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Abstract The development of successful coastal adaptation strategies for both the built and natural environments requires combining scenarios of climate change and socio-economic conditions, and risk assessment. Such planning needs to consider the adaptation costs and residual damages over time that may occur given a range of possible storm conditions for any given sea level rise scenario. Using the metric of the expected value of annual adaptation costs and residual damages, or another metric that can be related to the elevation of flooding, a simplified method to carry this out is presented. The approach relies upon developing damage-flooding depth probability exceedance curves for various scenarios over a given planning period and determining the areas under the curves. While the approach does have limitations, it is less complex to implement than using Monte Carlo simulation approaches and may be more intuitive to decision makers. A case study in Maine, USA is carried out to illustrate the method.

1 Introduction

Being at the nexus of the terrestrial and marine environments, the coastal zone faces a variety of natural and anthropogenic stressors. Climate change impacts, especially sea level rise (SLR), are exacerbating these stresses to both the natural and built environments. Resulting major marine-related climate change impacts include increases in tidal inundation, higher storm surges, increased beach erosion, changes in circulation and

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chemistry, changes in freshwater supply, and saltwater intrusion. With increased storm precipitation projected for many watersheds, greater nutrient, contaminant, and sediment loads will also be delivered to estuaries.

The anthropogenic component of future stresses in coastal zones under scenarios of climate change could be large. For example, Kirshen et al. (2008) estimated cumulative expected values of damages of tens of billions of dollars to buildings and contents in the metropolitan Boston area from increased coastal flooding over the next century under global SLR scenarios of 0.6 m to 1.0 m. Lost economic output could also be significant as has been demonstrated for storm surge events in coastal Maine (Colgan and Merrill 2008). Neumann et al. (2010a, b) determine the economic losses both locally and along the coast of the continental USA to SLR over time and show the benefits of considering adaptation in loss calculations. Their work is being enhanced to include storm surge damages.

Nicholls (2004) estimated that regionally over the Earth by 2080, the population in the 1000-year floodplain could increase by 50 to 200% over the 1990 amount with most of the increase in the non-industrialized world. In urban areas, these changes will further exacerbate existing problems such as population growth, traffic congestion, poverty, social inequities, aging infrastructure, and land use change.

Built environment adaptation planning first requires an interdisciplinary location-specific impact assessment followed by evaluation of adaptation actions. Options for coastal flooding adaptation due to SLR include: (1) doing nothing and rebuilding each year, (2) accommodation to flooding (e.g., with floodproofing, controlled flooding in certain areas, evacuation), (3) retreating from the floodplain, and (4) protection with hard and soft approaches such as seawalls, revetments, and beach nourishment, and the restoration and enhancement of natural features such as coastal sand dunes, wetlands, coral reefs, and mangroves that mitigate the strength of waves and storm surge.

The Intergovernmental Panel on Climate Change (IPCC 2007) reports that globally 33 to 44% of wetlands could be lost by 2080 given a sea level rise (SLR) of 36 to 76 cm. Changes in the composition and coverage of different wetland types translate into changes in coastal ecosystem communities and the benefits they provide. Ecosystem benefits and services that could be negatively impacted as part of this process include nutrient cycling, natural pollutant buffering, production from fisheries, erosion and flood control, and biodiversity. Although some coastal wetlands will migrate into adjacent low-lying areas in response to sea level rise, the amount of newly-formed wetlands may be limited by development and the armoring and engineering controls used to protect the built environment in coastal areas.

Other coastal habitats may also provide ecosystem services that are significant to climate change adaptation planning and evaluation. For example, estuaries and seagrass/algal beds have two of the three highest ecosystem services values per acre (Costanza et al. 1997), providing nutrient cycling, recreation, food production, and disturbance regulation benefits. With climate change, and continued reliance on suboptimal measures to protect the built environment, these ecosystem services may be irrevocably harmed.

Similar to planning efforts for the built environment, adaptation planning focused on the natural coastal environment begins by identifying sensitive components of the ecosystems along with the most significant natural and anthropogenic stressors. Adaptation options to preserve the integrity of natural coastal ecosystems include land management, restoration/revegetation, shoreline hardening, and sediment delivery maintenance (National Research Council 2007). Options are selected after identifying specific vulnerabilities and key ecosystem services that need to be maintained or enhanced in order to meet management goals. Coastal zone land management strategies (e.g., planning, regulations, incentives, and acquisitions) can encourage an orderly retreat of wetland habitat landward in response to SLR. Sediment delivery to critical coastal ecosystems can be enhanced by constructing engineering structures (e.g., groins) to trap sediments, beach/marsh nourishment programs, and developing and implementing regional sediment management plans (U.S. EPA 2009). Although shoreline hardening is generally not considered a sustainable approach to preserving coastal habitat, certain hardening techniques such as sills and breakwaters can be effective in reducing wave action, trapping sediment, and preserving or enhancing vegetated zones. The use of such structures, however, are quite limited from a regulatory viewpoint from state-to-state.

Scenario-based risk assessment can be used as a framework for impact and adaptation analysis. Here we summarize this process and briefly illustrate it with a past complex application, discuss how it the process can be simplified, and then present a case study with the simplified approach.

2 Scenario-based risk assessment

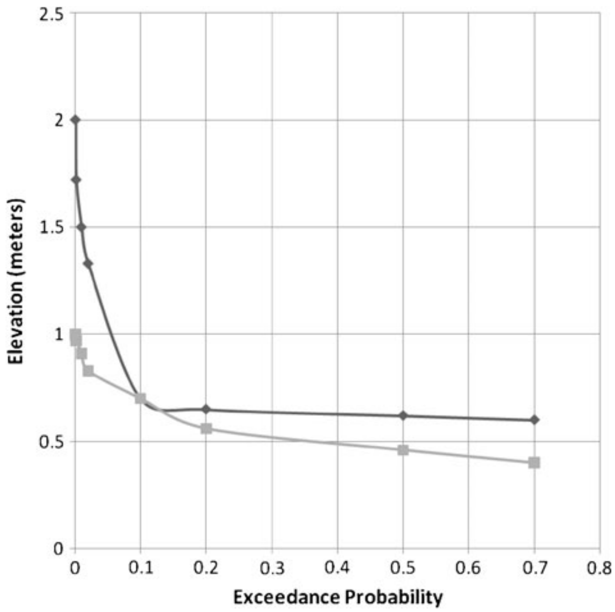
In a risk-based approach under a stationary climate where the probabilities of possible climate-related events are known, the costs and benefits of the performance of a system over a wide range of climate-related possibilities are evaluated using expected values. The expected value of annual damages is the sum across the set of all possible damaging events of the product of the likelihood of a given event and the damages associated with it. Yearly expected value damage estimates are summed to estimate the total expected value over the planning period, with or without discounting as desired. A reasonable design can be determined by evaluating the performances of many alternatives and then selecting the best performing one as measured by expected value cost and residual damages. The risk-based approach is in contrast to a more traditional approach of limiting evaluation of performance to a single design condition, e.g., a certain wind speed or flood volume. Risk analysis is advantageous because, for example, using only the flood peak with a certain probability of exceedance each year (e.g. the 1% or 100 year storm) misses the damages associated with events of other probabilities. Depending upon the shape of the damage probability exceedence curve, the use of a single design condition may result in a project that does not result in minimum costs or maximum benefits. In addition, what is a good design condition for one site, may not be reasonable for another because even though two locations may have the same 100 year event, they may have different event sizes associated with other probabilities. This is shown in Fig. 1. Risk analysis avoids these problems.

Risk-based decision making based on known probabilities of various outcomes has been considered for use in infrastructure and environmental management for at least several decades (for example, conferences on its application in water resources have been held at least since 1985–one of the latest was in 2002, Haimes et al. 2002). This methodology is now used by the US Army Corps of Engineers in support of its flood management programs.

One of the challenges of climate change impact and adaptation analysis is that it is difficult to assign probabilities to possible future climate conditions (particularly SLR, Titus et al. 2009) and to other factors such as population change. While there are references where some experts have quantified these types of uncertainties, here we use scenarios of these drivers without assigned probabilities. A scenario is an internally consistent plausible future that might evolve from present conditions given various driving forces (Groves and Lempert 2007).

Scenarios can be combined with risk analysis by, for each adaptation option, determining the expected values of the impacts upon infrastructure and environmental systems for

Fig. 1 Example of flood elevation curves with same 0.1 exceedance, different other exceedances



multiple combinations of socio-economic and climate change scenarios. This is because it is usually possible to assign probabilities to the events in each single socio-economic and climate scenario even though it is not possible to assign probabilities to the scenarios themselves occurring. For example, given an assumed rate of SLR, the probabilities of storm surges of various elevations occurring can be determined. The adaptation option that performs best over all the possible scenarios becomes the preferred option (a robust decision). As shown in the simple example in Fig. 2, the analysis can be organized in a structure similar to a decision tree. In Fig. 2, it is assumed that the two adaptation options on the left hand side of the figure are being considered. The effectiveness of each option is

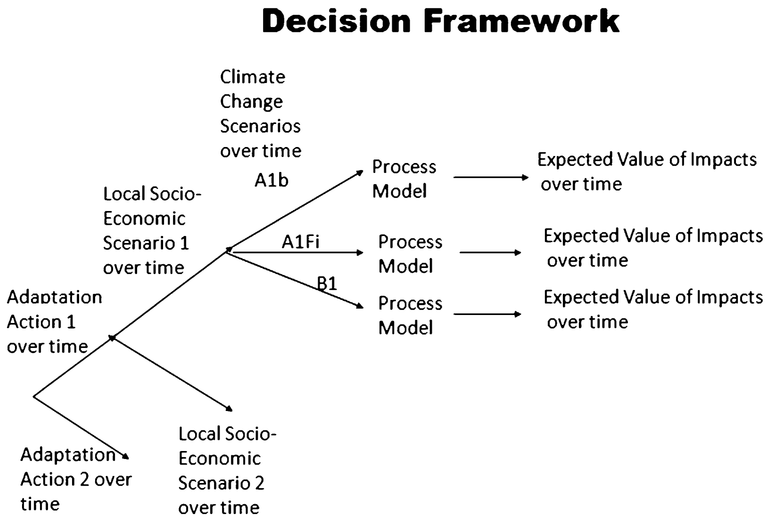


Fig. 2 Framework for scenario-based risk assessment

evaluated for each socio-economic scenario, and within each socio-economic scenario, for each climate change scenario. A dynamic process model is used to determine the expected values of the combined impacts of each combination of socio-economic and climate conditions. The results are on the right of the figure; the performance of each adaptation option under each possible set of scenarios. Impacts can be measured with multiple criteria or indicators that cover the range of environmental, economic, and social factors. The robust solution is the adaptation option that is better than all the other options for no matter what is the scenario. If no such adaptation option is found in the initial round of analysis, then the values of the scenario causing the lack of a dominant option can be examined. If the critical values in the scenario are not plausible, then that scenario can be removed. Another approach is to move backwards from a desired outcome to find the adaptation action that is robust. New adaptation options can also be tested. If the uncertainties can be resolved by assigning probabilities to them, the process becomes a decision tree (for example see Hobbs et al. 1997).

This approach was used by Kirshen et al. (2008) to examine the impacts of SLR on coastal flooding in metro Boston. Other examples are given in IPCC (2007). A variation on this approach is to use optimization theory to find the robust adaptation action (e.g., Groves et al. 2007).

Within the constraints of study resources and available information, the adaptation options selected for evaluation can be as complex as necessary. For example, in Kirshen et al. (2008), some adaptation options varied over time as a function of coastal flooding that occurred. Expected values of the annual damages for each year were determined using the following relatively complex and time consuming procedure. An historical year of recorded daily maximum sea levels (SL) measured at Boston MA from 1920 to 2000 was randomly assigned to each year in the study period from 2000 to 2100 and the highest SL elevation that had occurred in that historic year was extracted. This process was repeated 100 times to develop 100 possible time series of future annual maximum annual sea levels (i.e. bootstrapping, Vogel and Shallcross 1996). SLR rises were added to each year based upon the SLR climate change scenario. Then coastal impacts to buildings and contents were determined for each of the 100 possible time series of elevations over the period 2000 to 2100 (Monte Carlo simulation) and the resulting damages for each year were averaged to obtain the expected value of damages for that year. Because the process accounts for 100 possible patterns in timing of future storm surges, uncertainty in timing of future storm surges is inherently included. Although only economic damages were considered, the method could easily be expanded to include environmental and other metrics as needed by the user.

An example of how the results of this approach can be presented to stakeholders is shown in Fig. 3 (from Kirshen et al. 2008). Figure 3 shows the expected values of annual damages and costs over time to coastal buildings and contents in metropolitan Boston under 0.6 m of SLR by 2100 with several adaptation scenarios. This type of information, perhaps also summarized by showing the total discounted damages and costs over time and regional maps of damages and costs, can help coastal decision-makers at all levels of government make better, more informed, adaptation assessments. Details of the specific adaptation options and the analytical approach are available in Kirshen et al. (2008) and are not repeated here.

3 Simplified method

Many agencies and stakeholders do not have the financial or technical resources to use Monte Carlo simulation to determine expected value of impacts over time. A method to

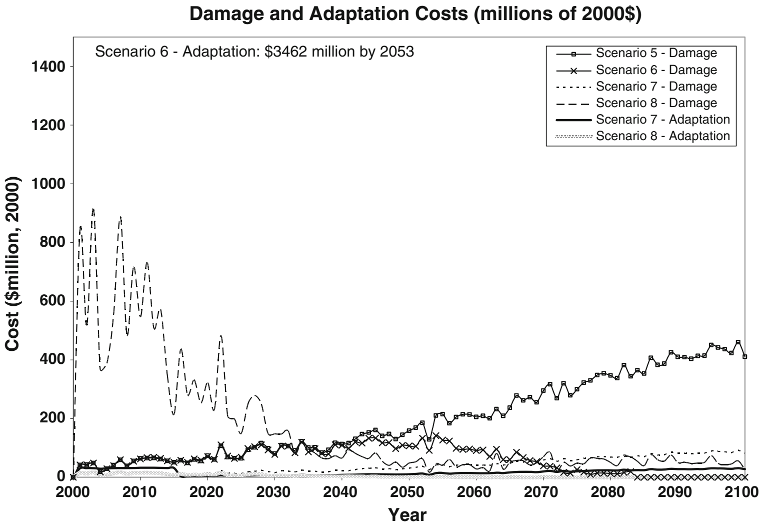


Fig. 3 Example of results of scenario-based risk assessment on built environment from Kirshen et al. (2008)

approximate such analysis, described here, is based upon developing exceedance curves of flood elevations.

By assigning flood damages to the flood elevations in a coastal flood frequency curve such as Fig. 1, the elevation frequency curve becomes a damage frequency curve. The area under the curve is the expected value or average of the annual damages for the period for which the flood frequency curve is valid. Hallegatte et al. (2011) uses a similar methodology to estimate mean annual flood losses in Copenhagen. These curves change over time as the climate changes. Changes over time can be approximated by increasing elevations on the Y axes by the subsequent increases in sea level. If this is done for several of the sea level increases projected over specific time intervals (e.g., the present, 2020, 2040, 2060, 2080, 2100) for a particular climate change scenario, then an expected value damage estimate for each time period can be determined. From these data, an expected value damage-versus-time curve can be developed for a climate change scenario by interpolating between the points. The area under the expected value damage-versus-time curve is the total damages expected over the entire time period. If land use change scenarios over time are employed, the depth-damage relationships each time period can be adjusted to reflect the changes. The shape of the curve in future time periods can also be changed to reflect phenomena such as increasing storm intensity over time. Other evaluation metrics in addition to cost can be used if they can be related to depth. These analyses result in impacts of the status quo or Do-Nothing Adaptation Option.

Variations on this approach can be used for examining impacts of adaptation options implemented at specified times such as (1) accommodation to flooding (e.g., flood proofing and elevating of infrastructure or controlled flooding in certain areas), (2) retreating from the floodplain, and (3) protection with hard and soft approaches. Options (1) and (2) can be estimated by changing values of the damages associated with each depth at each time period as flood proofing or retreat is gradually implemented. Option (3) can be approximated by altering the depth-damage function so that there are zero damages up to the protection elevation, and beyond that the damages are equal to the present damage function, assuming that once the barrier is overtopped, all land areas are flooded up to that elevation.

4 Case study

An illustrative example of the simplified scenario-based risk assessment is presented below as a case study for Old Orchard Beach (OOB), Maine in the northeastern USA, shown in Fig. 4. This town has a population of 8,900 that swells to over 70,000 during peak tourism season and a long sandy beach along which most of the hotels, restaurants, and other commercial real estate are located. For this example, it is assumed that OOB has three options to adapt to increased coastal flooding from SLR for the planning horizon from 2010 to 2050; 1) taking no action; 2) nourishing the beach in 2010 (the assumed date of construction) to an elevation of the present 100 year floodplain plus 0.305 m (action100+); 3) nourishing the

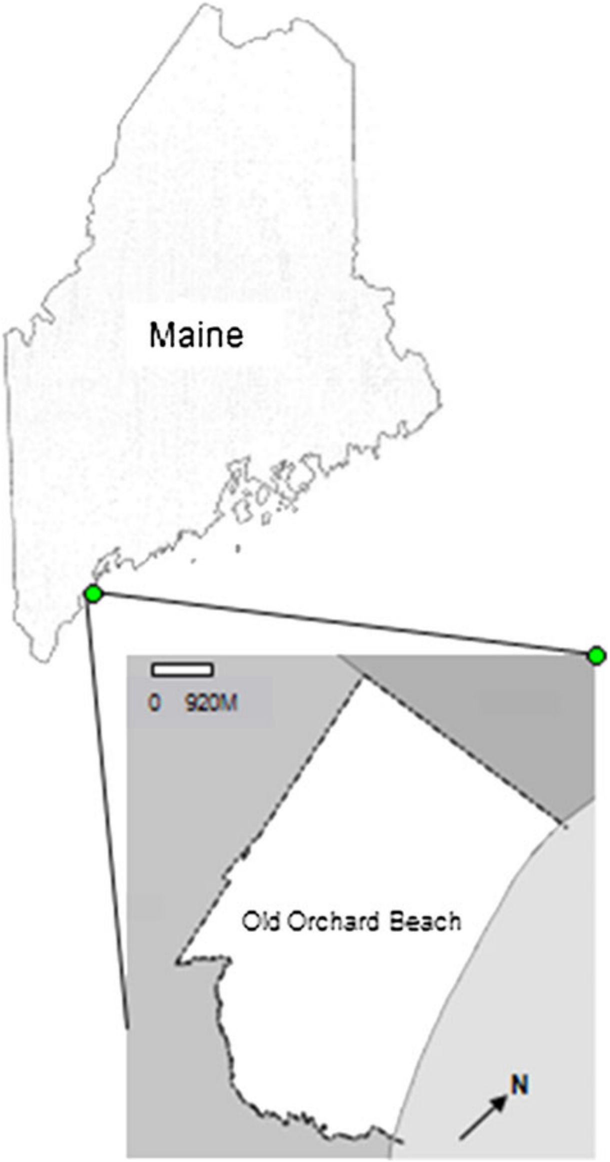


Fig. 4 Old Orchard Beach, Maine study area

beach in 2010 (the assumed date of construction) to an elevation of the present 50 year floodplain plus 0.305 m (action 50+). Even though many coastal areas are already using beach nourishment and it may be a short term adaptation to climate change, it is not sustainable in the long run and may have unacceptable social and environmental costs. We only use it here as a straightforward example to illustrate the methodology without endorsing it use as optimal solution.

Two scenarios of SLR over the next several decades are provided in Table 1. These are the high and low values of eustatic SLR estimated from Fig. 4 in Ramsdorf (2007) between the assumed date of construction, assumed to be 2010, and the future years. Only economic adaptation costs and residual damages are included. It is assumed there are no changes in land use values and the discount rate is zero. Losses from permanent inundation of land are not included in the analysis. The relatively small local SLR changes due to subsidence were not included in the analysis.

The procedure for each SLR scenario without adaptation is to: determine the damage-exceedance probability functions for each of the years 2010, 2030 and 2050 by estimating the storm surge damage associated with each flood elevation corresponding to each exceedance probability for each year; estimate the expected damage for each of these years by estimating areas under the damage-probability functions; and then use linear interpolation between the expected annual damage values to estimate expected values of the cumulative damage costs over time.

Damages are estimated by determining the depth of flooding in 0.305 m increments in OOB for each flooding scenario. These are converted to flood damages to building and contents using generic depth-damage relationships for residential structures with basements from the US Army Corps of Engineers (2003). These are based upon building replacement values, which are derived from assessors' tables. Direct costs for cleanup expenses, unpaid hours for cleanup and repair, emergency damage prevention actions, and other flood-related costs are not included in these damage functions. These estimation functions are best used for static flood inundation scenarios, and do not explicitly consider the potential impacts of waves and erosion (from D Moser, US Army Corps of Engineers, Institute for Water Resources, personal communication, July 1, 2009). An Excel spreadsheet package based upon a digital elevation map from Industrial Economics, Inc. is used for these calculations.

Shown in Fig. 5 is the present flood exceedance curve for OOB based upon .01 and 0.1 values reported by the Federal Emergency Management Agency and estimated elevation values for 0.2 and 0.001 probabilities. It also includes the curves for the low SLR scenario for the years 2030 and 2050. The curve stops at 1.52 m (datum for all elevations is NGVD29) because below this elevation there is no damage. Figure 6 shows the damage-frequency curves for the years 2010, 2030 and 2050 for the low SLR scenario and no adaptation actions. The significance of the horizontal line at approximately $80 million is explained below. The area under each of these three curves is plotted with interpolation between them to develop Fig. 7, which shows the expected annual values over time for the low SLR scenario with no adaptation action. Similar information was developed for the high SLR scenario.

Table 1 SLR scenarios (centimeters)

cm	2030	2050
Low value	10	17
High value	22	37

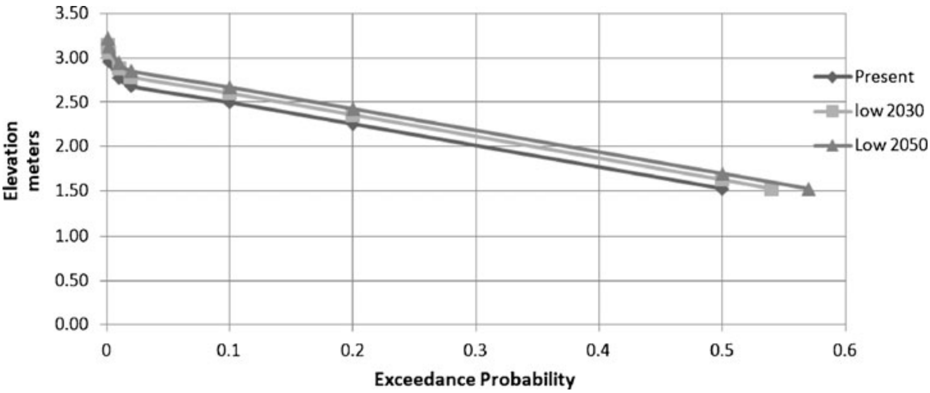


Fig. 5 Low SLR scenario exceedances

5 Damages

Present damages The total expected value of annual damages under no SLR is the area under the Present curve in Fig. 6, $17 million. This does not imply a prediction of $17 million in damages in 2010; it is the average of the annual damages over the period for which the flood curve is valid. Over the next 40 years, the total is 40 times that, or $680 million. This is shown in Table 2.

Low scenario–no action The total cost of taking no adaptation actions under a low SLR scenario over the period 2010 to 2050 is the area under the curve in Fig. 7, totaling $899.3 million.

Low scenario–nourishment to 50 year floodplain plus 0.305 m This brings flood protection to an elevation of 2.99 m. Above this, the same damage occurs as when the beach is overtopped at 2.99 m of elevation. To determine the amount of protection and residual damages, the damage line corresponding to 2.99 m, $80.5 million, is drawn across the damage-exceedance curves as in Fig. 6. For each scenario and time period, the area of the curve to the right of the intersection of this line with the exceedance curve is protected. The

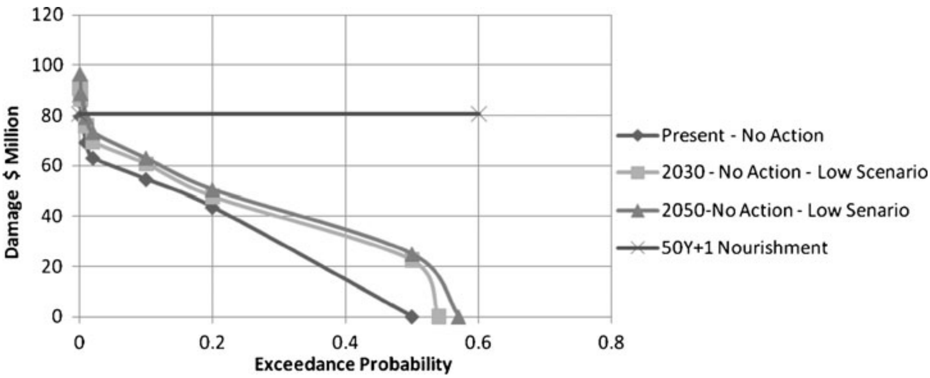


Fig. 6 No action-low scenario

area to the left of the intersection is the residual damage. The residual damages are thus determined for this adaptation option for 2010, 2030, and 2050. These are then plotted in a manner similar to Fig. 7 and the area under that curve determined. The total residual expected values damage over the period 2010 to 2050 is approximately $28.3 million.

Low scenario–nourishment to 100 year floodplain plus 0.305 m This brings flood protection to 3.08 m. Below this, there is no damage. Above this the same damage occurs when the beach is overtopped at 3.08 m of elevation or the $87.4 million damage line. The same procedure as described above is used. The expected value of the residual damage is approximately $0.

Other scenarios These are determined as above and summarized in Table 2.

6 Cost of nourishment for adaptation

Initial construction of the beach nourishment up to the present 100 year flood elevation is assumed to equal $3,280/linear m ($1,000/linear foot). Adding 0.305 extra meter of nourishment is assumed to cost $328/linear m ($100/linear foot). Every 10 years, 75% of the nourished beach must be redone. The estimated length of OOB to be nourished is 4.8 km. This results in initial cost of $17.23 million for the 100+action with three expenditures of $12.9 million for the periods ending at 2020, 2030, 2040. The total undiscounted cost is $60 million. The similar values for the 50+action are $16.1 million initial cost, $12.1 million for 10 year rebuilding, and total of $52.4 million. These are summarized in Table 2.

7 No regrets

Without SLR, the expected annual value of damages of $17 million over the period 2010 to 2050 totals $680 million. If nourishment is done to 2.99 m at a cost of $52.4 million, residual damage over the same period is dramatically lower, at approximately $ 3.4 million (50+ action). If nourishment is done to 3.08 m at the cost of $60 million, the residual expected damage over the same period is decreased to approximately $0 (100+ action). Therefore, both levels of beach nourishment appear to be attractive alternatives even without sea level rise because of the potential protection provided from large storm surge events.

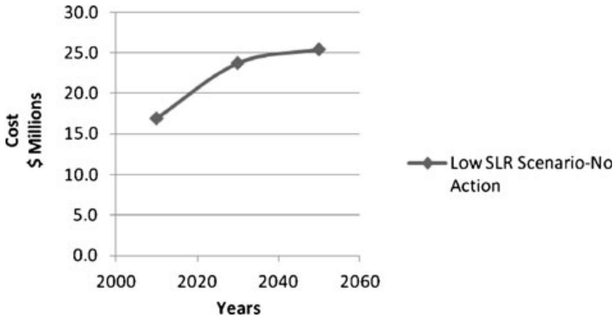


Fig. 7 Low SLR scenario-no action

Table 2 Scenario summary

SLR scenario	Adaptation	Expected value of residual damages $million	Expected value of adaptation cost $million	Total damage and cost $million
No SLR	No Action	680	0	680
	100 +	0	60	60
	50 +	3.4	52.4	55.8
Low	No Action	899.3	0	899.3
	100 +	0	60	60
	50 +	28.3	52.4	80.7
High	No Action	1016.6	0	1016.6
	100 +	37.6	60	97.6
	50 +	67.8	52.4	120.2

8 Robust decision

Not taking action results in higher costs for all scenarios, including no SLR. A robust decision is nourishing to the present 100 year floodplain plus 0.305 additional meters (100+ action). This action results in only slightly higher damages and costs if there is no SLR compared to 50 +, and lower total damages and costs than 50+ for both high and low amounts of SLR. It is also a reasonable no regrets decision because it results in lower total damage costs in the case of no SLR compared to no action.

9 Limitations

The example faces many of the same limitations of most current SLR analyses. These include the development of elevation exceedance curves using static inundation, static topography (e.g., the land surface does not change in response to accretion or erosion), ignoring potential changes in storm intensity under climate change, and limited choice of metrics. In theory, these could be included in the analysis by more accurate surge modeling, and more scenarios and metrics. The method utilized herein also cannot easily be used to model behavior responses that are based upon adaptive management. For example, this method would have difficulty dealing with a policy that would allow a structure to be flooded up to two times, but after the second time, the structure must be removed (or retreated) from the floodplain. In these cases, Monte Carlo simulation as utilized by Kirshen et al. (2008) would be appropriate. The methodology also requires quantification of metrics–some of which may be challenging such as distribution of impacts and other costs.

10 Conclusions and next steps

At least 100 coastal towns in New England will be seriously impacted by expected increases in sea level rise and storm surge intensity over the next century, if not the next few decades. Initial research described here provides a robust framework to help guide decision-makers through a series of simplified cumulative damage probability analyses. Damage assessment information has previously been missing from many adaptation analyses, partly due to the complex nature of the modeling required. The information presented herein provides a simplified approach to include such information in the local decision-making process. This approach is relatively easy to undertake with limited amounts of data, and the methodology is transferable amongst coastal communities. Armed with economic impact information from this model, communities will be able to initiate public processes to set aside potential funding for appropriate adaptation actions such as asset relocation, beach nourishment, land purchase, or the construction of barriers. The methodology described in this paper is currently being incorporated into a more robust yet user-friendly planning tool called COAST (Coastal Adaptation to Sea level rise Tool) by the Region1 Environmental Finance Center, and the University of New Hampshire COAST is intended for use by local and regional planners, municipal officials, university extension agents, and other decision-makers to help understand the potential economic impacts of different scenarios of sea level rise and the associated costs of different adaptation strategies. Additional near-term modifications include incorporation of map-based cost/risk output such a shown in Merrill et al. (2010) and a more accessible user interface.

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