved characteristics of housing consumers cause people to self-sort into neighbourhoods on the basis of their preferences for environmental quality. For example, higher levels of air pollution may be observed in urban areas that also have more jobs. More jobs, in turn, can increase housing values. If there is a failure to adequately control for such factors, then there may be an over or under-estimation of the price of air pollution (Mendelsohn and Olmstead, 2009).

2.2.2 Stated Preference Methods

Stated preference methods use carefully designed surveys that ask consumers how much they value environmental goods and services. The survey creates a hypothetical market for the amenity so that responses can be evaluated in a manner similar to behaviour observed in markets. The basic architecture of a contingent valuation survey is: (a) a description of the service/amenity to be valued and the conditions under which the policy change is being suggested, (b) a set of choice questions that ask the respondent to place a value on the service/amenity and (c) a set of questions assessing the socioeconomic characteristics of the respondent that will help in determining what factors may shift that value (Mendelsohn and Olmstead, 2009).

In early surveys, researchers simply asked people open-ended questions such as how much they were willing to pay for each amenity. However, such open-ended questions are limited in their ability to provide accurate results. Closed-ended discrete choice questions in which respondents offer a 'yes' or 'no' response when offered one or more specified prices for an environmental good or services, have largely replaced open-ended questions in contingent value studies.

Another problem with stated preference surveys is that the responses to willingness to accept questions have generally been many times greater than the responses to willingness to pay questions. This is especially true for non-use values. Factors that cause these large differences are still an active topic of research. Mendelsohn and Olmstead (2009) suggest that these differences are measurement problems while Flachaire et al. (2013) found that they can be due to protest behaviour, for example, many respondents refuse to pay at all.

2.3 Statistical methods

Costanza et al. (2008) estimate the value of risk alleviation of wetland for coastal communities using regression methods. The dependent variable is the log of damage per unit of gross domestic product, and the independent variables include the logs of wind speed and wetland area. The data set includes 34 major US hurricanes since 1980. It is found that a loss of one hectare of wetland in the model correspond to an average USD$33,000 increase in storm damage in specific storms. Using this relationship and the annual probability of hits by hurricanes of varying intensities, the value of coastal wetlands is mapped state by state.

2.4 Benefit transfer methods

Primary valuation of ecosystem service is time and money intensive. A low cost method of valuation is value transfer method, which is a procedure of estimating the value of an ecosystem by assigning an existing valuation estimate for a similar ecosystem.

There are three value transfer methods: unit value transfer where the value estimated for study sites (sites that we have values for) is used without adjustment, or with adjustment for income only, for policy sites (sites that need valuation); value function transfer (using an estimated value function from an individual primary study); and meta-analytic function transfer (using a value function estimated from the results of multiple primary studies) (Brander et al., 2012).

Marginal unit values for ecosystem services are likely to vary with the characteristics of the ecosystem site (area, integrity, type of ecosystem), beneficiaries (number, income, preferences), and context (availability of substitute and complementary sites and services). The transfer of values to an individual ecosystem site needs to account for variation in these characteristics between study sites (sites that we have values for) and policy sites (sites that need valuation). Otherwise, the transfer error is possibly large (Brander et al., 2012).

2.4.1 Benefit transfer for wetland

Brander et al. (2012) propose to use meta-analytic function transfer to estimate the demand curve of ecosystem services. Similar to other commodities such as oil where large changes in the total supply of the commodity will change the market equilibrium and therefore commodity price, Brander et al. argued that large changes in the total area of wetland would affect the value of ecosystem services delivered by one hectare of wetland. As a result, to obtain accurate estimates of the value of ecosystem services delivered by one hectare of wetland in a future scenario where the total area of wetland is significantly changed, it is essential to know the demand curve of ecosystem services.

The meta-analytic value function estimated by Brander et al. (2012) can be summarised as:

$$\ln y_i = \beta_0 + \beta_1 X_{1,i} + \ldots + \beta_n X_{\mathrm{n},i} + \varepsilon_i \ ,$$

where y_i is the value of ecosystem services provided by wetland *i* (measured in 2003 USD per hectare per year), and *X* are explanatory variables that cover valuation method (contingent valuation, choice experiment, hedonic pricing, travel cost method, replacement cost, net factor income, production function, market prices, opportunity cost, marginal valuation[1]), characteristics of the wetland (wetland type, wetland size before change), types of ecosystem services (flood control and storm buffering, surface and groundwater supply,

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[1] This is a dummy variable taking on a value of 1 if the study determines the marginal value, and 0 if it determines the average value.

water quality improvement, commercial fishing and hunting, recreational hunting, recreational fishing, harvesting of natural materials, fuel wood, non-consumptive recreation, amenity and aesthetics, natural habitat and biodiversity), the total area of wetland in the region and socio-economic and geographical characteristics of the site (real GDP per capita, population in 50 km radius, wetland area in 50 km radius). The estimated results are provided in Table 2 of Brander et al. (2012).

2.4.2 Benefit transfer for beach value

The study by Ghermandi and Nunes (2013) is conducted at the global scale for coastal recreational values, the results of which suggest that if one uses a zonal travel cost method to value a beach, the expected value of one hectare of beach per year is given by:

$$\exp(-1.166+0.001*Pre-0.01*HDM)*(GDP^{0.798})*(POP^{0.554})*$$

$$(\text{Anthropogenic pressure}^{(-0.23)})$$

where GDP is GDP per capita, POP is the population density within 20km of the beach, Anthropogenic pressure is an index that measures human pressure on the marine ecosystem within 20km of the site, as defined by Halpern et al. (2008). Pre is the average rain or snowfall during the wettest month of the year, and HDM is heating degree month defined as:

$$HDM = \max(18.3-Tjan, 0) + \max(18.3-Tfeb, 0)+\ldots+\max(18.3-Tdec,0),$$

where Tjan is the mean temperature in January.

2.5 Optimal Timing

Optimal timing has been found to be an important aspect in cost benefit analysis. The insight is that even though investing now may generate a positive net present value, deferring investment to a future time may provide even higher net present value. This is illustrated by Truong and Trück (2010) for the case of bushfire risk management.

In their study, Truong and Trück (2010) examine the optimal time to construct a fire trail that separates a residential housing area from an urban forest. The fire trail is costly to construct and, once it is constructed, the investment decision cannot be reversed (the fire trail cannot be sold, and construction materials cannot be re-used for other purposes). They found that the annual benefit of the project increases over time due to the increasing risk of bushfire under climate change. The annual cost of the project, which includes interest expense on the investment capital and maintenance cost, is constant over time. In the years when the annual benefit is lower than the annual cost, the project is not beneficial and it is best to time the investment to avoid these years. If the NPV of the project is positive, but the current annual benefit is lower than the current annual cost, then the NPV of the project can be increased by deferring investment to a future year. The optimal time to invest is when the annual benefit is equal to the annual cost. When the annual benefit is higher than the annual cost, it is optimal to invest immediately. As shown in Figure 3, immediate investment in the fire trail will result in a NPV of about $1.5 million. However, if the investment is deferred by one year, a much higher NPV can be obtained. More details on the model proposed by Truong and Trück (2010) are provided in Appendix A.

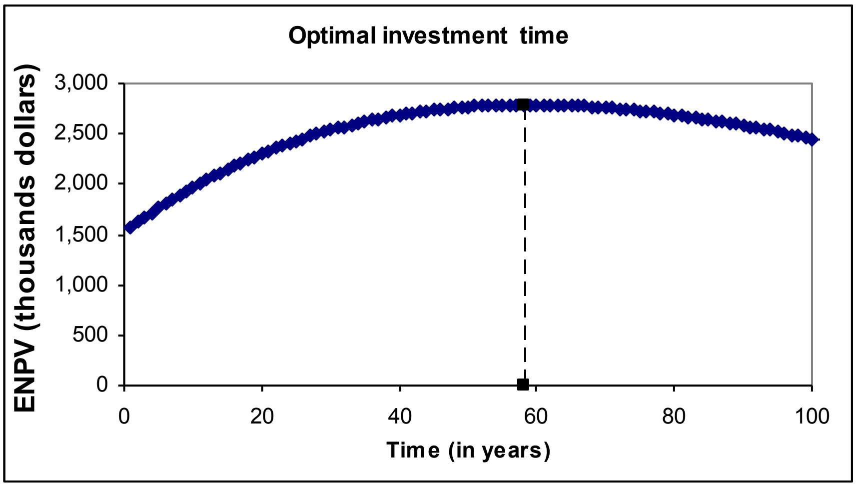

Figure 3 Optimal investment time for the fire trail project in Truong and Trück (2010).

2.6 Multi-Criteria Analysis

Multi-criteria analysis is a powerful valuation method for cases where it is not possible to monetize all project outputs. In many adaptation studies, one needs to incorporate the value of flexibility of adaptation options, the social costs induced by distributional effects of adaptation, and the aesthetic impact of adaptation strategies. MCA can help to integrate all these aspects in a single decision making framework in a meaningful way.

2.6.1 General Framework

Many MCA methods have been proposed in the literature, several of which may be quite complex and can be considered as a ‘black box’ by decision makers. A review of MCA methods is available in Govindan and Jepsen (2016).

In conducting a MCA to evaluate dairy effluent management options in Australia, Hajkowicz and Wheeler (2008) explicitly avoid ‘black box’ methods and use the weighted summation (WS) with linear transformation MCA method. This method is also called linear utility MCA method by Prato (2003). Hajkowicz and Wheeler (2008) also carry out the analysis with another method called PROMETHEE II, which is an outranking method, to check the robustness of the results. More details on these MCA methods can be found in Appendix B. We adopt the weighted summation or linear utility MCA method in this study.

Prato (2003) uses the weighted summation approach to rank five water management alternatives for the Missouri River system. However, instead of using standardised scores (as in the case of Hajkowicz and Wheeler, 2008), Prato (2003) used relative scores, where an alternative (usually the current management scheme) is selected as a base alternative and the performance of other alternatives is evaluated relative to the base alternative. Relative scores provide a sense of how different alternatives perform compared to a system that may be familiar to the decision maker (e.g. a system that is currently implemented), and may be more intuitive than standardised scores. Using relative scores, alternatives that have an overall performance score of 0 is considered as desirable as the base alternative while those with positive scores are more desirable. The advantage of relative scores is that the ranking of alternatives does not change when additional alternatives are considered. For standardised scores, additional alternatives may change the range of raw scores and change the ranking of alternatives (see Appendix C for more details).

Prato (2003) also outlines a non-linear utility using the square root functional form. However, because the relative scores can be negative, in which case the square root utility does not exist, the author does not use the non-linear utility function in his empirical evaluation.

2.6.2 Criteria weight elicitation

In conducting MCA, criteria weights play an important role and it is important to obtain an accurate evaluation of these weights. In environmental economics studies, criteria weights are obtained by asking decision makers direct questions about these weights (Prato, 2003). It is often quite difficult for decision makers to come up with criteria weights in that context. As suggested by Xia and Wu (2007), the weights obtained using this approach are often biased and the MCA results may be considered as unreliable.

de Almeida et al. (2016) present two methods for eliciting criteria weights. The first method, called ‘exact weight’, involves comparing an alternative with known performance scores in all criteria with another alternative that has the performance score in one criterion left unspecified. The decision maker is asked to specify the missing performance score for the second alternative so that he is indifferent between the two alternatives. This information is then used to calculate the weights.

The second method is called ‘flexible weight’. With this method, the decision maker is presented with two hypothetical alternatives whose performance scores are all specified. The decision maker is then asked to select the preferred alternative. The observed decision is used in a linear programming problem to infer criteria weights. We have designed a speadsheet tool to determine criteria weights for this second method.

2.6.3 Criteria selection

Regarding criteria selection for flood management, a summary of criteria used in ranking flood management alternatives in previous studies is provided by Chitsaz and Banihabib (2015). They indicate that expected annual damage is the most common criterion, followed by protection of wildlife habitat, then expected average number of casualties per year, and technical feasibility and construction speed.

3 Review of Climate Adaptation Studies in Coastal Areas

With climate change, the sea level is predicted to rise and the severity of storm surges is predicted to increase (Bernier and Thompson, 2006). These environmental changes may lead to aggravated problems of coastal erosion, surface salinity and flooding damages in coastal areas. Previous studies have examined the issue of whether to invest in hard protection measures such as dykes or sea walls and what is the optimal time to invest (Jonkman et al. 2009, Broekx et al. 2011, Woodward et al. 2011, Tsvetanov and Shav 2013, Lickley et al. 2014, Pol et al. 2014). Such measures may be more appropriate for developed regions where expensive buildings and infrastructures have been constructed. In less developed regions, soft protection measures such as wetland restoration or retreat may be a better option. Soft protection measures have been evaluated by Turner et al. (2007), Cardoso and Benhin, (2011), Lisetti et al. (2011), Martínez-Paz et al. (2013). In addition, the problem of alleviating coastal erosion has been examined by Yohe et al. (1995), van Vuren (2004), Smith et al. (2009), Roebeling et al. (2011), Arias et al. (2012). In the following, we provide a detailed review of some important studies to highlight the methods that have been used and the issues that are encountered in conducting project valuation for coastal adaptation. We will classify the studies by applied methods, i.e. CBA versus optimal timing, to focus on methodological issues.

3.1 CBA studies

Turner et al. (2007) provide a cost benefit analysis for managed realignment (retreat) scenarios as well as a holding the line strategy (maintain the position of the shoreline with protection strategies) for the Humber estuary in north east England. The construction of sea walls in the past effectively stops the natural and adaptive migration of ecosystems at the land-sea interface. In response to rising sea levels, a modified coast is unable to adapt by migrating landwards and valuable intertidal habitats are eventually lost through inundation and erosion. Loss of wetland reduces the ability of the intertidal zone to absorb energy and water, and reduces its ability to defend against waves and tides, especially during storm conditions. It also results in increased capital and maintenance costs for engineered defences. Loss of wetland also means loss of a number of ecosystem services it provides. Wetland represents significant reservoirs of biodiversity and attracts a range of conservation designations. Under the EU Water Framework Directive, the loss of conservation area must be compensated for on a 'like-for-like' basis. Managed retreat seems to offer a way of mitigating this problem by deliberately breaking defences, allowing the coastline to recede and the intertidal zone to expand.

Turner et al. (2007) deliberately select a study site that avoids trade-off between realignments and people, property assets and nature conservation designation sites to avoid the use of a mixed approach to coastal management. They suggest that when the policy appraisal involves complex social justice/nature conservation and ethical concerns, CBA will not be decisive and MCA is preferred.

Lisetti et al. (2011) provide a cost benefit analysis of realigning (retreating) the defence line for the east coast of England where flooding exacerbated by storm surge and sea level rise is a major issue. Existing sea walls help to protect buildings and infrastructure (including road and car parks), but also obstruct the migration of wetland that adapts to sea level rise. The status quo of maintaining existing sea walls would result in gradual loss of wetland while a managed realignment that move the sea walls landwards to maintain the wetland would result in a loss of agricultural land. Along the English east coast, coastal squeeze has resulted in complete loss of wetland, but managed realignment can create or restore wetland. The created or restored saltmarshes dissipate wave energy and provide a soft and more sustainable flood defence. They also provide ecosystem services including carbon storage benefits, fisheries productivity, recreation and amenity benefits (e.g. bird watching), existence value benefits (e.g. biodiversity maintenance) and reduction in maintenance cost for sea walls.

Lisetti et al. (2011) use market data to estimate the maintenance cost savings on hard defences and the benefit of fish production. They use the damage-cost-avoided method to value carbon storage benefits of wetland. For the recreation and amenity benefits of wetland, they use the stated preference method. Stated preference techniques are survey based studies in which respondents are asked to state their willingness to pay for a policy against a status quo policy. This technique may provide more accurate estimates of the regional specific values than the benefit transfer method when appropriately designed.

Roebeling et al. (2011) provide a cost benefit analysis for various adaptation measures, including construction of new groins, artificial nourishments, extension of existing groins and construction of longitudinal revetments to reduce coastal erosion. The benefits transfer approach is used to value coastal ecosystems and the wave climate is assumed constant. It is found that constructing new groins is not attractive while artificial nourishments, extension of existing groins and the construction of longitudinal revetments provide positive returns to investment.

Hinkel et al. (2013) provide a cost benefit analysis for a status quo of no protection and beach nourishment to deal with coastal erosion. In the status quo, if land for more valuable uses such as housing or industry is lost to erosion, then those activities would relocate elsewhere at the expense of the dominant agricultural or lower value land. The number of people forced to migrate is calculated as the product of the land area eroded and the average population density per segment, assuming the population is spread evenly over the area. Emigration is valued at three times per capita income. Buildings and infrastructure are assumed to be fully depreciated before being swallowed by the sea, based on the argument that erosion due to sea-level rise is a slow process and the losses can be anticipated.

Hinkel et al. (2013) assume that tourism income increases with population and regional income. This may be reasonable since tourists are often attracted to regions with more available recreational activities and services and is consistent with the findings by Ghermandi and Nunes (2013) that the visit frequency by tourists is positively correlated to the region's population and income. Therefore, as the region's land erodes, there is a decline in the population and in the income from tourism. In determining the level of nourishment, they assume that the marginal benefit of nourishment is comprised of only the land that is otherwise lost, and the marginal cost is the cost of nourishing sand. As a result, the optimal level of nourishment is binary, taking a value of zero if nourishment cost exceeds the land value and a value equal to erosion level otherwise.

3.2 Optimal timing studies

van Vuren et al. (2004) provide a framework to optimise beach nourishment timing for the Netherlands. The beach is assumed to erode at a linear rate due to sea level rise and storm surges. Erosion causes damage to the coastal area in terms of land and building structures such as restaurants, hotels, holiday resorts, etc. Damage by erosion is summarised by a damage function that takes recession level as the independent variable. van Vuren et al. (2004) consider nourishment as an erosion mitigation option. Nourishment has a fixed cost and a variable cost. The model provides the optimal times to renourish the beach and the corresponding nourishment cost.

Smith et al. (2009) provide a similar framework to optimise beach nourishment time for the U.S. In contrast to van Vuren et al. (2004), they argue that with nourishment, the beach not only erodes linearly due to the influence of sea level rise, but also exponentially due to the impact of nourishment that makes the facial profile of the beach steeper. Smith et al.'s (1995) model provides the optimal times to renourish the beach as well as the optimal beach width to be nourished.

McNamara et al. (2015) extend Smith et al.'s (2009) model to allow for storm surge risk. Both Smith et al. (2009) and McNamara et al. (2015) adjust the models developed in forestry economics using the analogy between nourishment and forest production: the nourishment cycle is similar to tree harvest cycle and storm surge risk is similar to fire risk. Erosion due to storm surge is often called short term erosion. It is often argued that short term erosion is usually followed by rapid short term accretion so that the net change is often negligible; see e.g. Hinkel et al. (2013).

Woodward et al. (2011) provide a real options framework to take into account climate change uncertainty and the value of investment flexibility in flood risk management[2]. In their study region, the flood defence system is due for refurbishment and rebuilding it to the existing height does not offer further protection if water levels increase in the future. Raising the crest level to the maximum height only offers limited protection since the base of the system is small and the maximal height is limited. Another alternative is to widen the base so that the height can be increased now or at a future time. Increasing the height now offers higher protection, but if water level remains unchanged in the future, investment in height may not justify the investment cost. A more flexible strategy is to leave the investment in height to a future time. Other alternatives to reduce flood risk include setting back defences (managed retreat), flood proofing properties and improving the flood warning system.

Woodward et al. (2011) evaluate three adaptation strategies for the Thames Estuary: refurbish defences, widen the base of the defence and raise crest level according to expected rise in sea level. The time horizon is 100 years and these adaptation strategies can be implemented in 2010 or 2040 only. Using different discount rates, Woodward et al. (2011) present the NPV of different adaptation strategies. It is found that real options have potential to provide significant economic benefits to long term flood risk management.

Jonkman et al. (2009) examine the optimal level of flood protection for New Orleans. In their model, each dike height corresponds to a certain probability of flooding. Increasing the height of the dyke reduces the probability of flooding and therefore the expected damage. When the dyke is already very high, the benefit of an additional increase in the dyke height (in terms of flood risk reduction) is low while the (construction) cost is high. Conversely, when the dyke is low, increasing the dyke height by one unit will have a large impact on flood risk while having only a small marginal construction cost. The total cost of expected flood damage and dyke construction cost, therefore, can be optimised with the dyke height. Jonkman et al. (2009) assume that damage increases at the rate of 1% per year due to economic growth and increasing flood probability (1% per year) as a result of sea level rise. To find the optimal level of protection, they consider safety levels of 1/100 (i.e. 1 in 100 year or more frequent events result in no damage), 1/500, 1/1000, 1/5000, 1/10000, 1/100000. The damages at these safety levels are obtained by using the corresponding storm surge level in a hydraulic simulation model. Jonkman et al. (2009) find that the optimal protection level is 1/1000, which is substantially higher than the level 1/100 often assumed as an engineering standard. The high protection level is attributed to the highly populated and therefore high exposure area of New Orleans.

Lickley et al. (2014) examine the optimal protection strategy over time to reduce the damage from flooding and sea level rise in a region. In their framework, for each time period, given the level of protection in place, the decision maker determines the additional level of protection to be developed (doing nothing is equal to zero additional protection). Lickley et al. (2014) estimate flood risk by using climatic conditions from Global Climate Models (GCM) together with a statistical-deterministic hurricane model (by Emanuel et al. 2006) to simulate a large set of synthetic hurricanes. Simulated storm data are then used in a hydrodynamic model (Overland Surges from Hurricane model by Jelesnianski et al. 1992) to generate storm surges. Sea level rise is modelled to shift the loss distribution over time. The

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[2] Although Woodward et al. (2011) are not specific in how they model real options, a good reference on the standard real options model can be found in Dixit and Pindyck (1994). When the benefit of the investment project is uncertain, and investment is irreversible, the decision to invest is similar to the decision to exercise an American call option. The optimal investment decision can be determined in the same way as for the call option.

framework is used in a case study to determine the optimal heights of the considered levee in each decade during period 2010-2100.

Tsvetanov and Shah (2013) examine the value of the option to delay investment in hard protection measures such as sea walls or levees to reduce damages from coastal floods. They use the HAZUS-MH MR4 risk assessment software developed by the Federal Emergency Management Agency to simulate floods and damages. The HAZUS model uses 100 year flood still-water elevation to compute the wave height at the shoreline. Wave height is then used in combination with wave peak periods and the faverage slope to calculate the so-called 'wave run-up' which is the height above still-water level reached by waves after breaking. Wave height and wave run-up, together with loss exposure obtained from census data, are then used to determine flood damages. To incorporate the impact of sea level rise, still-water elevations in future years are assumed to be the current elevation plus the sea level rise. Sea level rise is assumed to be linear in time.

Flood damages include (i) repair and replacement costs for damaged buildings, (ii) building content losses, (iii) building inventory losses, (iv) reallocation expenses for businesses and institutions, (v) capital related income losses, (vi) wage losses, (vii) rental income losses to building owners.

Tsvetanov and Shah (2013) assume that the sea barrier is constructed and expanded to protect the region against a 100-year flood or an event of smaller magnitude at all time. The cost of constructing sea barriers includes construction and maintenance cost, costs of future retrofitting, as well as social costs (loss of wetland, ocean view, recreational space, and shoreline erosion). Loss of recreational space and view can be accounted for as part of the initial costs and the cost of expanding the structure. Erosion and loss of wetland is generally a slow and continuous process and can be viewed as a variable cost component. Tsvetanov and Shah (2013), however, do not provide details on social costs, nor how they are obtained.

Mills et al. (2014) provide a framework to determine land use policy in a coastal area under the uncertainty of sea level rise. They consider a coastline with a wetland that is threatened by sea-level rise. They sought to decide how much land should be set aside to allow the wetland to migrate as sea-level rise advances. If the wetland's migration is obstructed by developed structures, the obstructed part of the wetland is lost. How far sea-level rise will increase is uncertain. The wetland migration distance that maximises the expected value of the wetland plus development is the optimum. The authors show that the optimal distance leads to significant increases in development benefits (by 119%, 99% and 64% for sea-level rise of 0.7, 0.95 and 1.2 m, respectively), and only a small decrease in the expected conservation benefit (by 2%) compared to the maximum distance that leaves the wetland unaffected by development.

Truong and Trück (2016) used Mills et al.'s (2014) framework to analyse the principal-agent problem that may arise in the context of coastal development under sea-level rise uncertainty. They suggest that the principal-agent problem (i.e. the mismatch of incentives to achieve the maximised social benefits due to development benefits accruing to property developers, and property losses and conservation benefits accruing to the society at large) may result in a suboptimal removal of the flexibility that can help society cope with the uncertainty of sea-level rise. A more serious consequence is that coastal regions that are developed with permanent structures (rather than socially optimal transportable structures) are likely to be protected in the case of high sea-level rise at the loss of environmental assets, due to the strong political power of coastal property owners.

To overcome the principal-agent problem, Truong and Trück (2016) suggest to insist upfront on the development of socially optimal structures in areas that are at inundation risk. For example, the use of removable properties has been incorporated into planned retreat policy of Byron Shire Council, NSW, Australia (Niven & Bardsley, 2013). The policy states that for the development to be approved, owners need to accept that the structure must be relocated or removed when the erosion escarpment encroaches to within 20 m of the structure. The use of removable structures reduces the social cost of purchasing costly permanent properties in high sea-level rise scenarios and provides the means to make full use of land in at-risk regions for development benefits. It is also a way to overcome the uncertainty posed by sea-level rise in development decision making.

Chapter 2. Case Studies

In this chapter, we present three worked out examples to illustrate the use of valuation methods for adaptation to coastal erosion. In the first example, we provide a multi-criteria analysis to integrate the flexibility value, the social cost, and the intangible impacts of adaptation options with their net present values. The framework is applied to Mollymook Beach in Shoalhaven. In the second example, we provide a cost benefit analysis for a sand nourishment program that takes into account coastal erosion uncertainty and Bayesian learning on this uncertainty over time. The framework is extended to consider a decision to invest in a groyne that helps to reduce beach nourishment cost. With erosion uncertainty explicitly considered and the investment in the groyne irreversible, the provided model is a real options model that provides better investment decisions compared to the usual net present value rule where investment is recommended whenever the NPV is positive. This framework is applied to a case study in Mandurah. In the third example, we conduct a cost benefit analysis that involves a valuation of land with historical values in Town Beach, Port Macquarie.

Description of innovative valuation frameworks is inevitably technical. To enable readers to grasp the main features of the framework and the main results, we provide a non-technical summary for each framework.

1. Case study 1: coastal erosion in Shoalhaven

Coastal erosion has been recognised as an important risk in eight beaches in Shoalhaven - the most visited local government area in NSW, outside of the Sydney region. To enable the management of erosion risk, the Council of Shoalhaven has commissioned a number of engineering studies to evaluate the risk in these beaches. These studies identified protection measures, including beach nourishment and seawall, for the beaches and provided some estimates on the cost of each measure.

Traditionally, ‘protect’ is considered as the default response to coastal erosion. However, as the height of the protection structures reaches a functional limit and cannot be increased further, and the cost of protection is realised to be expensive, more attention is now paid to retreat options (Rupp-Armstrong and Nicholls, 2007). The suitability of each adaptation option depends on the local context. In areas that are well developed, and have little space to move back, retreat may not be feasible and protection is preferred. The choice is then between beach nourishment and a protection structure. Beach nourishment is often expensive, but helps to maintain the beach for recreation activities. While protection structures may have a lower total (discounted) cost, they have the disadvantages of imposing negative visual impact on the beach and reducing the beach width as the sea level rises. Protection structures also have high sunk costs and are inflexible such that it is difficult to switch from a protection structure to other adaptation strategies at a future time.

In coastal areas that are less developed and have hinterland available for development, retreat may be less costly than protection. As suggested by Yohe et al. (1995), from the societal perspective, it is not the value of the coastal front land that is lost in the retreat policy, but the much lower value of hinterland. This feature makes retreat especially attractive in terms of economic values, but also problematic in terms of distributional effects. As the sea level rises and the coastal front properties are eroded, all properties behind the coastal front properties become nearer to the shoreline and increase in value. Although the owners of ocean front properties lose a large amount, a significant part of their loss is transferred via the market force to other property owners. The net loss to the society is effectively the loss of the eroded land, but valued at the price of hinterland. Substantial losses to ocean front property owners may create resistance to a retreat policy. Even if retreat provides substantially higher benefits than other options, in terms of beach recreational values and avoiding the high cost of protection, resistance from property owners may prevent retreat from being implemented.

Litigation cost is one source of social costs that may arise from distributional impacts of a retreat policy. Local councils can be liable to erosion damage or loss on residential land if they are aware of the risk caused by sea level rise and still approve development plans that do not deal adequately with the risk (Macken, 2006). They can also be accused of being negligent if they did not ask sufficiently probing questions of the developer. Until 2008, there have been a few local governments that consider climate change impacts when preparing development plans (Dunckley and Allen, 2008). The impact of litigation on policy implementation is clearly demonstrated by the case of Wellington Shire Council in Victoria. In 2008, when Wellington Shire Council in Victoria was about to introduce a plan to prevent further development in the 90 Mile Beach area, residents in the 90 Mile Beach area threatened the Council with legal action, suggesting that the plan would be seen as a bad signal to potential buyers and reduce their property values. The Council dropped the development ban, and allowed dwellings to be constructed with stricter building codes and on the condition that landowners indemnify the council of any responsibility in the event of flood (Dunckley and Allen 2008, Doherty 2008).

As protective structures, seawalls are increasing likely to be controversial as they may result in a reduction of beach width, altering waves so that they are less suitable for surfing and thus may be opposed by beach users. For example, Houghton (2016) documents the protests by surf loving activists in 2002 that forced Warringah Council to abandon the proposed plan to develop seawalls in Collaroy beach to protect houses in Sydney, Australia.

Given the significant impact of distributional effects, some studies have called for the incorporation of distributional effects of adaptation options into the decision making framework (Yohe et al. 1996, Clement et al. 2015, Niven and Bardsley, 2013). For example, Yohe et al. (1996) suggest that adopting the cost benefit paradigm that ignores transfers will mask social costs that could be enormous. Clement et al. (2015) suggest that ignoring redistributive conflicts when evaluating coastal management policies may undermine the relevance of cost benefit analysis in public decision making.

Distributional effects are, however, only one factor that can affect the selection of environmental policies. This is illustrated by the case of AB32 climate change mitigation policy in California that imposes major changes and costs on businesses and population, but was still strongly supported by voters in the 2010 general election. The acceptance of the policy is largely due to the population's understanding of the environmental problem addressed by the policy. In climate change adaptation, environmentalists may be divided in their opinions. Many environmentalists may not believe in the physics of anthropogenic warming and oppose or are simply unwilling to support adaptation policies (Mazmanian et al., 2013). It is important to acknowledge the uncertainty of climate change and to evaluate the flexibility that each adaptation option possesses to deal with the situation when uncertainty unfolds.

1.1 Non-technical summary

We introduce a multi-criteria framework that incorporates important aspects of adaptation decision making. Considered criteria include economic efficiency, loss to ocean front property owners, loss to beach users, adaptation flexibility and visual impact on the beach.

We introduce a method to elicit criteria weights developed in the logistic management literature to estimate criteria weights for the case study.

Economic efficiency is based on the economic value of the region obtained under the considered adaptation option, which is the sum of recreational value (estimated by previous travel cost studies) and the property values in the region, net of adaptation costs. For beach nourishment, it is the maximum value of the region that is obtained when nourishment time is optimised. The optimisation framework is important when there is a large fixed cost (e.g. costs of equipment deployment, environmental assessment and survey) involved with each case for nourishment. In such cases, annual or more frequent nourishment may be prohibitively costly. For a seawall, we assume that the base of the seawall is constructed now to protect against 1-in-100 year storm surges, and additional height is raised at the beginning of each decade in consistence with the sea level rise forecast for that decade. For retreat, we assume that 1m erosion leads to a loss of 1m of land and the structure on that land. The value of lost land is the value of interior land, rather than that of ocean front land. Note that one could consider also a mixed protection strategy, e.g. nourishing the beach for some time and then switch to a seawall. However, when uncertainty is not explicitly considered, Neumann et al. (2011) suggest that such a strategy is not optimal. In the presence of uncertainty, it may be optimal to nourish the beach while waiting for the uncertainty to resolve, and switch to other adaptation options when the level of erosion becomes more certain. Such a strategy of maintaining the decision making flexibility is considered when we evaluate the flexibility value of each adaptation option.

To evaluate the flexibility of an adaptation option, we use a real options framework similar to the model proposed by Mills et al. (2014). We define the flexibility value of an adaptation option as the sum of the region's value in the first 20 years under that adaptation option and the value obtained for the remaining 80 years when sea level rise uncertainty unfolds: therefore an optimal adaptation is selected with the recognition that the initial adaptation option is in place. For example, if a seawall is implemented at the initial time, then other adaptation options cannot be selected when further information about sea level rise is available. This is due to the high sunk cost of constructing the seawall and the high cost to remove the seawall. It may also be due to the litigation from property owners that prevents governments from reversing the seawall constructions. In contrast, it is possible to switch to other adaptation options if retreat or beach nourishment is chosen at the initial time. Note that although both retreat and beach nourishment are both flexible and allow the decision maker to switch to other adaptation options at a future time, they have different costs of maintaining flexibility. In using the flexibility value, we consider both the flexibility and the cost of maintaining that flexibility by each adaptation option.

To investigate potential social costs of adaptation options, we calculate the loss borne by ocean front property owners and by beach users. Loss is calculated as the difference between the value obtained by a stakeholder when there is no sea level rise and the value obtained when there is sea level rise with the impact of sea level rise alleviated by a selected adaptation measure.

The visual impact of the adaptation alternatives is evaluated based on 1-5 rating schemes where 1 represents minimal visual impact and 5 represents very strong (negative) visual impact. This evaluation can be conducted with a group of experts, or stakeholders as done by Mathew et al. (2012).

The obtained performance scores of adaptation options are then standardised for each criterion, so that they are between zero and one. The weights for the criteria are elicited by asking the decision maker to specify a performance score in one criterion of a hypothetical adaptation option B so that it is as preferred to a pre-specified (hypothetical) adaptation option A.

The empirical results for the Mollymook Beach of Shoalhaven can be summarised as follows. The economic value obtained from the region using different adaptation strategies for different sea level rise scenarios are presented in Table 1. Although for all adaptation strategies, the economic value obtained in the region is lower when sea level rise is higher, some interesting patterns emerge when adaptation strategies are compared. Retreat provides the highest values under all scenarios while the value provided by beach nourishment is higher than the value obtained for building a seawall when the sea level rise is low and is lower when the sea level rise is high. For the median level of sea level rise, retreat provides the highest value, followed by the seawall and then beach nourishment. The superior performance of retreat is largely due to the high supply and low price of interior land in the area. Note that we use the price of residential land, which is many times higher than the price of agricultural land. If the price of agricultural land is used, the economic value under retreat is even higher.

Table 1 Economic values of the region under different adaptation options across different sea level rise scenarios ($M).

Sea level rise (cm)	Retreat	Nourishment	Seawall
32	138.45	115.60	112.33
61	136.28	106.83	108.29
90	134.12	98.95	104.00

To obtain the flexibility value for each adaptation option, it is necessary to consider the optimal adaptation when sea level rise uncertainty unfolds. The concept of uncertainty needs to be formalised. This is done by considering the lower to upper levels of sea level rise in Table 1 as a 95% confidence interval of a normal distribution. The normal distribution is then discretised to give a discrete distribution of sea level rise as in Table 2, where each level of sea rise has a probability of 0.2. As shown in Table 2, if retreat or nourishment is selected at time t = 0, then for all sea level rise scenarios, retreat provides the highest value to the region from year 20 onwards. Conditional on retreat being selected at time t=0, the value obtained for the remaining periods from year 20 onwards is 0.2×(55.91+54.81+54.52+54.24+53.23) = $54.54M. The value obtained from implementing retreat at the initial time is obtained by adding the value obtained in the first 20 years ($81.76M) to $54.54M, which gives $136.30M.

For the case where beach nourishment is selected at t=0, since the optimal nourishment cycle is 19.5 years, which means that sea-level rise uncertainty unfolds just after the beach is re-nourished. Since the beach width and the adaptation options to be selected are the same as the case when retreat is selected at t = 0, the values obtained from year 20 onwards conditional on nourishment being selected at t = 0 are the same as the case when retreat is selected at t=0. For the provided case study, retreat is the optimal choice for any realisation of sea level rise and the expected value obtained from year 20 onwards is $54.54M. Since the value obtained in the first 20 years from beach nourishment is $75.64M, the value obtained from implementing beach nourishment at time $t= 0$ is then $130.18M.

In contrast, if the decision maker selects constructing a seawall at the initial time, then retreat and nourishment cannot be adopted when sea-level rise is realised. The expected value obtained from year 20 onwards is 0.2×(54.98+51.30+50.28+49.24+45.34) = $50.23M.

The value obtained from implementing a seawall at the beginning is, therefore, $50.23M plus the value obtained in the first 20 years ($58.01M), which is $108.24M.

Table 2 Values obtained from year 20 onwards conditional on the adaptation selected at initial time t=0 ($M).

SLR (cm)	Retreat or Nourishment at t = 0			Seawall at t=0
	Retreat	Nourishment	Seawall	Seawall
14.35	55.91	50.23	45.76	54.98
51.35	54.81	45.57	43.85	51.30
61.00	54.52	44.52	43.43	50.28
70.60	54.24	43.48	42.81	49.24
104.40	53.23	40.10	40.89	45.34

Distributional effects of different adaptation options are shown in Table 3. The loss borne by ocean front property owners is largest under the retreat option, followed by seawall and then beach nourishment. In contrast, beach users lose most under the seawall scenariol, followed by beach nourishment. Retreat does not result in any loss to beach users since the beach width is maintained constant over time. For both property owners and beach users, losses are higher when the sea level rise is higher.

Table 3 Losses to different stakeholders across sea level rise scenarios ($M).

SLR (cm)	Ocean front property owners			Beach users		
	Retreat	Nourishment	Seawall	Retreat	Nourishment	Seawall
32	6.24	2.07	2.23	0	1.40	1.51
61	11.90	2.67	4.39	0	1.81	2.97
90	17.55	3.12	6.70	0	2.11	4.53

The performance scores of adaptation options under different criteria are summarised in Table 4. The standardised performance and weighted scores of these adaptation options are shown in Table 5. As can be seen from Table 5, even when the weight attached to the loss to ocean front property owners is quite high, retreat is still a preferred adaptation option due to its high economic performance, its flexibility value, its zero loss to beach users and the low visual impact. Given the assumptions for this case study, the second best option is provided by the nourishment strategy, while building a seawall is the least preferred option.

Table 4 Performance of adaptation alternatives.

Criteria	Retreat	Nourishment	Seawall
Economic efficiency (NPV)	$136.28M	$106.83M	$108.29M
Flexibility value	$136.30M	$130.18M	$108.24M
Loss to ocean front property owners	$11.90M	$2.67M	$4.39M
Loss to beach users	$0.00M	$1.81M	$2.97M
Visual impact	1	2	5

Table 5 Standardised performance and weighted scores of adaptation alternatives

Criteria	Retreat	Nourishment	Seawall	Weight
Economic efficiency (NPV)	1	0	0.0496	0.3839
Flexibility value	1	0.7819	0	0.1850
Loss to ocean front property owners	0	1	0.8137	0.2433
Loss to beach users	1	0.3906	0	0.0783
Visual impact	1	0.75	0	0.1055
Weighted score	0.76	0.5	0.22	

In summary, we provide a multi-criteria analysis that takes into account economic efficiency, adaptation flexibility, social costs resulted from distributional impacts and visual impacts of adaptation options. Empirical results show that retreat can result in a much higher economic value compared to protection measures, which is due largely to the relatively low value of interior land. In addition, retreat does not cause losses to beach users and has low visual impact. The acceptance of retreat, however, depends significantly on the society's understanding of the impacts of each adaptation option. It is therefore important to provide education on climate change and adaptation impacts so that the society appreciates the implementation of a retreat strategy. When retreat is not yet readily accepted, nourishment can be used to preserve the flexibility.

1.2 Modelling framework[3]

1.2.1 Multi-Criteria Analysis

We consider the problem of ranking *M* alternatives based on *N* attributes. Let the performance of alternative *j* on attribute *i* be x_{ij}, then alternative *j* can be represented by $X_j = (x_{1j},...,x_{Nj})$. Also, let $\overline{x}_i$ be the maximum performance in attribute i, i.e. $\overline{x}_i = \max_j x_{ij}$, and $\underline{x}_i$ be the minimum performance in attribute *i*. We use an additive utility function that has been widely used in environmental economic studies (see, for example, Prato (2003), Hajkowicz and Wheeler (2008) to represent the preference of the decision maker:

$$U(X_j) = \sum_{i=1}^{N} k_i u(x_{ij}), \tag{1}$$

where k_i is the weight attached to attribute *i* and $u(.)$ is a standardising function that takes the form:

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[3] This section follows closely the work and framework provided in Truong et al. (2016).

$$u(x_{ij}) = \begin{cases} \dfrac{x_{ij} - \underline{x}_i}{\overline{x}_i - \underline{x}_i} & \text{for positive attributes where more is better} \\[2ex] \dfrac{\overline{x}_i - x_{ij}}{\overline{x}_i - \underline{x}_i} & \text{for negative attributes where less is better.} \end{cases}$$

Through function $u(.)$, raw performance scores are converted to standardised performance scores that are in the interval [0, 1]. An alternative *j* that has the best performance in attribute *i* will get a standardised score $u(x_{ij}) = 1$, while an alternative l that has the worst performance in attribute i will obtain a standardised score $u(x_{ij}) = 0$. With utility function (1) , alternative j is selected over alternative l if $U(X_j) > U(X_l)$.

1.2.2 Criteria Weight Elicitation

Ranking alternatives requires an elicitation of the weight k_i for each attribute *i* (assuming that we have determined performance X_j for each alternative j using methods in the sections below). We elicit attribute weights by using the method developed in the logistics management literature (see, for example, Barla 2003, Xia and Wu 2007, de Almeida et al. 2016). Specifically, we present the decision maker with a hypothetical alternative *A* that has the best performance in the first attribute and the worst performance in all other attributes, i.e. $u(x_{1A}) = 1$ and $u(x_{iA})|_{i \neq 1} = 0$, and another hypothetical alternative *B* that is different from *A* in only two aspects: (1) the performance of *B* in the first attribute is marginally lower than that of *A* by 1 unit, and (2) the performance of *B* in attribute h, $h \neq 1$, remains to be specified. We then ask the decision maker to specify the performance of alternative *B* in attribute h, x_{hB}, so that she is indifferent between *A* and *B*. Since $U(X_A) = U(X_B)$, we obtain a relation between k_1 and k_h:

$$k_1 = k_1 u(x_{1A} - 1) + k_h u(x_{hB}), \quad h = 2, \dots, N. \tag{2}$$

Relations (2) can be used together with the condition that all weights adding up to 1 to determine attribute weights $k_1, \dots, k_N$. In the following, we will consider the problem of ranking three options to adapt to coastal erosion: retreat, beach nourishment and building a seawall. We will consider five attributes: i) the net present value (NPV) of the option, ii) flexibility value, iii) loss borne by property owners, iv) loss borne by beach users, and v) the visual impacts on the beach.

1.2.3 Valuing the beach

The beach provides aesthetic and environmental benefits for recreational activities that may include swimming, sunbathing and surfing and other water sports. The value offered by the beach view is partly capitalised in the value of ocean front properties, while the value obtained from recreation can be measured based on the willingness to pay of beach users and the frequency of their visits. The sum of the ocean front property values and the recreational value can be used as an estimate for the value of the beach.

As suggested by previous studies Gopalakrishnan et al. (2011) and Mcnamara et al. (2015), the value of the beach depends on width of the beach. A wider beach reduces erosion and flooding risk for ocean front properties, thus increases its value. A wider beach also provides more space for recreation and reduces the crowdedness. Following Gopalakrishnan et al.

(2011), we model the value of the beach to depend on the beach width according to a power function:

$$V_B = A_1 w^{\beta_1} + A_2 w^{\beta_2} \ , \tag{3}$$

where *w* is the width of the beach, β_1 is the beach width elasticity of ocean front property prices, β_2 is the beach width elasticity of recreational value and A_1 and A_2 are constants. In Equation (3), the first component is the value of ocean front properties and the second component is the recreational value of the beach.

1.2.4 Retreat

With the wide trend of coastal squeeze and the high cost of holding the line, retreat is being seriously considered in Europe and other areas (Rupp-Armstrong and Nicholls 2007, Ledoux, and Turner 2002). In the case when retreat is implemented, we assume that no protection is provided. As a result, one metre of recession will result in a loss of one metre of land and any structure on that land. As discussed above, the land value that is lost is not the value of ocean front land but the value of the interior land. In addition, with the retreat strategy, inland migration of the beach is not hindered by any protection structure and the beach width can be assumed to be constant over time.

Given the lack of evidence of accelerated sea level rise, at least in Australia (Watson, 2011), we assume that the sea level will rise at a constant rate of α metres per year so that given the current level $S_0 = 0$, the sea level S_t at time t is given by:

$$S_t = \alpha t$$

This assumption has been adopted in previous studies, see e.g. Smith et al. (2009), Gopalakrishnan et al. (2011). As the sea level rises at rate α, the beach is assumed to recede at the rate $b\alpha$ metres per year, where *b*>1. The value of land that is lost to erosion in year t is then $b\alpha P_t$, where P_t is the price of hinterland in year t. Assume that the value of structures is distributed uniformly in the region and let H_t be the value of structures over 1 metre cross-shore length at time t, then the value of structures lost to erosion in year t is $b\alpha H_t$. The discounted value of land and structures lost to erosion over period (0, T] is then

$$\sum_{t=1}^{T} e^{-rt} b\alpha (P_t + H_t), \tag{4}$$

where *r* is the discount rate. The NPV of retreat is then

$$B = A_1 w_0^{\beta_1} + A_2 w_0^{\beta_2} - \sum_{t=1}^{T} e^{-rt} b\alpha (P_t + H_t) \tag{5}$$

In (5), the third component is the loss due to erosion, which may not be large since the land price P_t is the price of hinterland, rather than the price of ocean front land. The loss to ocean front property owners may be much larger. Let *L* be the length of ocean front properties, then the loss to ocean front property owners in year t is $b\alpha \frac{A_1 w_0^{\beta_1}}{L}$ and the loss over period (0, T] is given by:

$$\sum e^{-rt} b\alpha \frac{A_1 w_0^{\beta_1}}{L}. \tag{6}$$

Note that each period, erosion causes a loss of $b\alpha \frac{A_1 w_0^{\beta}}{L}$ to current ocean front properties owners. However, a value $b\alpha(\frac{A_1 w_0^{\beta}}{L} - P_t - H_t)$ is gained by other property owners in terms of rising property values. The net loss to the society is therefore only $b\alpha(P_t + H_t)$.

1.2.5 Beach nourishment

In the absence of fixed cost, a beach can be optimally nourished whenever erosion is observed. However, as suggested by Smith et al. (2009), there are usually high fixed costs involved with nourishment including equipment mobilisation and environmental assessments and surveys. In this case, it is optimal to nourish the beach only after a certain number of years when erosion is sufficient to justify the fixed cost. The optimal time to nourish can be determined using the framework proposed by Smith et al. (2009).

Smith et al. (2009) model beach erosion to be composed of two components, an exponential erosion component that occurs for a nourished beach and a linear component that is due to sea level rise. Exponential erosion occurs in nourished beach due to the steepened shore face that is established after nourishment and the fact that added sand tends to be eroded more quickly than the original sand. Using Smith et al. (2009)'s model, the beach width at time t is given by:

$$w_t = (1-\mu)w_0 + \mu e^{-\theta t} w_0 - b\alpha t \tag{7}$$

In Equation (7), μ is the fraction of the initial beach width w_0 that erodes exponentially, θ is the rate of exponential erosion, and $b\alpha t$ is the erosion due to sea level rise. When $\mu = 0$, erosion is induced by sea-level rise only.

The nourishment cost is composed of a fixed cost *c* and a variable cost that is linear in the build-out width of the beach. The linearity is due to the Bruun rule that suggests that the amount of sand required to nourish 1 metre of the beach width is constant (Smith et al. 2009). We suppose that the beach is nourished every τ years when its width reduces from w_0 to w_τ. The cost of one nourishment is then:

$$C = c + \phi(w_0 - w_\tau), \tag{8}$$

where ϕ is the variable cost that involves a conversion from beach width to sand volume. The net value obtained in one cycle is:

$$v = \sum_{t=1}^{\tau} e^{-rt} r A w_t^{\beta} - [c + \phi(w_0 - w_\tau)]$$

and the value obtained over all cycles is:

$$NPV(\tau) = v + e^{-r\tau} v + e^{-2r\tau} v + ... = v / [1 - e^{-r\tau}] .$$

The optimal nourishment cycle time τ^* can be determined using numerical optimization (e.g. using the Excel solver), and the NPV of beach nourishment at the optimal times can be obtained accordingly. Assume that the cost of nourishment is borne by the public, the value obtained by property owners is

$$\sum_{t=1}^{\tau^*} e^{-rt} r A_1 w_t^{\beta_1} / [1 - e^{-r\tau^*}].$$

The loss borne by property owners is the difference between the value of the properties when the beach width remains at w_0 and the property value when the beach width is eroded by sea level rise but optimally managed with beach nourishment:

$$A_1 w_0^{\beta_1} - \sum_{t=1}^{\tau^*} e^{-rt} r A_1 w_t^{\beta_1} / [1 - e^{-r\tau^*}].$$

Similarly, the loss to beach users is:

$$A_2 w_0^{\beta_2} - \sum_{t=1}^{\tau^*} e^{-rt} r A_2 w_t^{\beta_2} / [1 - e^{-r\tau^*}].$$

1.2.6 Seawall

We assume that the seawall is designed to allow the height to be raised incrementally to reduce the sunk cost of the seawall and improve the flexibility of this adaptation strategy. Such a design has been adopted in the study by Ng and Mendelsohn (2005). Furthermore, the height of the seawall starts from h_{t_0} when it is initially constructed, and increases every 10 years in anticipation of sea level rise over that 10 year period. The cost of seawall construction is assumed to be proportional to the square of the height of the seawall, as suggested in previous studies, see e.g. Yohe et al. (1999), Ng and Mendelsohn (2005) and DCCEE (2009):

$$K = \psi \times h^2 \times \Delta,$$

where ψ is the cost of constructing a 1 metre tall and 1 metre long seawall, *h* is the height of the seawall, and Δ is the length of the seawall.

Although the eventual cost at the end of the time horizon T is $\psi \times h_T^2 \times \Delta$, this cost incurs gradually over time, with $\psi \times h_{t_0}^2 \times \Delta$ occurring at time t_0, $\psi \times (h_{t_0+10}^2 - h_{t_0}^2) \times \Delta$ at time $t_0 + 10$ and so on. This reduces the discounted cost of the seawall and also allows the construction of the seawall to respond to observed sea level rise to some extent.

We also assume that when the seawall is installed, the maximum beach width is restricted by the distance from the water line to the seawall. As a result of sea level rise, the width of the beach evolves as:

$$w_t = w_0 - b\alpha t \tag{9}$$

The NPV of this strategy is then

$$\sum_{t=1}^{T} e^{-rt} r[A_1 (w_0 - b\alpha t)^{\beta_1} + A_2 (w_0 - b\alpha t)^{\beta_2}] - I,$$

where $I = \sum_{i=1}^{T/10} \psi(h_{t_i}^2 - h_{t_{i-1}}^2)\Delta$ is the investment cost of the seawall.

Assume that the investment cost is borne by the public, the value obtained by property owners is:

$$\sum_{t=1}^{T} e^{-rt} r A_1 (w_0 - b\alpha t)^{\beta_1} \quad ,$$

and the loss borne by ocean front property owners is

$$A_1 w_0^{\beta_1} - \sum_{t=1}^{T} e^{-rt} r A_1 (w_0 - b\alpha t)^{\beta_1} \ .$$

The loss to beach users is:

$$A_2 w_0^{\beta_2} - \sum_{t=1}^{T} e^{-rt} r A_2 (w_0 - b\alpha t)^{\beta_2} \ .$$

1.2.7 Adaptation flexibility

Adaptation flexibility is an important factor that helps to deal effectively with the uncertainty of climate change. As discussed by Dixit and Pindyck (1994), high sunk costs of investment projects make decision making after project investment less flexible. After committing to an investment decision that is difficult to reverse due to high sunk costs, it is difficult for the decision maker to adopt alternative strategies to react when uncertainty unfolds. Hallegatte (2009) suggests various strategies to maintain flexibility, including investing in small projects first and only investing in projects with large investment costs when climate change is serious. In addition, a large project should be designed in a way that it can be invested in sequential stages such that the cost of the project can be gradually committed based on climate change observations. Ekström and Björnsson (2005) suggest that real options values can be used as a measure of flexibility since it is objective and it also provides a sense of economic significance of flexibility in the considered context.

In this paper, we use a simple real options model proposed by Mills et al. (2014) to provide a test on the flexibility of adaptation measures. In particular, we assume that the uncertainty of sea-level rise remains until year 20 when the level of sea rise unfolds and remains constant thereafter. Conditional on the adaptation option selected at the initial time, the decision maker then selects the adaptation option that maximises the regional net benefit for the remaining time periods. For example, having constructed the seawall, the decision maker may not have any other choices other than maintaining and raising the seawall[4]. In contrast, with retreat or beach nourishment, the adaptation measure can be changed to one of the three measures upon observing sea-level rise. Prior to the realisation of sea-level rise, cost and benefit of each adaptation option are evaluated at the most likely sea-level rise, i.e. the

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[4] Theoretically, any installed seawall can be dismantled, possibly at substantial costs. However, litigation from property owners may prevent the government from reversing seawall constructions. For example, in a recent court case in 2010, Byron Shire Council is ordered by the court to maintain a geobag revetment that the Council has approved in 2001 in front of a residential property to protect the property from coastal erosion (Elliott, 2010).

median level. The flexibility value of an adaptation measure is the sum of net value obtained from that measure in the first 20 years and the expected value obtained from year 20 onwards when the decision maker selects the optimal adaptation conditional on the measure she selected at time t=0.

1.3 Parameter estimation

We apply the proposed framework to Mollymook beach. To estimate the loss in land value when the coast erodes in Mollymook, we use the land value in Milton, a suburb that is more than three kilometres away from the coastline of Mollymook beach. The distance of Milton is sufficient since Gopalakrishnan (2010) found that beach width stops to affect the prices of properties that are over 100 metres from the beach. In 2015, a parcel of 675 m^2 of residential land in Milton (4 Porter CCT, Milton) is valued at $135,000. This gives a price of $200 per m^2 of land.

Table 6 Estimated parameters

Parameters	Value
Base value of ocean properties (A_1)	$10,844,353
Base value of public recreation (A_2)	$7,331,170
Initial beach width	60 (m)
Beach length	2070 (m)
Elasticity of beach value w.r.t beach width	0.5
Residential land value	$200/(m2)
Annual recession rate	0.423 (m)
Sand volume to nourish 1m beach width	43,333 (m3)
Fixed cost per nourishment	$9,750,000
Variable cost of nourishment	$30/m3
Value of structures per 1m of cross shore length	$299,326
Discount rate	4.5%

Parameters for optimising beach nourishment are estimated as follows. In Mollymook, the beach recedes at the rate of $b\alpha = 0.423$ m per year, it takes 43,333 m^3 of sand to extend the beach width by one metre, according to SCC (2012). To estimate the cost of nourishment, we use data provided by AECOM (2010). According to AECOM (2010), equipment required to dredge and mobilise sand needs to be engaged from overseas and the cost of equipment mobilisation depends on the scale of operation. The total equipment mobilisation and environmental studies for four beaches (Collaroy, Narrabeen Lagoon, Manly, Cronulla) is $39M, which gives a fixed cost of $9.75M per beach. The cost per one cubic metre of sand is $30 and the amount of sand to nourish one metre width of beach is 43,333 m^3 as estimated by SCC (2012). This gives the variable cost for Mollymook is $1.33602M per one metre of beach width.

To estimate the value of structures, we use the number of houses at Mollymook beach estimated by ABS (2011), which is 861 houses. The replacement cost of a house is calculated by subtracting the land value from the property value. We use property at Oxley Cres, Mollymook Beach NSW 2539, that has a land value of $177,000, and a property value of $490,000, which gives a replacement cost of $313,000 per house. These houses are located on the average cross shore length of 1.2km, and the value of structure per one metre of cross shore length is then $313,000*861 /1200=$224,577. In addition, the value of infrastructure across the 93m cross shore length is 17.5M (SCC, 2012), which gives \$188,172 per one metre of cross shore length. The total value of structures per one metre of cross shore length is then \$299,326.

For the seawall, the initial height required to bear a 1-in-100 year storm surge is six metres and it costs \$23,000 to build a seawall that is one metre long and six metres high (SCC, 2012). Based on this information, the estimate of ψ is \$639. The required length of the seawall to protect properties is 1055 metres. Estimated parameters are summarised in Table 6.

1.4 Empirical Results

1.4.1 Cost benefit analysis

The economic value obtained from the region using different adaptation strategies for different sea level rise scenarios are presented in Table 1. For all adaptation strategies the economic value obtained in the region is lower when sea level rise is higher, however comparison of adaptation strategies reveals some interesting patterns. Retreat provides the highest values under all scenarios while the value provided by beach nourishment is higher than the value obtained building a seawall when the sea level rise is low and is lower when the sea level rise is high. For the median level of sea level rise, retreat provides the highest value, followed by building a seawall and then beach nourishment.

1.4.2 Flexibility value

Suppose that retreat is adopted at time t=0. In 20 years' time when the level of sea rise is realised, any of the three adaptation strategies can be selected. As shown in Table 2, regardless of the realised sea level rise, retreat provides the highest value to the region and is still the preferred adaptation option. Conditional on retreat being selected at time t=0, the value obtained for the remaining periods from year 20 onwards is 0.2 ×(55.91+54.81+54.52+54.24+53.23) = \$54.54M. The value obtained from implementing retreat at the initial time is obtained by adding the value obtained in the first 20 years (\$81.76M) to \$54.54M, which is \$136.30M.

For the case where beach nourishment is selected at t=0, since the optimal nourishment cycle is 19.5 years, the sea-level rise uncertainty unfolds just after the beach is re-nourished. The beach width at the time of sea-level rise realisation is then 60m. Since any of the three adaptation strategies can be selected and the initial beach width is the same as in the case that retreat is adopted at time t=0, the value obtained for each level of sea-level rise is the same as the case when retreat is adopted at time t=0. Retreat is the optimal choice and the expected value obtained from year 20 onwards is \$54.54M. Since the value obtained in the first 20 years from beach nourishment is \$75.64M, the value obtained from implementing beach nourishment at time t= 0 is then \$130.18M.

In contrast, if the decision maker selects seawall at the initial time, then retreat and nourishment cannot be adopted when sea-level rise is realised. The expected value obtained from year 20 onwards is 0.2×(54.98+51.30+50.28+49.24+45.34) = \$50.23M. The value obtained from implementing a seawall at the beginning is, therefore, \$50.23M plus the value obtained in the first 20 years (\$58.01M), which is \$108.24M.

1.4.3 Distributional effects

To investigate potential social costs of adaptation option, we calculate the loss borne by ocean front property owners and by beach users across different sea level rise scenarios. Loss is calculated as the difference between the value obtained by a stakeholder when there is no sea level rise and the value obtained when there is sea level rise with the impact of sea level rise being alleviated by a selected adaptation measure. As can be seen from Table 3, the loss borne by ocean front property owners is largest under the retreat option, followed by seawall and then beach nourishment. In contrast, beach users lose most under the seawall scenario, followed by beach nourishment. We assume that retreat does not result in any loss to beach users since the beach width is maintained constant over time. For both property owners and beach users, losses are higher when the sea level rise is higher.

1.4.4 Baseline analysis

The results of cost benefit analysis, distributional effect analysis and flexibility analysis for the three adaptation options are summarised in Table 4. In addition, we also present the valuation of visual impact of the adaptation alternatives based on a 1-5 rating scheme, where 1 represents minimal visual impact and 5 represents very strong (negative) visual impact.

As shown in Table 4, although retreat provides the highest value to the society as a whole, is the most flexible option, results in no loss to beach users and has little visual impact on the beach, it results in a large loss to ocean front property owners. Beach nourishment, on the other hand, provides the least value to the region, but result in the least cost to property owners while it also maintains adaptation flexibility. Flexibility maintained by the nourishment strategy is important since in the future, when the society is more receiving towards retreat or when more information on sea level rise is available, it is possible to switch from nourishment to other adaptation strategies to adapt to the new situation. As can be seen, if it is possible to switch from nourishment to retreat in 20 years' time, then the economic value provided by nourishment is similar to that provided by retreat. In contrast, while the seawall currently provides a higher economic value than nourishment, it provides a far lower value when reaction to new information at a future time is allowed for, due to the inability of the decision maker to switch from a seawall to other options. In addition, the seawall also results in the highest loss to beach users, high loss to ocean front property owners and has the highest visual impact on the beach.

1.4.5 Multi-criteria analysis

The weights of the five criteria can be elicited as follows. First, we ask the DM to consider a hypothetical adaptation option A that has the highest NPV of \$136.28M, the worst flexibility value (\$108.24M), the worst loss to property owners (\$11.90M), the worst loss to beach users (\$2.97M) and the worst visual impact, which can be represented by $X_A = (136.28, 108.24, 11.90, 2.97, 5)$. We then present the DM with another adaptation option B that has a NPV of \$1M lower than the highest NPV, a flexibility value of x_{2B} to be determined, the worst loss to property owners (\$11.90M), the worst loss to beach users (\$2.97M) and the worst visual impact, i.e. $X_B = (135.28, x_{2B}, 11.90, 2.97, 5)$. We then ask the DM to specify x_{2B} so that she is indifferent between A and B. Suppose the DM specifies that $x_{2B} = 110.24$, i.e. to compensate for the reduction in the NPV by \$1M, the DM requires a potential gain of \$2M when uncertainty about sea-level rise unfolds.

In the second step, we present the DM with an adaptation option C that has a NPV of \$1M lower than the highest NPV, the worst flexibility value (\$108.24M), a loss to ocean front property owners of x_{3C} to be determined, the worst loss to beach users (\$2.97M) and the worst visual impact, i.e. $X_C = (135.28, 108.24, x_{3C}, 2.97, 5)$. We ask the DM to specify x_{3C} so that she is indifferent between C and A. Suppose the DM specifies that x_{3C}=11.40, i.e. to compensate for a reduction of the NPV of $1M, the loss to property owners needs to be decreased by $0.5M.

In the third step, we present the DM with an adaptation option D that has a NPV of $1M lower than the highest NPV, the worst flexibility value ($108.24M), the worst loss to property owners ($11.90M), a loss to beach users of x_{4D} to be determined and the worst visual impact, i.e. $X_D = (135.28, 108.24, 11.90, x_{4D}, 5)$. We ask the DM to specify x_{4D} so that she is indifferent between D and A. Suppose the DM specifies that x_{4D}=2.47, i.e. to compensate for a reduction of the NPV of $1M, the loss to beach users needs to be decreased by $0.5M.

In the last step, we present the DM with an adaptation option E that has a NPV of $1M lower than the highest NPV, the worst flexibility value ($108.24M), the worst loss to property owners ($11.90M), the worst loss to beach users ($2.97M), and a visual impact score x_{5E} to be determined, i.e. $X_E = (135.28, 108.24, 11.90, 2.47, x_{5E})$. We ask the DM to specify x_{5E} so that she is indifferent between E and A. Suppose the DM specifies that x_{5E} = 4.5, i.e. to compensate for a reduction of the NPV of $1M, the visual impact score needs to be improved from 5 to 4.5.

The standardised performance scores of the adaptation alternatives and hypothetical alternatives A, B, C, D and E are provided in Table 7.

Table 7 Standardised Scores of Adaptation Options

Criteria	Adaptation Alternatives			Hypothetical Alternatives				
	Retreat	Nourishment	Seawall	A	B	C	D	E
Economic Efficiency	1	0	0.0496	1	0.9660	0.9660	0.9660	0.9660
Flexibility value	1	0.7819	0	0	0.0713	0	0	0
Loss to property owners	0	1	0.8137	0	0	0.0542	0	0
Loss to beach users	1	0.3906	0	0	0	0	0.1684	0
Visual impacts	1	0.75	0	0	0	0	0	0.125

Using the standardised scores and the elicited information, Equation (2) gives:

$$\begin{aligned} k_1 &= 0.9660k_1 + 0.0713k_2 \\ k_1 &= 0.9660k_1 + 0.0542k_3 \\ k_1 &= 0.9660k_1 + 0.1684k_4 \\ k_1 &= 0.9660k_1 + 0.125k_5 \end{aligned}$$

Together with the condition that $k_1 + k_2 + k_3 + k_4 + k_5 = 1$, these equations give $k_1 = 0.3839$, $k_2 = 0.1850$, $k_3 = 0.2433$, $k_4 = 0.0783$ and $k_5 = 0.1055$. Using these criteria weights, the overall utility of retreat, nourishment and seawall are 0.76, 0.50 and 0.22, respectively. Retreat would be most preferred, followed by beach nourishment and then building a seawall.

2. Case Study 2: Adaptation to Coastal Erosion at Falcon Bay, Mandurah

Mandurah is a coastal area that is highly vulnerable to sea level rise (DCCEE, 2009). Storm tide modelling results indicate that if a one in 200 year storm similar to tropical cyclone Alby (which happened in 1978) occurred today, about 560 buildings would be exposed. A sea level rise of 1.1m would increase this exposure to nearly 3000 buildings, with a total replacement cost of $2.8 billion.

We examine coastal erosion risk at Falcon Bay, a coastal settlement area located approximately nine kilometres southwest of Mandurah. Falcon Bay has a long history of beach erosion, resulting in a need for sand nourishment from time to time. Historical evidence and predicted future changes in weather patterns indicate that in the absence of management response to coastal erosion, sea level rise will increase the risk of erosion in the coastal zone.

For Falcon Bay, the study by Hazelwood and More (2012) suggests that the number of buildings affected by storm tide inundation is small and can be ignored. The number of buildings affected by coastal recession is shown in Table 8.

Table 8 Number of building exposed to erosion risk in Falcon Bay

Year	Probability of Exceedance											
	0.0001	0.01	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	0.99
2030	21.42	21.4	17.14	17	15	14.3	10.71	7.14	3.57	2.86	1.42	0.71
2070	738	307	76.92	30.77	26.15	24.61	23.07	21.54	16.92	15.38	13.84	1.54
2100	2784	1679	625	324	210	114	63	40	23	19	15	7

Recession data are provided by Cowell and Barry (2011) and are summarised in Table 9.

Table 9 Distribution of 2100 recession (m)

Year	Probability of Exceedance											
	0.0001	0.01	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	0.99
2030	154	130	107	97	89	82	77	72	67	62	56	47
2070	479	407	299	254	225	202	182	163	146	127	105	60
2100	884	674	487	412	364	362	294	264	235	204	165	100

MP Rogers and Associates (2010) examine historical data for sand bypassing, hydrographic surveys and historical beach renourishment volumes to determine whether any further coastal protection structures are required to stabilise this site. It is found that an annual sand volume of 100,000m^3 moves in the south to north direction along the coast. As a result, the northern end of Falcon Bay adjacent to Rakoa Street is vulnerable to erosion from heighted wave energy. MP Rogers and Associates (2010) recommend using sand nourishment to manage erosion risk. The nourishment strategy includes sand bypassing and trucking with an annual cost of $870,000.

In conjunction with sand nourishment, a rubble mound groyne can also be constructed to further reduce erosion. The groyne costs between $100,000 to $150,000 to construct and requires an initial beach nourishment of 45000 m^3 of trucked sand, with the estimated cost of $1.8 million if the sand is not sourced locally and $450,000 if the sand can be supplied from outside the region.

In this section, we provide a cost benefit analysis for a sand nourishment program that takes into account coastal erosion uncertainty and Bayesian learning on this uncertainty over time. We also extend the framework to consider the decision to invest in the groyne that helps to reduce beach nourishment cost. This is a real options model with erosion being uncertain, and the uncertainty decreases over time as more observations on erosion become available. The real options model provides better investment decisions compared to the usual NPV rule where investment is recommended whenever the NPV is positive.

2.1 Non-technical summary

As sand nourishment is conducted annually in Falcon Bay, the beach width can be considered constant under sand nourishment. Without nourishment, the beach retreats landwards and the beach width is also constant. As a result, recreational values of the beach do not change in this case study. To evaluate the net present value of the sand nourishment program, we need to consider only the impact of erosion on building and land loss.

The sand nourishment program helps to avoid the risk of building and land loss. Its benefit is then the expected loss of building and land from erosion when the beach is not nourished. To evaluate this expected building loss, we construct a loss curve that relates erosion distance to the number of buildings lost. This loss curve is estimated based on the results of engineering modelling work by Hazelwood and More (2012).

The loss curve is defined as a function of erosion distance that is cumulative over time. This is necessary, since over a long time period, cumulative erosion can be quite large and endangers buildings that are currently considered as safe. This, however, does not mean that annual erosion is always positive. In fact, stochastic variation in the beach profile can result in erosion in one year and accretion in other years. To allow for both positive and negative erosion, we model annual erosion to follow a normal distribution. Since erosion is proportional to sea level rise and the future level of sea rise is uncertain, the parameters of the erosion distribution should be considered as uncertain. We consider the mean of the distribution of annual erosion as unknown and to follow a prior distribution that describes the prior knowledge about coastal erosion and sea level rise. The prior distribution of the erosion mean is updated over time via the Bayes' rule whenever observations on annual erosion become available.

The benefit of the sand nourishment program in terms of avoided building loss is the sum of annual discounted expected loss over the considered time horizon. Annual discounted expected building loss is obtained as a product of discounted building replacement cost and the annual expected building loss that is obtained using the loss curve.

In addition to building loss, there is also land loss. The present value of annual land loss is obtained as a product of discounted land price and the annual expected land loss. The net present value of the sand nourishment program is obtained by subtracting the cost of the program from the sum of the present values of expected building and land loss.

The proposed modelling framework explicitly incorporates the uncertainty of coastal erosion due to climate change. This is important since with a convex loss curve, using a deterministic framework will result in an underestimation of the adaptation benefit.

Empirical results suggest that the nourishment program has a substantially positive NPV, which is due significantly to the high price of residential land ($600/m^2). Note that the price of residential land is much higher than the price of agricultural land ($2/m^2), perhaps due to some restrictions of the conversion from agricultural land to residential land. If agricultural land can be converted to residential land to relax the tight constraint of residential land supply, the benefit of the nourishment program will be lower. When the benefit of protecting land is valued using agricultural land price, a negative NPV is obtained and retreat is preferred to nourishment, based on the NPV criteria. There are, however, social costs and tensions involved with retreat, and these may be the reasons why policy makers prefer nourishment despite its high costs.

The sand nourishment program is expensive, the cost of which can be reduced if a groyne is constructed. We consider a groyne that helps to reduce the sand nourishment demand by 10%. Since the benefit of the groyne investment is uncertain due to the uncertainty about erosion and nourishment demand, and the investment cost is sunk once committed, the decision to invest in the groyne is similar to the decision to exercise a financial call option. It is only optimal to invest in the groyne if the net present value of the groyne exceeds the value of the option to invest. We provide a framework to model the option to invest in the groyne and to determine the optimal investment decision.

To determine the optimal investment decision, we first calculate the net present value of the project. This is relatively simple, since the benefits of the project are proportional to the costs of sand nourishment, and coastal erosion is assumed to follow a normal distribution. In the second step, the value of the option to invest is determined. In this demonstration, we assume that the annual rate of erosion is known exactly in 20 years' time. The value of the option can then be calculated via simulation in excel. In the third step, we compare the net present value with the option value. The groyne is optimal to invest immediately if the net present value is higher than the option value; otherwise it is optimal to wait until erosion uncertainty unfolds.

Note that the option modelling framework is simplified to provide a clear demonstration on the working of a real options model. In a more realistic model, we might also need to allow uncertainty to unfold over time.

2.2 Cost benefit analysis of sand nourishment

We conduct a cost benefit analysis for a sand nourishment program with the assumption that buildings that are exposed to erosion are lost. We model the cumulative erosion loss over period (0, t] as a quadratic function of the cumulative recession over period (0, t]:

$$L_t = aR_t^2 + bR_t + c, \tag{10}$$

where R_t is the total distance of recession from time 0 to time t.

This loss function can give rise to both concave and convex curves. As illustrated in Figure 4, a quadratic function provides a good fit on the building loss estimates provided by Hazelwood and More (2012).

The cumulative erosion distance R_t is the sum of annual erosion $X_1, \ldots, X_t$:

$$R_t = X_1 + X_2 + \ldots + X_t.$$

We assume that annual coastal recession is independently and identically distributed according to a normal distribution:

$$X_i \sim N\left(\mu, \sigma^2\right),\ i = 1,\ \ldots,\ t.$$

The normal distribution allows recession to take both positive and negative values so that both accretion and recession are allowed by the model. This flexibility also allows sea level change to be both negative and positive as observed in practice.

We assume that σ is a fixed constant while μ is random, to model the uncertainty in climate change and recession processes. The distribution of μ is modelled as:

$$\mu \sim N\left(\mu_0, \sigma_0{}^2\right).$$

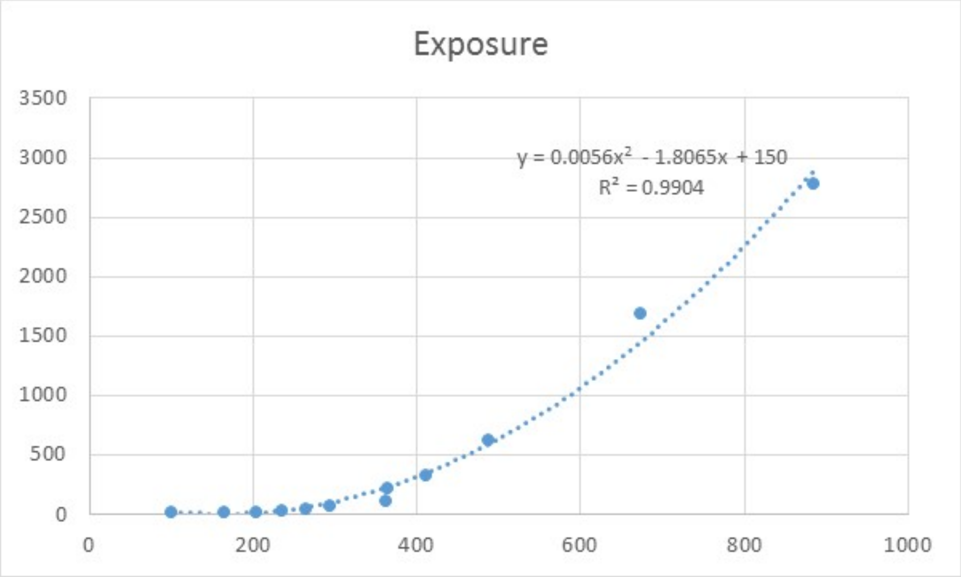

Figure 4 Loss curve as a function of recession distance.

We use the Bayes' rule to learn about μ when observations on recession are available. Suppose that we observe the recession in a given year as X_1. As shown by Gelman et al. (2004), the distribution of μ then becomes $N(\mu_1, \sigma_1{}^2)$, where

$$\mu_1 = w\mu_0 + \left(1-w\right)X_1$$

$$\sigma_1^2 = w\sigma_0^2$$

where $w = \sigma^2 / \left(\sigma^2 + \sigma_0^2 \right)$.

The distribution of *X* after incorporating the new observation, which is called 'posterior predictive' distribution, is given by:

$$X \sim N(\mu_1, \sigma^2 + \sigma_1^2). \tag{11}$$

We calibrate the parameters μ_0, σ_0, σ using estimates provided by Hazelwood and More (2012). Using the expectation of the identity:

$$E(R) = \mu$$

yields $E(R) = \mu_0$.

We therefore set μ_0=E(R) = 3.86.

The standard deviation σ is set equal to the empirical standard deviation of *X*, which is 4.21.

Estimation of parameter σ_0 is based on the condition:

$$Pr[\, c_1 \leq \mu \leq c_2] = N\left(c_2 \mid \mu_0, s_0^{\,2}\right) - N\left(c_1 \mid \mu_0, s_0^{\,2}\right).$$

We use c_1 and c_2 corresponding to a cumulative probability of 0.2 and 0.8, respectively. The estimated value of σ_0 is then 1.66.

Without any observation, the distribution of *X* in (11) is dictated by the prior distribution:

$$X \sim N(\mu_0, \sigma^2 + \sigma_0^{\,2}). \tag{12}$$

We use (12) to calculate the NPV of a sand nourishment program for a time horizon T = 100 years. The net benefit of nourishing for the entire 100 years is compared to the net benefit of no nourishment and to bear the erosion losses.

Without sand nourishment

Without protection, the number of buildings lost to erosion at time t is determined by the loss function in Equation (10). Note that this is the cumulative number of buildings lost, not the loss amount. To determine the loss amount, we use the average building replacement cost C = \$586,956 (\$1.35 billion for 2300 buildings). Assume a discount rate *r*, the present value of loss in period t is given by:

$$\begin{aligned}
B_t &= e^{-rt} C\, E\left(L_t - L_{t-1}\right) \\
&= e^{-rt} C\, E\left[a\left(R_t^{\,2} - R_{t-1}^{\,2}\right) + b\left(R_t - R_{t-1}\right)\right] \\
&= e^{-rt} C\, E\left[a X_t \left(2R_{t-1} + X_t\right) + b\, X_t\right] \\
&= e^{-rt} C\, [aE\left(X_t^{\,2}\right) + 2a\left(t-1\right)\mu_0^{\,2} + b\mu_0] \\
&= e^{-rt} C\, [\, a(\sigma^2 + \sigma_0^2) + a\left(2t - 1\right)\mu_0^2 + b\mu_0]
\end{aligned}$$

The total present value of loss over period (0, T] is then

$$V = B_1 + B_2 + \dots + B_T$$

In addition, if the area is not protected, land will be lost. The present value of land loss in year t is the product of the shoreline, the erosion distance, the price of the land and the discounting factor:

$$G_t = e^{-rt} E\left[X_t\right] P_L K,$$

where P_L is land price, K is the length of the shoreline of the study area. The total present value of land loss is

$$F = G_1 + G_2 + \dots + G_T$$

We use the price of residential land ($600/m^2) provided by Peron-Naturaliste Partnership (2012).

With sand nourishment

With a sand nourishment program, sand is added to the beach annually to compensate for erosion. The annual cost of nourishment depends on the erosion level. The cost of nourishment required for an erosion distant *X* is *XM*, where *M* is the cost of nourishing one metre of erosion. We estimate *M* by dividing the total nourishment cost per year ($870000) estimated by Carroll (2011) by the average erosion distance per year (3.86 m). The estimated value of *M* is $148,973/m.

The expected present value of nourishment cost in period t is then:

$$D_t = e^{-rt} E\left[X_t\right] M = e^{-rt} \mu_0 M$$

The total sand nourishment cost for T years is:

$$S = D_1 + D_2 + \dots + D_T$$

The NPV of the sand nourishment project is given by

$$NPV = V + F - S.$$

Results

Using the estimated parameters, the building protection benefit over 100 years is

V = $4,792,265.

If uncertainty is ignored, i.e. recession is assumed to be deterministic at the expected value of 3.86m per year, then the building protection benefit would be underestimated by $1million (at $3,725,315). This is because the loss curve is convex and therefore the expected loss is higher than the loss calculated at the expected recession level.

The benefit of protected land is

F = $38,151,945.

The cost of sand nourishment is

$$D = \$17,914,612.$$

And the NPV of sand nourishment is

$$NPV = \$25,029,598.$$

Discussion

In the case of Falcon Bay, there is no fixed cost involved with sand nourishment since sand is bypassed from a local area and nourishment can be done annually. As such, the decision of whether to nourish the beach or to let erosion reduce land and increase the risk of losing buildings can be made by comparing the cost of nourishing one metre of beach with the benefit of saving one metre of land and the benefit of reducing the erosion risk for buildings. Although the cost of nourishment is dependent on sea level rise and the coastal process, and is therefore uncertain, there is no need to employ a dynamic decision making framework in this case.

It is, however, still important to incorporate the impact of uncertainty. Since the erosion loss curve is convex, using a deterministic cost benefit analysis framework can result in an understatement of the adaptation benefit.

Note that the substantially positive NPV of the nourishment program is due significantly to the high price of residential land ($600/m^2). The price of residential land is much higher than the price of agricultural land ($2/m^2), perhaps due to some restriction of the conversion from agricultural land to residential land. If agricultural land can be converted to residential land to relax the tight constraint of residential land supply, the benefit of the nourishment program would be significantly lower. When the benefit of protecting land is valued using agricultural land price, a negative NPV is obtained and retreat is preferred to nourishment, based on the NPV criteria. There are, however, social costs and tensions involved with retreat, and these may be the reasons why policy makers prefer nourishment despite its high costs.

2.3 Switching to groyne

Beach nourishment has been considered as a status quo management strategy for coastal regions, since it does not result in any irreversible changes. With nourishment, there is no need for retreat and the associated social tensions can be avoided.

The cost of beach nourishment is, however, high and uncertain, depending on the level of erosion that is linked to sea level rise. To reduce nourishment costs, groynes can be installed in the direction that is perpendicular to the beach to reduce longshore sand movements. A system of groynes has been constructed in northern beaches in Mandurah and a new groyne has been proposed by MP Rogers and Associates (2010) to be installed in Falcon Bay. The construction cost is $600,000 and the maintenance cost is $15,000 every five years. We suppose that the groyne helps to reduce the nourishment cost by k = 10%. For simplicity, we consider an infinite time horizon in this section.

The construction of the groyne is, however, not reversible. In the case that erosion turns out to be low, the benefit of the groyne is low and the investment into the groyne can be a bad investment. We therefore need to take into account both investment timing and the impact of uncertainty when determining whether to invest in the groyne.

To examine the investment in the groyne, we model the cumulative erosion distance R_t as a sum of annual erosion $X_1, \ldots, X_t$:

$$R_t = X_1 + X_2 + \ldots + X_t,$$

where the annual coastal recession is assumed to be independently and identically distributed according to a normal distribution:

$$X_i \sim N\left(\mu, \sigma^2\right),\ i = 1,\ \ldots,\ t.$$

We assume that σ is a fixed constant while μ is random, to model the uncertainty in climate change and recession processes. The distribution of μ is modelled as:

$$\mu \sim N\left(\mu_0, \sigma_0^{\ 2}\right).$$

As shown above, the distribution of *X* in (11) with non-random parameters is given by:

$$X \sim N(\mu_0, \sigma^2 + \sigma_0^{\ 2}). \tag{13}$$

Given the nourishment cost of M per 1m of erosion and the erosion in period t is X_t, the expected benefit given by the groyne in period t is:

$$e^{-rt} E\left[kMX_t\right] = e^{-rt} kMm_0$$

The value of the project when invested at a time T is the sum of the expected benefit from time T to infinity. This is given by

$$V_T = e^{-rT} kMm_0 / r,$$

and the NPV of the project is

$$NPV_T = e^{-rT} kMm_0 / r - e^{-rT} I,$$

where *I* is the investment cost.

To illustrate the impact of uncertainty on the investment decision, we follow Mills et al. (2010) to assume that after T = 20 years, we know the annual rate of erosion exactly. At time T, we will invest in the groyne if

$kMX / r > I$ or $X > rI / kM$, and not invest otherwise.

The value of the option is then:

$$W = e^{-rT} E\left[max\left(kMX / r - I,\ 0\right)\right]. \tag{14}$$

The option value *W* in (14) can be easily calculated, e.g. by using simulation in MS Excel. If W > NPV$_0$ then waiting until time T for the uncertainty to resolve is optimal. At time T, if erosion is higher than the level rI/kM, then investment is optimal, otherwise, the groyne should not be invested.

Using 100,000 simulations, we get W = \$411,978. If the NPV obtained by immediate investment is less than \$411,978, it is optimal to wait. Since the NPV of investing now is \$559,650, which is higher than the value that would be obtained by waiting, it is optimal to invest in the groyne immediately.

Note that we have kept the framework to a simple two period model to provide a clear illustration of the real options framework. The model can be readily extended to a more realistic multi-period framework. In a more general framework, it may be necessary to allow the nourishment cost to increase over time to reflect the increasing difficulty in supplying sand to negate the impact of sea level rise, as suggested by French (2004). In recognition of the growing cost of nourishment, the investment in the groyne will then be more beneficial.

3. Climate Change Adaptation in Town Beach, Port Macquarie

Town Beach is located in the more densely populated part of Port Macquarie. It has historical connections to the earliest years of European settlement in the district and attracts a large number of regional, interstate and international visitors. Overlooking the beach and adjacent river side is a diverse range of holiday accommodation, including a caravan park with cabin accommodation, motels, hotels and holiday apartments. The accommodation has advantages of proximity to urban services such as restaurants and shops, outstanding coastal views, and visitors can enjoy safe beach and scenic coastal walks. The diversity of coastal features provides diverse recreational opportunities, including estuary, beach and rock fishing. The scenic coastal outlook has encouraged extensive redevelopment of prime coastal land adjacent to the beach.

Town Beach is Crown Land that is managed by Port Macquarie Hastings Council as Community land. Rotary Park is owned by the Crown and managed by the Council.

Figure 5 Study Area at Town Beach (PMHC, 2010).

A community workshop was held in 2004 to obtain qualitative assessment on the value of Town Beach from representatives, Council, Council's consultant and other stakeholders. Value statements are organised into three categories: natural/environmental, social/community and economic. These three key strands of sustainable management known as 'triple bottom line' are promoted in the NSW Coastal Policy (1997).

Table 10 Values in Town Beach.

Natural/Environmental Values	Social/Recreational/Community Values	Economic Values
- A beach close to the CBD - Enjoy views from the higher ground - Sunrise and sunset walks are popular, including the bush and birds of Flagstaff Hill - View of dolphins playing in the surf, whale watching	- A very accessible (close to CBD) and safe beach - The beach is focal point for both tourists and locals - Good beach for body boarders, surfers. - Historical importance, from Flagstaff Hill to entrance - People fish off the breakwall	- Important resource for the town's tourism - Port Macquarie is known as a tourist town for families - International tourists visit Town Beach - View and access to the beach is an important contributor to economic values of adjacent residential/tourism properties - Connectivity of Town Beach and CBD of Port Macquarie adds to the economic value of both town centre and the beach

The habitat for threatened and protected migratory species is limited in the Town Beach vicinity and it is most likely that such species would be recorded within the vegetation on the southern headland, rather than the central areas of Town Beach, where habitat is scarce and recreational use is high. The high level of urbanisation and the low levels of native habitat for threatened species suggest that the Town Beach area is unlikely to be a significant area for threatened species.

The heritage of Town Beach includes Flagstaff Hill which is a signal station established in 1821, a Gaol Point Lookout adjacent to the beach which is a part of the original site of the Port Macquarie convict gaol. Although the buildings of the gaol were demolished in 1920, the current lookout at Gaol Point presents outstanding views across the entrance to the river and the beach.

3.1 Erosion Risk Quantification

Erosion in Town Beach was analysed by SMEC (2005) based on photogrammetry. For easy reference, SMEC (2005) divides Town Beach into two blocks, each has different sections as in Figure A.2 provided in SMEC (2005). A profile 1.10 belongs to block 1 and section 10.

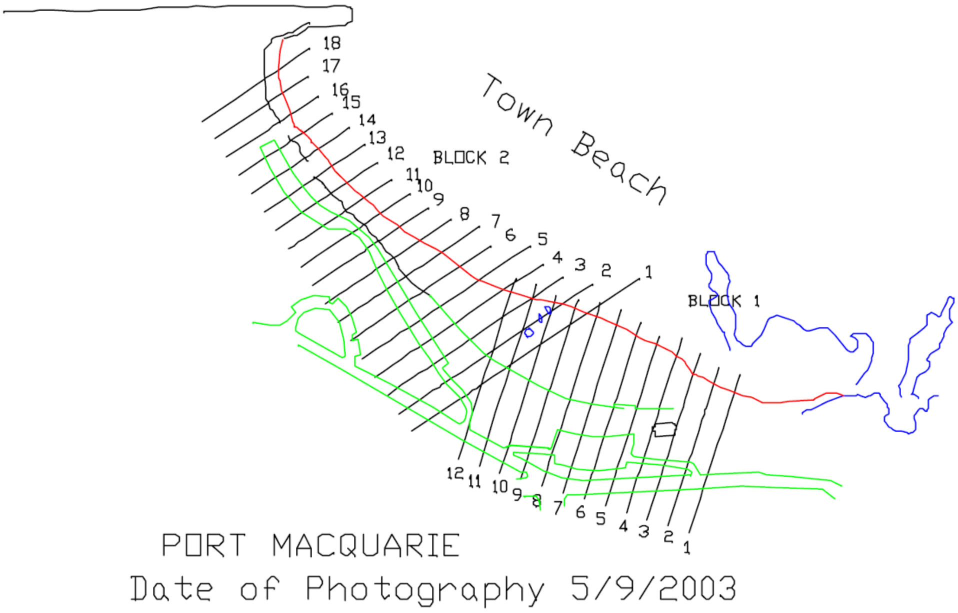

Figure 6 Photogrammetric Block Divisions at Town Beach (SMEC, 2005).

The beach is the sandy area between the waterline and the dunes. Beach berm is where sand-binding grasses may exist. Typically, the overall beach system extends from several kilometres offshores in water depths of about 20m to the back beach dune or barrier region that may extend up to several hundred metres inland. Breaker zone is the zone where offshore sand bars build up and waves break. During storms, waves remove sand from the beach face and beach berm and transport it beyond the breaker zone.

Main coastal hazard in Town Beach includes:

- long term coastline recession due to sea-level rise
- long term coastline recession
- short term coastal erosion resulting from severe storms
- wave runup inundation of low lying areas.

SMEC (2005) constructd a coastal hazard risk line as the sum of the recession due to SLR (calculated based on the Bruun rule), the long term coastline recession estimated based on historical recession rates provided by photogrammetric data, and the short term coastal erosion resulting from a design storm.

Results on long term erosion due to sea-level rise indicate that in 2050, the total beach recession for three scenarios of sea-level rise of 0.05m, 0.15m and 0.30m are 1.3m, 3.8m, and 7.6m, respectively. The total beach erosion is 15 m^3/m, 45m^3/m and 90 m^3/m. In 2100, the total beach recession for three scenarios of sea-level rise of 0.1m, 0.35m and 0.85m are 2.5m, 8.9m, and 21.6m, respectively. The total beach erosion is 30m^3/m, 105m^3/m and 184m^3/m.

Erosion caused by a design storm is estimated by simulating design storms' impacts on the beach profiles. A design storm is defined as a storm that has 1% chance of occurring in any one year and has a duration of 12 hours. This corresponds to a wave height of 7.7m. The volume of beach sand that can be eroded from the beach and dunes during a design storm is called storm cut or storm erosion demand. Storm cut can be quantified empirically with data obtained from photogrammetric surveys. The predicted storm cut from a design storm is presented in Figure 7.

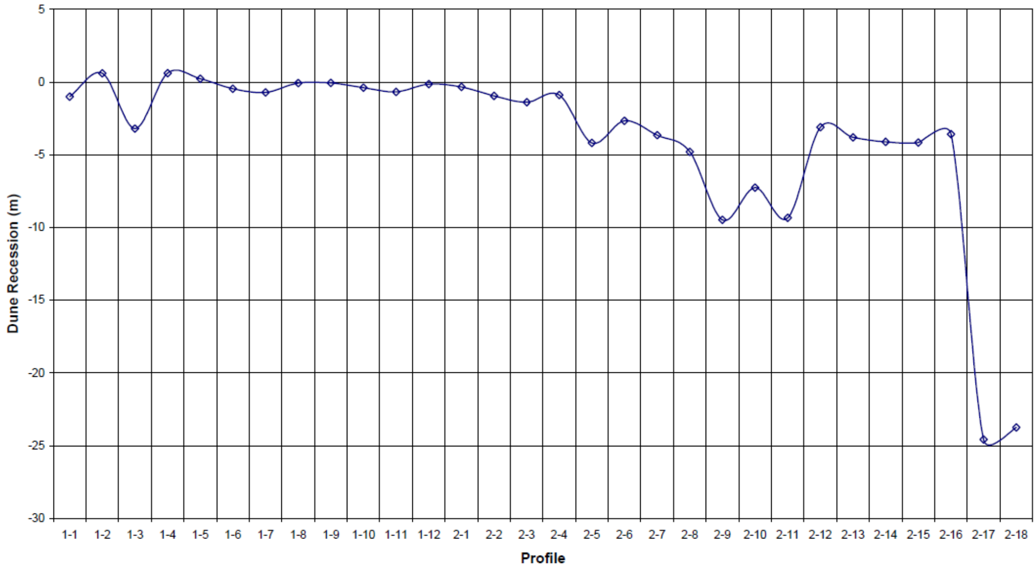

Figure 7 Predicted storm erosion from a design storm for all profiles (SMEC, 2005).

The coastal hazard limit is depicted in Figure 8. It indicates that, without remedial action, parts of the foreshore access road and car park are at risk and the recreation area is subject to high coastal hazard risk within the 50 year planning period.

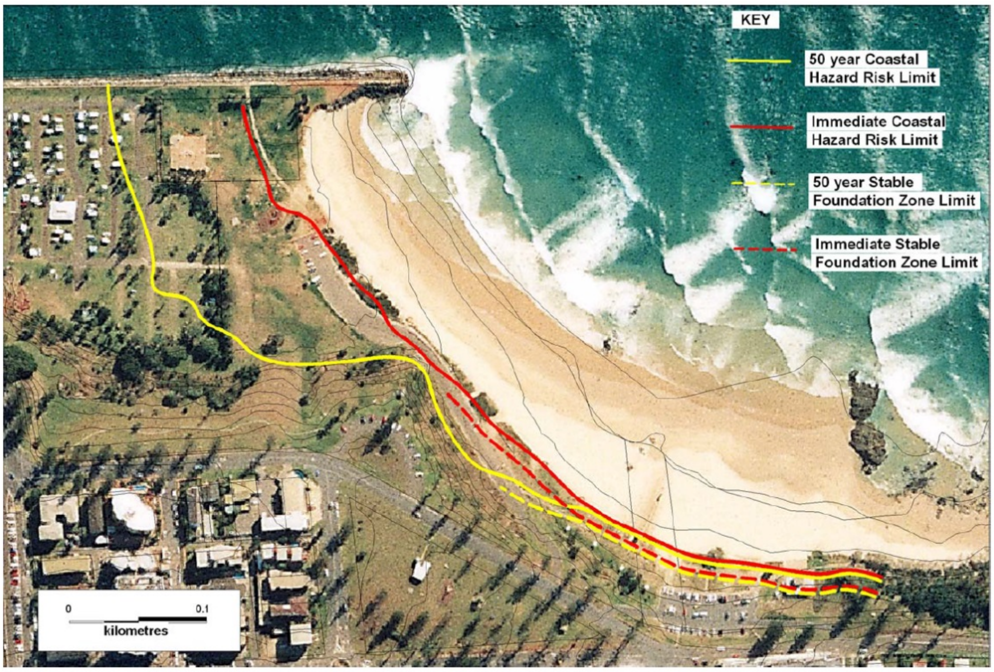

Figure 8 Estimated coastal hazard limit in Town Beach (SMEC, 2005).

Measured long term beach recession

Observations for dune recession at 3.0m AHD for various profiles of Town Beach over period 1971-2003 are provided in Figure 9. It can be seen that before 1979 when the breakwater was constructed, there was not much recession. After that, erosion was rapid, especially for Profile 2.17, and 2.12. Erosion has slowed down since 1989.

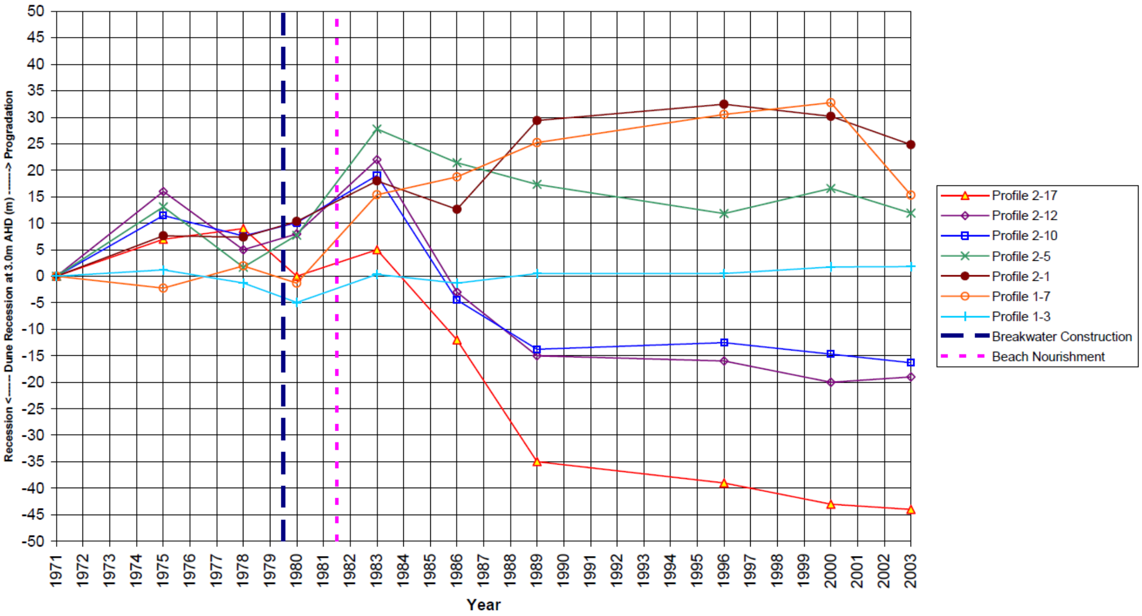

Figure 9 Measured dune recession between 1971 and 2003 (SMEC, 2005).

The rate of beach recession can be quantified by the measurement of eroded volumes or the measurement of the translation of the dune face over time. For Town Beach, both methods give similar results, indicating that the northern section is eroding at an average rate of 6.9 m^3/m/year above AHD (with a maximum of 9.1 m^3/m/year) and the central section at 0.8 m^3/m/year above AHD, and no recession at the southern end of the beach. Figure 9 indicates that dune face has receded by up to 45 m since 1980, an average of 2.0 m per year.

For a near-shore beach profile extending to a depth of 11.4 m AHD, the total volume of sand eroded from the beach profile would average 23 m^3/m/year at the northern end and 3m^3/m/year at the central section. The total rate of loss of beach sand from the coastal compartment is around 2,300 m^3/year.

Erosion due to SLR

With climate change, the severity and frequency of storms could increase, rainfall intensity could increase and there could be a more severe wave climate. Sea-level rise may lead to a shoreline response of coastal recession. The most widely accepted method of estimating shoreline response to sea-level rise is the Bruun Rule. Measurements of sea-level rise show that there is considerable variation in the data and, for Fort Denison in Sydney, the mean sea level in 1997 is actually lower than that measured in 1914. These variations may be due to the inter-decadal ENSO phenomenon.

Table 3.1 provides estimates of the overall long term recession and erosion expected at Town Beach due to sea level rise. A mid-level sea-level rise scenario indicates a sea-level rise of 0.15m by 2050 and 0.35m by 2100, which leads to an estimated additional beach recession by 3.8m by 2050 and 8.9m by 2100.

Storm erosion and wave runup

SMEC (2005) use the SBEACH model to estimate the risk presented to storm erosion and wave runup. The predicted recession of dune face according to SBEACH caused by one design storm event for 12 hours for all profiles is provided in Figure 7 above. It can be seen that erosion is dramatic for profiles 2.17-18 (25m) while only mild erosion (0-10m) for other profiles. Note that these erosions are caused by only one storm event (12 hour duration, 100 year ARI storm). The erosion at Profiles 2.17-18 could threaten the existing access road, car park and the amenity of the foreshore recreation area. The corresponding dune erosion volume is 40m^3/m.

SMEC (2005) also provide the estimate for the maximum and 2% wave runup. The maximum wave runup could affect the car park and part of the access road. Since the ground levels in the foreshore recreation area, the caravan park and car park at the northern end of the beach are below three metres AHD, then these areas are subject to wave overwash hazard. This means that some waves are likely to overtop the dune during the peak of the tides during a 100 year ARI storm event, increasing the erosion rate and presenting risk to people using the foreshore park or car park. The maximum wave runup is estimated to be 5.1-9.1 m AHD and the 2% wave runup is 4.7-8.2 m AHD. The significant wave runup is 4.2-7.1 m AHD while the average wave runup is 3.7 - 5.9 m AHD. The range of estimates reflects the variation across beach slope and wave conditions.

High levels of wave runup and coastal risk at the northern end of Town Beach would preclude the development of this part of the foreshore for structures such as residences or public buildings as the risk to this development would be high.

Along the southern section of the beach, parts of the access road are at threat of erosion within the 50 year time frame, and future buildings, including those located at the site of the present day surf club may require special design considerations seaward of the Stable Foundation Zone limit.

3.2 Adaptation options

A number of options are available to address the ongoing erosion at the northern end of the beach. PMHC (2010) suggests that it is not feasible to do nothing and accept the ongoing erosion. For the hard engineering measures, groynes are considered ineffective at Town Beach since the predominant direction of sand movement/loss is offshore. Submerged offshore breakwater is suggested to be prohibitively expensive and potentially dangerous to boating traffic. A seawall or terminal revetment along the full length of the northern section of the beach is prohibitively expensive and detracts from the beach amenity. The adaptation options that are considered feasible include:

- Option 1: Sand nourishment and a short (50m) seawall adjacent to the area of greatest beach recession at the northern end of the beach (Profiles 2.17, 2.18 in Figure 6). The cost is $4000/m of seawall and the total cost of the seawall is $200,000. The ongoing sand nourishment cost is $30,000-45,000/year.
- Option 2: Dune reconstruction through sand nourishment to return the northern end of the beach to its 1980 alignment. Dune crest height is 4.6m AHD is required to prevent 1% wave runup level. Dune reconstruction requires 15000m^3 of sand with, and need to be reconstructed every 10 years. The cost is $20/m^3 and the total cost of dune construction is $300,000 every 10 years. The ongoing sand nourishment cost is $30,000-45,000/year.

We will conduct a cost benefit analysis for Option 1. To further simplify the problem, we consider only adaptation for Profiles 2.17 and 2.18. Erosion in other profiles are small and not considered.

3.3 Cost Benefit Analysis

We compute the net present value (NPV) of the adaptation measure that involves constructing a short 50m seawall adjacent to the area of greatest beach recession at Profiles 2.17 and 2.18 together with sand nourishment for these sections of the beach. The cost of this strategy includes $200,000 investment cost for the seawall, an annual seawall maintenance cost of $4000/m, and an annual cost of sand nourishment of $23,000.

The benefit is the protection of the land that is 50 m along the beach from erosion and the expected sand loss from storm surge. As calculated by SMEC (2005), the annual land erosion rate for Profiles 2.17 and 2.18 includes 0.076 m/year due to sea level rise and 2 m/year due to long term erosion. The sand loss in a 1% storm event is 40m^3/m, so for 50m, the sand loss is 2000m^3. In addition, there is also some benefit in terms of reduced risk of wave overwash and inundation. Such benefit, however, may be small since in the at risk area, there are no houses, just recreational land, car parks and roads. Furthermore, no deaths were recorded in historical storm surge events in NSW. We therefore ignore the benefit of reducing wave overwash risk.

An important component in the cost benefit analysis is the valuation of erodible land in Town Beach. Since coastal erosion increases the land prices of all remaining land in the region, the price that is normally applied to eroded land is the price of land that is not in the vicinity of the beach. However, in the case of Town Beach, the erodible land has historical connections with European settlement that are not present in other land and the historical values need to be accounted for.

Determining land value

To determine the historical value of land in Town Beach, we compare the land value of two ocean front houses; one in Town Beach and one in Dunbogan that is 26km from Town Beach. These land values are provided by the Valuer General and available through Google Earth.

We use the land value of property in Iluka Way in Dunbogan that is $210,000 per 664m^2 or $316.27/m^2. For Town Beach, we use the land value of a property in Lord Street that is $677,000 per 866m^2 or $781.75/m^2. The difference in land value of $465.50/m^2 may reflect the premium for proximity to the town as well as the historical value of the land (among others). We use this value as the maximum historical value of land in Town Beach.

The value of the land without premium on historical connections or proximity to the beach is estimated based on the value of non-developed land in Kooloonbung creek reserve that is two kilometres from Town Beach. This land has a value of $357,000 per 49.39 ha or $0.72/m^2. The value of erodible land in Town Beach is then $466.22/m^2.

Cost Benefit Analysis Results

The NPV of the adaptation strategy is given by:

$$NPV = \sum_{t=0}^{50} \left[\frac{P \times L_t - M_t - 0.01 * C_t}{(1+r)^t} - I \right] ,$$

where L_t is the amount of land eroded in year *t*, M_t is the maintenance cost of the seawall and annual sand nourishment in year *t*, C_t is the cost of sand lost in a design storm, and *I* is the investment cost of the sea wall, and *r* is the discount rate.

As demonstrated in the Excel spreadsheet, given the value of the land that is determined based on market value, the NPV is $89,728.

4. Concluding remarks

From the case studies of coastal erosion adaptation, several interesting results emerge. It is found that for the first case study, retreat provides a much higher economic value compared to protection measures. In the case that retreat cannot be implemented at the present time due to political barriers, it is found that (based on the assumptions for the case study) beach nourishment is more attractive compared to a seawall. This is due to the ability of beach nourishment to preserve adaptation flexibility that allows to react to the unfold of sea level rise uncertainty and allows the implementation of retreat in a future time when society has a better understanding about the benefits of retreat and the cost of protection measures. It is also possible that better mechanisms will be available in the future to reduce the social cost of retreat. This result is consistent with UK studies that advocate the demolition of seawalls to alleviate the impact of coastal erosion on environmental assets (Turner et al. 2007, Lusetti et al. 2011). The superior performance of retreat is due to the low price of hinterland. With the price of residential land used in our case studies, we found that retreat could be the preferred adaption option in Shoalhaven, while nourishment is preferred in Mandurah. However, if the price of agricultural land was used, retreat might be the preferred option in both regions.

We also found that in conducting the cost benefit analysis of the nourishment program in Mandurah, it is important to incorporate the uncertainty of coastal erosion. Failing to do so will result in an underestimation of the adaptation benefit when the loss curve is convex and an over-estimation of the benefit when the loss curve is concave.

Appendix A. An example of optimal investment timing

Truong and Trück (2010) provide a simple framework for investigating optimal investment timing of catastrophic risk reduction projects. Different from other studies, the modelling framework proposed by Truong and Trück (2010) is statistically sound while easily lends itself to economic intuition. The framework is implemented in Excel, and can be easily used by users.

In this model, the total loss in the region due to catastrophes in year t, S_t, is modelled by a compound Poisson process:

$$S_t = \sum_{k=0}^{N_t} X_k, \quad X_k \overset{iid}{\sim} F(x),$$

where *F* is the distribution function for the severity of the losses, N_t is a homogenous Poisson process with intensity $\lambda_t > 0$ and N_t is independent from X_k.

A property of the compound Poisson process is that the expected aggregate loss, $E(S_t)$, is equal to the product of the expected number of events λ_t and the expected individual loss $E(X_t)$:

$$E(S_t) = \lambda_t E(X_t).$$

Suppose that the investment project has investment cost I and reduces the catastrophic risk by a proportion of k. The investment problem is then to find the investment time τ to maximise the net present value of the project:

$$\max_{\tau} \sum_{\tau=0}^{\infty} e^{-rt} k\lambda_t E(X_t) - I ,$$

where *r* is the discount rate.

Truong and Trück (2010) use expert opinions to estimate the loss frequency, the expected loss value and the effectiveness of the project in mitigating risk.

Appendix B Weighted summation MCA and PROMETHEE II MCA

In WS, we consider a set of *n* options, *m* criteria. The performance of option *i* against criterion *j* is measured by raw performance score x_{ij}. The importance of criterion *j* is measured by weight w_j. The values for x_{ij} and w_j may be at an ordinal or cardinal level of measurement. To make criteria comparable, raw scores x_{ij} are standardised to provide scores s_{ij} between 0 and 1:

$$s_{ij} = \frac{x_{ij} - \min_i x_{ij}}{\max_i x_{ij} - \min_i x_{ij}} \text{ if a higher value for } x_{ij} \text{ represents better performance,}$$

and $$s_{ij} = \frac{\max_i x_{ij} - x_{ij}}{\max_i x_{ij} - \min_i x_{ij}} \text{ if a lower value for } x_{ij} \text{ represents better performance.} \quad (15)$$

The overall performance score u_i for option *i* is given by:

$$u_i = \sum_{j=1}^{m} w_i s_{ij} . \quad (16)$$

To check the robustness of the results with respect to MCA method, Hajkowicz and Wheeler (2008) carry out the analysis with another method called PROMETHEE II, which is an outranking method. With this method, a preference function $P_j(i,i')$ is defined for option *i* versus option *i'* as

$$P_j(i,i') = \begin{cases} 0 \text{ if } s_{ij} \le s_{i'j} \\ s_{ij} - s_{i'j} \text{ if } s_{ij} > s_{i'j} \end{cases},$$

where s_{ij} is defined as in (15).

The weighted preference index is obtained by

$$\pi(i,i') = \sum_{j=1}^{m} P_j(i,i') w_j .$$

A positive and negative outranking flow is then determined by:

$$\phi^{+}(i) = \frac{1}{n-1} \sum_{i'=1}^{n} \pi(i,i')$$

$$\phi^{-}(i) = \frac{1}{n-1} \sum_{i'=1}^{n} \pi(i',i) .$$

The net outranking flow for each option is then determined by:

$$u_i = \phi^{+}(i) - \phi^{-}(i) .$$

Appendix C Relative score versus standardised score in MCA

To demonstrate the use of relative scores, we consider two attributes: financial benefits and biodiversity. We assume that these two attributes are equally important and the same weights are assigned to each attribute, whether relative scores or standardised scored are used. Also, assume that the raw score for biodiversity is such that higher score indicates a better performance in terms of biodiversity. Suppose initially that there are three alternatives to be ranked and for relative scores, Alternative 1 is selected as the base alternative. Raw performance scores of different alternatives are as in Table 1.

Using the relative score method, the overall performance of Alternative 2 is given by:

$$\frac{10-30}{30}\times 0.5+\frac{10-5}{5}\times 0.5=0.22,$$

and the overall performance of Alternative 3 is given by:

$$\frac{60-30}{30}\times 0.5+\frac{2-5}{5}\times 0.5=0.2.$$

Using the standardised score method, the overall performance of Alternative 2 is given by:

$$\frac{10-10}{60-10}\times 0.5+\frac{10-2}{10-2}\times 0.5=0.5,$$

and the overall performance of Alternative 3 is given by:

$$\frac{60-10}{60-10}\times 0.5+\frac{2-2}{10-2}\times 0.5=0.5$$

The results are summarised in Table 1. It can be seen that using relative scores, Alternative 2 is preferred while using standardised scores, Alternative 2 and Alternative 3 are equally desirable.

Table 1. Ranking of alternatives when three alternatives are considered.

	Alternative 1	Alternative 2	Alternative 3
Financial benefit ($)	30	10	60
Biodiversity	5	10	2
Overall performance (Relative Score)		0.22	0.2
Overall performance (Standardise Score)		0.5	0.5

Now suppose that we also consider Alternative 4. Since the base alternative is the same, relative scores of Alternatives 2 and 3 are unchanged. In contrast, the overall performance of Alternative 2 under standardised score approach is given by:

$$\frac{10-10}{80-10}\times 0.5+\frac{10-0}{10-0}\times 0.5=0.5,$$

and the overall performance of Alternative 3 is given by:

$$\frac{60-10}{80-10} \times 0.5 + \frac{2-0}{10-0} \times 0.5 = 0.45 \cdot$$

Ranking of alternatives, therefore, depend on the number of considered alternatives under standardised score approach.

Table 2. Ranking of alternatives when an additional alternative is used.

	Alternative 1	Alternative 2	Alternative 3	Alternative 4
Financial benefit ($)	30	10	60	80
Biodiversity	5	10	2	0
Overall performance (Relative Score)		0.22	0.2	
Overall performance (Standardise Score)		0.5	0.45	

Appendix D. Method to elicit criteria weight

To demonstrate the method, suppose we need to evaluate three alternatives A, B, C using three criteria. We use i to index criteria, i=1, …,3.

Let x_i be the raw performance score in criterion i, $v(\cdot)$ be the standardisation function. For the highest score b_i in criterion i, $v(b_i) = 1$ and for the worst score w_i in criterion i, $v(w_i) = 0$.

The overall score of an alternative A is denoted by $V(A)$:

$$V(A) = \sum_{i=1}^{3} k_i v(A_i),$$

where k_i is the weight of criterion i.

Exact weight

Consider alternative A with raw performance score:

$$x_A = (b_1, w_2, w_3),$$

i.e. A receives the best score for criterion 1 and the worst scores for criterion 2 and 3. The overall score of A is then

$$V(A) = k_1 .$$

Consider alternative B with raw performance score:

$$x_B = (w_1, x_2^I, w_3),$$

i.e. B receives the worst score for criterion 1 and 3 and x_2^I for criterion 2. The overall score of B is then

$$V(B) = k_2 v(x_2^I).$$

Now we ask the decision maker (DM) to specify x_2^I such that he is indifferent between alternative A and B. Since A is indifferent to B, the overall score of A is equal to that of B and

$$k_1 = k_2 v(x_2^I). \qquad (1)$$

Now consider another alternative C with raw performance score:

$$x_C = (w_1, w_2, x_3^I).$$

The overall score of C is

$$V(C) = k_3 v(x_3^I).$$

We then ask DM to specify x_3^I so that he is indifferent between A and C. This gives

$$k_1 = k_3 v(x_3^I) \quad (2)$$

Equations (1), (2) and the condition that weights sum to 1 provide the weight for each criterion.

Flexible weights

Exact weight elicitation using indifference relation as above may be criticised since DMs are often uncertain about indifference relation. de Almeida et.al. (2016) suggest use of flexible weights where the indifference relation is not required.

Step 1

The first step is to rank criteria in terms of their relative importance. We can present the DM with alternatives X and Y to choose from, where

$$x_X = (b_1, w_2, w_3)$$

and $x_Y = (w_1, b_2, w_3)$.

Since $V(X) = k_1$ and $V(Y) = k_2$, if X is chosen over Y, then $k_1 > k_2$.

Suppose that criteria are ordered in a way that

$$k_1 > k_2 > k_3 . \quad (3)$$

We then try constrain (3) to see if we can solve the problem at hand by ranking alternatives we defined.

Suppose that the problem to be solved has alternatives $\{A_j\}_{j=1}^3$. We then try to find a combination of weights that satisfies (3) such that an alternative A_j is preferred to all other alternatives. For example, to check if A_1 is a optimal alternative, we solve the mathematical problem:

$$\max_{k_1, k_2, k_3} \sum_{i=1}^{3} k_i v(x_{i1})$$

subject to:

$$\sum_{i=1}^{3} k_i v(x_{i1}) \geq \sum_{i=1}^{3} k_i v(x_{i2})$$

$$\sum_{i=1}^{3} k_i v(x_{i1}) \geq \sum_{i=1}^{3} k_i v(x_{i3})$$

$$k_2 \leq k_1 - 0.00001$$

$$k_3 \leq k_2 - 0.00001$$

$$k_1 + k_2 + k_3 = 1$$

$$k_1, k_2, k_3 \geq 0 \ .$$

If a solution exists for the above problem, then there exists a weight combination such that alternative A1 is better than A2 and A3. We say that A1 is a potentially optimal alternative. If no solution exists, it means that A1 is a dominated alternative. After we have checked for all alternatives and only one alternative is potentially optimal, then that alternative is optimal. In that case, we stop the process. If more than one alternative is potentially optimal, we proceed to step 2.

Step 2

In the second step, we seek more information from DM to reduce the weight space. We present the DM with alternatives X1 and Z to choose from, where

$$x_{X_1} = (x_1^{'}, w_2, w_3)$$

and $x_Z = (w_1, b_2, w_3)$.

Suppose that DM chooses X1 over Z, then we have

$$k_2 < k_1 v(x_1^{'}) \ .$$

We then present DM with alternatives X2 and Z, where

$$x_{X_2} = (x_1^{''}, w_2, w_3),$$

where $x_1^{''}$ is quite low such that DM chooses alternative Z over X2. Then

$$k_2 > k_1 v(x_1^{''}).$$

In the similar way, let $x_2^{'}$ and $x_2^{''}$ be the scores in criterion 2 such that

$$k_3 < k_2 v(x_2^{'})$$

and $k_3 > k_2 v(x_2^{''})$.

We then use linear programming to check if there is a combination of weights satisfying the above conditions such that an alternative dominates all other alternatives. For example, to check if alternative A_1 is optimal, we solve the problem:

$$\max_{k_1, k_2, k_3} \sum_{i=1}^{3} k_i v(x_{i1})$$

subject to:

$$\sum_{i=1}^{3} k_i v(x_{i1}) \geq \sum_{i=1}^{3} k_i v(x_{i2})$$

$$\sum_{i=1}^{3} k_i \, v(x_{i1}) \geq \sum_{i=1}^{3} k_i \, v(x_{i3})$$

$$k_2 \leq k_1 \, v(x_1^{'}) - 0.00001$$

$$k_1 \, v(x_1^{''}) \leq k_2 - 0.00001$$

$$k_3 \leq k_2 v(x_2^{'}) - 0.00001$$

$$k_2 v(x_2^{''}) \leq k_3 - 0.00001$$

$$k_1 + k_2 + k_3 = 1$$

$$k_1 , k_2 , k_3 \geq 0 \; .$$

If a solution exists for the above problem, then there exists a weight combination such that alternative A1 is better than A2 and A3. If no solution exists, it means that A1 is a dominated alternative. After we have checked for all alternatives and only one alternative is potentially optimal, then that alternative is optimal and the process stops. Otherwise, we seek more information from DM to restrict the weight space further and solve the linear programming problems again. The process is repeated until the optimal alternative is found or until no more information can be provided by DM.

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