The Economics of Protection against Sea-Level Rise: An Application to Coastal Properties in Connecticut

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October 5, 2012

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Research for this paper was supported by the Center for Environmental Sciences and Engineering (CESE) at the University of Connecticut and by the U.S. Department of Agriculture. The views expressed in this paper are solely ours and are not to be attributed to any of the sponsors. We extend our gratitude to Kathleen Segerson, Stephen Ross, and Michael Willig for their helpful comments and suggestions. Any remaining errors are our own.

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ABSTRACT

As a consequence of rising global sea levels, both the magnitude and frequency of coastal storms are expected to increase, which necessitates evaluating coastal flood adaptation measures. In this study, we conduct a benefit-cost analysis of coastal protection for 57 census blocks along the coast of Connecticut. The broad research question we address is whether benefits of coastal protection outweigh its costs. In cases where coastal armoring is desirable, our framework also allows us to determine the optimal timing of construction that maximizes expected net benefits. Our results suggest that in such cases coastal armoring can substantially alleviate the burden of total flood-related costs in the study area. The present value of cost savings due to coastal protection (relative to no protection) in the area over the next century amount to more than 26% with moderately high (physical, environmental, and amenity) costs and discount rate and range up to 41% under more conservative assumptions on the model parameters. Furthermore, the results we obtain imply that the optimal timing of protection may vary across different coastal regions.

Keywords: climate change; sea-level rise; coastal flooding; coastal protection

Journal of Economic Literature Classification: D61, D82, Q54, Q58
1. Introduction

Among the potential impacts of climate change, sea-level rise has spurred worldwide concerns, with global rise projections reaching up to several feet by the end of this century (Nicholls et al. 2008). In addition to environmental damages (erosion, wetland loss, surface salinization) and property loss resulting from higher sea levels, another alarming consequence of sea-level rise is the increase in magnitude and incidence of coastal floods (Bosello et al. 2012). Michael (2007) shows that economic costs of episodic flooding in the U.S. may substantially outweigh damages from inundation of low-lying property by the rising sea. Furthermore, flooding raises additional concern due to the lower awareness to this type of risk, as coastal floods are uncertain events whose rising threat is generally not perceived by the public until they take place. Thus, evaluating coastal flood adaptation measures is fundamental for policy formulation purposes.

Presently, flood insurance has been required by most mortgage lenders from owners of flood-prone property in the U.S. (Bin et al. 2008). In theory, properly set insurance premiums should result in individuals incorporating potential flood costs in their decisions to settle in risky areas. Yet, since its establishment in 1968, the federally-subsidized National Flood Insurance Program (NFIP) has been associated with low uptake\(^1\) and premiums set below the true expected flood losses (King 2011; Landry and Jahan-Parvar 2011). As with most price policy instruments, raising insurance premiums has faced stark opposition (Postal 2011), which would make charging actuarially fair premiums politically infeasible. Given that the notion of an actuarially fair insurance program remains unrealistic (e.g., Yohe et al. 2011), we focus on alternative policy responses to the coastal flooding problem.

In our analysis, we assume that zoning restrictions are placed to prevent further development in all coastal areas. Zoning restrictions are encouraged by Section 303 of the

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\(^1\) This can be partly attributed to the fact that insurance purchase is not always enforced beyond the initial year of the mortgage contract (Landry and Jahan-Parvar 2011).
U.S. Coastal Zone Management Act (CZMA) of 1972\textsuperscript{2} and have been used in almost all coastal states.\textsuperscript{3} Assuming away the costs of enforcing this policy and some possible negative spillover effects (e.g., welfare loss to individuals outside of our study area for whom moving into one of our restricted coastal zones would have been optimal), the policy is justified from a benefit-cost perspective, as it leads to a reduction of potential flood-related property damages. Nevertheless, as a standalone policy measure, it is unlikely to provide a long-term solution to the flooding problem, as increasingly more of the existing property becomes endangered due to the rising sea level. Hence, in a dynamic setting, it may be welfare-improving to complement zoning restrictions with other flood adaptation strategies.

Some possible adaptation strategies include armoring the shoreline with “hard” structures, such as seawalls and levees. These structures need to be maintained and expanded periodically in order to cope with the rising sea levels. Thus, sea-level rise leads to higher costs of protection, triggering debates regarding the financing of this adaptation measure (Gornitz et al. 2004; Koch 2010) and necessitating careful benefit-cost analyses prior to coastal armoring. Alternatively, residential properties in the flood-prone areas can be raised and floodproofed in order to minimize damages once a flood occurs (Medina 2006). Another potential adaptation response is managed retreat, which incorporates a wide variety of policy actions, including removal of structures in danger of collapse into the sea, terminating subsidies for rebuilding of structures in high risk zones, or establishing setback lines determined by sea-level projections (Gornitz et al. 2004).

This study evaluates coastal armoring as a potential complement to zoning restrictions. Our goal is to quantify the net benefits of armoring and establish whether it should be considered among the list of potential adaptation strategies. Thus, retreat and

\textsuperscript{2} See \url{http://coastalmanagement.noaa.gov/about/czma.html#section303}.

\textsuperscript{3} A feature of the CZMA is that state participation is voluntary. Nevertheless, all coastal states, except for Alaska, are currently enforcing the Act. See \url{http://coastalmanagement.noaa.gov/mystate/welcome.html}.
structural retrofitting are not considered in the current specification, although our conceptual model is quite general and can be used in future research to incorporate these strategies. The broad research question we address is whether benefits of coastal protection outweigh its costs. In coastal areas where armoring is desirable, our framework also allows us to determine the optimal timing of construction that maximizes expected net benefits.

The option to delay protection in time is an important contribution of this paper to the existing literature on coastal flood protection. While Yohe et al. (1995) develop a framework which allows them to determine the optimal timing of initiating protection against coastal property inundation due to gradual sea-level rise, to our knowledge no similar framework has been implemented in evaluating protection against stochastic flood events. Previous studies on coastal flood protection (e.g., Nicholls and Tol 2006; Kirshen et al. 2006; Tol et al. 2006; Heberger et al. 2009) consider only a policy decision of the type “protect today or abandon forever.” In contrast, we model sea-level rise as a gradual process, which allows us to determine not only whether an area should be protected, but also the optimal timing of protection.

Our framework features benefit-cost analysis under uncertainty regarding the implementation of a potentially irreversible project (or one with prohibitively high disinvestment costs). In the analysis, we employ the HAZUS-MH physical impact model (see Scawthorn et al. 2006a, 2006b; FEMA 2009) to translate climate characteristics and physical conditions into damage losses from potential flooding. We opt for the physical impact model rather than its counterpart, the statistical model approach, in view of a significant limitation of statistical models: these models are based on historical relationships

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4 The broad literature in this area dates back to seminal papers by Arrow (1968), who identifies the role of irreversibility in the optimal timing of investment, along with Arrow and Fisher (1974) and Graham (1981), who apply the concepts of quasi-option value and option value, respectively, when measuring benefits of environmental projects in the presence of uncertainty. Subsequent research has employed these concepts to a wide range of benefit-cost analysis contexts, including land preservation (e.g., Chambers et al. 1995; Messina and Bosetti 2003; Bosetti et al. 2004), greenhouse gas mitigation (Chao and Wilson 1993; Morath 2010), and transportation (e.g., Geurs et al. 2006; Laird et al. 2009; Chang et al. 2012).
between climate and activity in a given sector and thus cannot fully account for future changes that go beyond historical values, e.g., potential adaptation strategies that have not been implemented in the past (Hallegatte et al. 2011). Given the focus of our study on adaptation, we adopt the physical model approach which allows us to incorporate coastal protection and adequately assess its impacts on potential flood-related economic losses.

The aim of our study is to set up a tractable benefit-cost framework and demonstrate its application for a given coastal area. The study area we examine includes 57 census blocks along the coast of Fairfield County, Connecticut. Although Connecticut is not among the states historically prone to coastal flooding, recent storm events, including Hurricane Irene which hit the state severely at the end of August 2011 and caused storm surge of up to 7 feet along the coastline, may indicate that this trend has already started to change. Connecticut may also be considered a relevant case study for two further reasons. First, according to projections, sea level in the region may rise anywhere from 9 to 43 inches by 2080 (Gornitz et al. 2004), suggesting a substantial increase in flood risk for coastal areas. Furthermore, more than 2 million people (roughly 60% of the population of Connecticut) inhabit the state’s coastal area at the moment and could suffer the consequences of potential severe floods (Frumhoff et al. 2007). Only five other states (Illinois, Massachusetts, New Jersey, Pennsylvania, and Rhode Island) exceed Connecticut’s population density in coastal areas (Crosset et al. 2004). Fairfield County, in particular, has the highest population density among the coastal counties in Connecticut, is abundant with high-valued waterfront property, and its coastal towns (e.g., Greenwich and Darien) are among the wealthiest in the U.S. (CT DEEP 2009).

The rest of the paper is organized as follows. Section 2 presents the conceptual framework used in our benefit-cost analysis. Section 3 discusses the data and estimation

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methodology. Section 4 describes the results under various parameter specifications. Section 5 summarizes the main findings of the study, points at some caveats, and lays out potential future extensions of the model.

2. Model

2.1 General Framework

In period $t$, it is possible that a stochastic flood event occurs in coastal area $j$. Let the random variable $R$ denote flood magnitude, measured in terms of storm water elevation, which ranges between $R_{\text{min}}$ and $R_{\text{max}}$. Also, let $f_t(R)$ denote the density function of $R$ at time $t$ and $D_{jt}(R)$ be the region-specific damages resulting from a flood of magnitude $R$ occurring at $t$. The expected flood-related damages for area $j$ at time $t$ are then given by:

$$ED_{jt}(R_{\text{min}}, R_{\text{max}}) = \int_{R_{\text{min}}}^{R_{\text{max}}} D_{jt}(R) f_t(R) dR.$$  \hfill (1)

We can obtain the present value of total expected damages over a given time horizon $[t_0, T]$ as follows:

$$PV(ED_{jt}) = \int_{t_0}^{T} e^{-r(t-t_0)} ED_{jt}(R_{\text{min}}, R_{\text{max}}) dt,$$  \hfill (2)

where $r$ is a discount rate and $ED_{jt}$ is obtained from equation (1).

Suppose an adaptation measure is implemented at time $t_A$ in addition to what is pre-existing in equation (1) in order to reduce the amount of flood damages. Then, the present value of the benefits of implementing this adaptation measure, discounted back to $t_0$, is derived from the total averted damages as follows:

$$PV(EB_{jt}, t_A) = \int_{t_A}^{T} e^{-r(t-t_0)} ED_{jt}(R_{\text{min}}, \bar{R}) dt,$$  \hfill (3)

where $\bar{R} \in [R_{\text{min}}, R_{\text{max}}]$ is the largest flood whose damages can be avoided through the particular adaptation measure.
The costs of implementing the adaptation strategy can be broken down into initial costs \( c \), incurred at time \( t_A \), and maintenance costs \( m \), incurred in subsequent periods.\(^6\) Thus, total discounted costs are given by:

\[
PV(C_{j,t_A}) = e^{-r(t-t_0)c_{j,t_A}} + \int_{t_A}^{T} e^{-r(t-t_0)m_{jt}dt}.
\]

(4)

Note that initial costs can be expressed as a continuous stream of per-period costs \( N_j \), i.e.,

\[
c_{jt_A} = \int_{t_A}^{\infty} e^{-r(t-t_0)}N_j dt = e^{-r(t-t_0)} \frac{N_j}{r}.
\]

(5)

Any empirical implementation of this framework necessitates the use of a finite time horizon. In that case, \( T < \infty \) and only the expected benefits up to period \( T \) are considered, so we also need to adjust the costs in order to conduct a valid benefit-cost analysis.\(^7\) Therefore, the relevant initial costs in our cost function become:

\[
\tilde{c}_{jt_A} = \int_{t_A}^{T} e^{-r(t-t_0)}N_j dt = (e^{-r(t_A-t_0)} - e^{-r(T-t_0)}) \frac{N_j}{r}.
\]

(6)

Combining equations (5) and (6), we obtain:

\[
\tilde{c}_{jt_A} = (1 - e^{-r(T-t_A)})c_{jt_A},
\]

(7)

which we use in equation (4) instead of \( c_{jt_A} \) throughout the remaining analysis.

Assuming risk-neutrality, a policy-maker solves:

\[
t^* = \arg\max_{t_A} [PV(EB_{j,t_A}) - PV(C_{j,t_A})] \quad \text{s. t. } t_A \in [t_0, T]
\]

(8)

in order to determine the optimal timing for initiation of the adaptation strategy. Note that in the case of \( PV(EB_{j,t^*}) - PV(C_{j,t^*}) \leq 0 \) no adaptation is implemented.

The above model is dynamic due to sea-level rise. \textit{Ceteris paribus}, as sea rises over time, coastal floods generate larger damages, resulting in greater benefits of adaptation. On

\(^6\) In the case of managed retreat maintenance costs are zero.

\(^7\) Note that the use of a finite time horizon makes our results sensitive to the length of the horizon. Nonetheless, for a large enough \( T \) the approximation error would be of small magnitude.
the other hand, costs of adaptation may also increase over time. If the strategy considered is coastal armoring, both height and length of structures necessary to provide adequate protection will increase due to sea-level rise. Similarly, additional raising and floodproofing of property would be necessary as sea level increases. In the case of managed retreat, more property in \( j \) is now vulnerable and needs to be vacated and moved out of harm’s way. Hence, with both benefits and costs of adaptation varying over time, a decision to implement an adaptation strategy that is not economically viable in earlier periods could become justified in later periods.

### 2.2 Application of the Model to Coastal Protection

We utilize the model to evaluate coastal protection in 57 census blocks along the coast of Fairfield County, Connecticut. The time horizon of our study is 100 years. During this period, a random flood event may occur in any year \( t \).\(^8\) In hydrology, a flood of given magnitude is typically classified by its recurrence interval which can be easily converted into probability of exceedance in a given year. Mathematically, exceedance probability is simply the reciprocal of the recurrence period. Thus, a 100-year flood has a 1% chance of being equaled or exceeded in any year. The usual assumption is that flood events are statistically independent of each other across time. Given this assumption, we can re-write equation (1) to express expected damages in census block \( j \) for year \( t \) as follows:

\[
ED_j(t, R^{max}) = \int_1^{R^{max}} D_j(R) f(R) dR, \quad t = 1, ..., 100, \tag{9}
\]

where \( R \) now denotes the flood recurrence interval.\(^9\)

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\(^8\) While in theory more than one flood event may occur at a given locality during the year, evidence of such multiple occurrences in the U.S. is rare. Thus, we make the simplifying assumption that only one random event takes place every year.

\(^9\) This framework assumes that a one-year flood, which is equaled or exceeded with certainty every year, generates no damages, i.e., \( D(1) = 0 \).
In order to compute $ED$, we need to transform the exceedance probability associated with each flood event into the corresponding probability of occurrence. In particular, we are interested in the probability of a flood event being equaled rather than equaled or exceeded. Suppose $x$ is a random variable denoting flood size. We follow the procedure introduced by Farrow and Scott (2011), who represent $R$ as a transformation of $x$, with $R(x)$ being the inverse of the exceedance probability of $x$, and utilize the fact that the exceedance probability of $R$ and $x$ is the same.\(^{10}\) Using substitution and the first fundamental theorem of calculus, they derive $f(R) = \frac{1}{R^2}$.

For each census block, we consider the net benefits of constructing a protective structure, such as a seawall or a levee. Federal regulations mandate that a coastal protective structure be maintained at a height sufficient to withstand a 100-year flood (44 CFR Part 65 2010). Thus, our analysis assumes that a structure is capable of protecting the region against a 100-year flood or an event of smaller magnitude. If a larger flood event takes place, the structure would be overtopped. In such instances, damages within the protected areas are assumed to be the same as in the absence of armoring.\(^{11}\) Therefore, we set $\bar{R} = 100$ and use the discrete-time version of (3) in order to derive the discounted expected benefits of protection.

The costs of protection include initial construction costs, maintenance costs, and costs of future retrofitting. It is reasonable to assume that, once a structure is built, it will be maintained and raised when necessary in order to ensure adequate protection at all times.\(^{12}\)

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\(^{10}\) For example, a 100-year flood event has the same probability of being equaled or exceeded as a flood of the size that corresponds to a 100-year flood event.

\(^{11}\) On the one hand, the presence of a seawall/levee may reduce total damages, even if the structure is overtopped, by slowing down the storm waters. On the other hand, if overtopping results in structural failure, debris from the structure could cause additional damage to the property behind it, while the costs of repairing the structure would also add to total damage costs. We make the simplifying assumption that the above effects fully offset each other.

\(^{12}\) If due to sea level rise a sea barrier can no longer grant protection against a 100-year flood, it fails to meet the Federal regulations. If the costs of removing the structure are relatively high, which one would anticipate given
Suppose that a structure is built in year $t_1 \geq t_0$ and needs to be raised in a later year $t_2$. In $t_1$, construction costs $c_{jt_1}$ are incurred, which we adjust to $\tilde{c}_{jt_1}$ using (7). The additional cost of raising the structure incurred in $t_2$ is denoted by $c_{jt_2}$, and the equivalent adjusted cost is $\tilde{c}_{jt_2}$.

We can modify equation (4) to reflect the above costs:

$$PV(C_{jt_0}) = e^{-r(t_1-t_0)}\tilde{c}_{jt_1} + \int_{t_1}^{T} e^{-r(t-t_1)}m_{jt}dt + e^{-r(t_2-t_0)}\tilde{c}_{jt_2} + \int_{t_2}^{T} e^{-r(t-t_2)}m'_{jt}dt,$$  

(10)

where $m'_{jt}$ are the additional maintenance costs due to the increase in the structure height.

Note that (10) can easily be extended to incorporate multiple instances of retrofitting.

Finally, we consider a scenario in which sea level increases by 3 feet by the end of our 100-year study period. This is approximately a 1-meter increase and has been considered a relatively reasonable prediction by recent studies (e.g., Kirshen et al. 2006, Heberger et al. 2009). In fact, rapid ice-melt scenarios predict sea-level rise for the area to reach 55 inches only by 2080 (NPCC 2009). Compared to these estimates, the sea-level projection we adopt falls within the more conservative spectrum of predictions. We assume a constant rate of sea-level rise over time, which results in a 0.3-feet increase every decade. As discussed earlier, due to sea-level rise, the optimal timing of protection may vary across regions.

3. Data and Methodology

We use the HAZUS-MH MR4 risk assessment software, developed by the Federal Emergency Management Agency (FEMA), to execute the flood simulations and damage analysis (Scawthorn et al. 2006a, 2006b, FEMA 2009). The Flood Module within HAZUS combines census data and user-supplied information on stillwater elevation, flood depth, wave height, and shoreline type to produce an estimate of the monetary value of flood-related direct economic losses. These losses are provided in 2006 dollars and include:

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the substantial length and height of structures in our analysis, the assumption of regular maintenance and retrofitting to keep up with the sea level is quite sensible.
(i) Repair and replacement costs for damaged buildings

(ii) Building content losses

(iii) Building inventory losses

(iv) Relocation expenses for businesses and institutions

(v) Capital-related income losses

(vi) Wage losses

(vii) Rental income losses to building owners

The last four categories depend on the building restoration or outage time which is estimated within HAZUS based on building characteristics and location.\(^\text{13}\)

Our study area, shown in Fig. 1, consists of four census tracts in southwest Fairfield County adjacent to the shoreline. The census tracts, with FIPS\(^\text{14}\) codes 108, 111, 112, and 113, cover a coastal area stretching from the New York/Connecticut state border on the west to the Greenwich Cove on the east. Each census tract is subdivided into smaller geographical regions called census blocks, which represent the lowest level of geography for which information is available in HAZUS. We use census blocks as our units of observation. In our analysis, we include only blocks for which HAZUS provides positive estimates of flood damages for at least one study period. Thus, our dataset contains 57 census blocks.

The frequency distribution of the number of buildings across census blocks in our dataset is presented in Fig. 2. The building count in most census blocks ranges between 6 and 50. The sample also features a few more densely populated outliers where the building count exceeds 70. As shown in Table 1, there is considerable heterogeneity across census tracts in terms of building count figures. Census tract 111 contains the areas with highest

\(^{13}\) When running the simulations over the entire 100-year period, we make the simplifying assumption that the real value of building contents remains unchanged over time. In reality, existing building and content values may depreciate due to aging.  

\(^{14}\) Federal Information Processing Standard (FIPS) codes are used to identify geographical entities, such as countries, states, counties, and county subdivisions. For more information, see [http://quickfacts.census.gov/qfd/meta/long_fips.htm](http://quickfacts.census.gov/qfd/meta/long_fips.htm).
building count, but it also exhibits substantial variation across census blocks. On the other hand, census blocks within tract 112 have the lowest average count in the sample.

In order to obtain \( D_{jt}(R) \), we run the HAZUS Flood Module at various stillwater elevations\(^{15}\) for each census block for five flood periods: 10, 50, 100, 200, and 500 years.\(^{16}\) Note that the variation in damages from a particular flood event across time is triggered by the change in sea level. Thus, for each census block \( j \) and sea level, indexed by \( s \), we have five data points corresponding to the flood return periods. We fit a log-log trend through the set of points at each \( j \) and \( s \).\(^{17}\) This gives us an interpolated damage function \( D_{js} = \exp(\alpha_{js})R^{\beta_{js}} \), which we can map to \( D_{jt}(R) \) by matching each year \( t \) with the corresponding level \( s \) in that year.\(^{18}\) The expected damages from equation (9) can then be obtained by solving:

\[
ED_{jt}(1,R^{\text{max}}) = \int_1^{R^{\text{max}}} \exp(\alpha_{jt})R^{\beta_{jt}} \frac{1}{R^2} dR = \frac{\exp(\alpha_{jt})}{\beta_{jt}^{-1}} ((R^{\text{max}})^{\beta_{jt}-1} - 1),
\]

\( t = 1, \ldots, 100. \) \hspace{1cm} (11)

Using equation (11), we calculate \( ED_{jt}(1,R^{\text{max}} = 100) \) for the entire time horizon of our study and plug the results into a discrete-time version of equation (3) to obtain the discounted benefits of initiating coastal armoring in year \( t \).\(^{19}\)

To derive the discounted costs of protection for a structure constructed in year \( t \) and maintained during the remaining time horizon, we use a discrete-time version of equation (10) in which the structure is retrofitted in time periods when sea level increases. Data on

\(^{15}\) Initial stillwater elevation data are obtained from local flood insurance studies available at [http://store.msc.fema.gov](http://store.msc.fema.gov).

\(^{16}\) Although in theory floods greater than a 500-year event may exit, HAZUS does not include simulations for those events. We anticipate that, since flood return periods beyond 500 years are statistically extremely rare, exclusion of such extreme events from our analysis would not affect our results substantially.

\(^{17}\) Other functional forms (linear, log-linear, and polynomial) were also fitted through the data, but showed worse fits relative to the log-log form.

\(^{18}\) A list of all \( \alpha_{jt} \) and \( \beta_{jt} \) values obtained from the interpolation is available from the authors upon request.

\(^{19}\) Note that the function \( \exp(\alpha)R^\beta \) yields \( D(1) > 0 \), while in reality damages become negligible for small flood events. Hence, we assume that \( D(R) = 0 \) for \( R < 2 \).
construction costs are collected from a report by the U.S. Army Corps of Engineers (2000). The report presents an average cost per linear meter for a steel sheet pile seawall at various structure heights. We convert these costs into year 2006 dollars and fit a quadratic polynomial trend through the report’s estimates in order to predict the costs for the specific design heights used in our study. The constant in the trend is 963.34 and can be broadly interpreted as the equipment cost incurred regardless of the structure height or type of project (initial construction or future retrofitting). Table 2 presents the predicted construction costs we obtain for a selected list of design heights. We then approximate the cost of raising an existing structure as the sum of a variable cost component equal to the difference in construction costs at the two heights and a fixed cost component given by the constant in the trend.20

To place our cost figures in the context of recent literature, note that we obtain construction costs of approximately $3,000 per linear foot for a 17-foot high seawall. Casselman (2009) presents cost estimates for a 17-foot seawall in Galveston Bay starting from $2 billion for the 60 miles involved. This translates approximately into $6,000 per linear foot, measured in year 2006 dollars. Kanak (2008) reports $1,600 per linear foot (approximately $1,500 in 2006 dollars) for the construction of a seawall in Wells, Maine. Our estimate lies in between these two numbers.

Next, we follow the standard approach in the existing literature and assume that annual maintenance costs in year $t$ are a constant fraction $\alpha$ of the total construction cost incurred up to year $t$. Previous studies (e.g., Gleick and Maurer 1990, Yohe et al. 1996, Heberger et al. 2009) take this fraction to be 10% for levees and 1% – 4% for seawalls. We

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20 To the extent that raising an existing sea barrier involves not only expanding its width and height, but also replacing parts of the initial structure, this method can lead to underestimation of retrofit costs. However, within our relatively simple framework, it offers a reasonable approximation, as it is preserves the sensible notion that constructing a barrier of a given height involves lower total costs when done all at once rather than piecewise over time.
choose a medium value $\alpha = 0.06$ for the baseline simulations and then demonstrate the impacts of changing this value in our post-estimation discussion.

Additional analysis is needed to determine the total length of protective structures necessary to prevent flooding in a given census block. Assuming that a seawall should be built along the shoreline from end to end is likely to vastly overstate the costs of protection, as there are numerous high-elevation areas within the shoreline that provide natural flood protection. In order to identify the remaining low-lying areas within a census block where hard structures should be raised, we use digital elevation data obtained from the U.S. Geological Survey (USGS) web page.\textsuperscript{21} The maps are uploaded to ArcGIS software and analyzed to determine the areas lying below the threshold level reached by surge water during a potential 100-year flood.\textsuperscript{22}

The next step is to determine the optimal height of the structures. According to the Code of Federal Regulations (44 CFR Part 65 2010, p. 301-304), the top of a protective structure should be established at one foot above the level reached by the one-percent wave.\textsuperscript{23} Hence, we add one foot to the sum of the stillwater elevation and one-percent wave height for the particular area in order to obtain the structure height. Knowing both total length and height of coastal armoring at any given year allows us to calculate the costs of initiating and maintaining protection in each census block.

In reality, sea level increases gradually every year. However, year-to-year changes are of small magnitude and should not have a significant impact upon potential flood damages. We thus assume that, within a decade, annual expected damages are constant. Over the course of each 10-year period, however, sea-level rise becomes substantial enough to affect flood damages. Thus, we run a loss estimate in HAZUS once for each decade.

\textsuperscript{21} See \url{http://seamless.usgs.gov}.
\textsuperscript{22} See the Appendix for more details.
\textsuperscript{23} One-percent wave refers to the wave height at the shore that could be either reached or exceeded with a 1% probability during a 100-year flood event. See the Appendix for more details.
incorporating a 0.3-feet rise in sea level compared to the preceding decade. Due to the within-decade stationarity of the model, a benefit-cost analysis on coastal protection need only be conducted once per decade. Thus, our results will indicate that it is optimal to either initiate protection of a given region from the start of a particular decade, i.e., from year $t = \{1, 11, 21, ..., 91\}$, or not protect the region at all.

4. Results

Using the discrete-time equivalent of equation (3) and a discount rate of 5%, we derive the present value of expected benefits of protection for each census block starting from any given time period. We compare those to the present value of protection costs, estimated by supplementing the discrete-time version of equation (10) with region-specific data on structure length and height. Area $j$ will be protected during the time period $[t, 100]$ iff $PV(EB_{j,t}) \geq PV(C_{j,t})$. Recall that we assume that a protective structure would need to be maintained and kept at the appropriate height in all subsequent years $\tau \geq t$. This implies that, once made, the decision to implement coastal armoring is “binding” and is not planned on being reversed in the following decades. Hence, $PV(C_{j,t})$ incorporates all future structural retrofitting costs and higher maintenance expenses that result from accommodating the rising sea level.

Graphically, the discounted expected net benefits of protection at time $t$ are represented by the vertical distance between the $PV(EB_{j,t})$ and $PV(C_{j,t})$ curves. If these net benefits are positive for at least one period, protection is initiated at $t$ where the distance is maximized. If $PV(C_{j,t})$ lies above $PV(EB_{j,t})$ for all periods, protection is not economically viable in the particular area. As seen in Fig. 3, $PV(EB_{j,t})$ exceeds $PV(C_{j,t})$ during years 31-

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24 While this approach could lead to a downward bias when estimating benefits and costs of protection separately, the bias would be less of a concern in the estimation of net benefits of protection, which are the relevant metric in our analysis.
The present discounted value of expected net benefits of protection is highest in year 61 ($319,720). Thus, protection in this area is initiated at the beginning of decade 7 of the study period.

The results of our benefit-cost analysis are displayed in the first column of Table 3. For more than a third of the sample, our estimates suggest that protection is optimal from year 1. In four census blocks, it is most efficient to delay the construction of protective structures until a later period. Intuitively, delaying protection leads to less instances of future retrofitting which would have added more to the total costs than a single instance of construction. Since maintenance costs are proportional to construction costs, such delay also reduces the total maintenance costs incurred during the study period. Note that these benefits of waiting exist even with no discounting and increase with the discount rate. On the other hand, postponing protection results in potential flood damages in the early decades. In the four regions where protection is initiated later in time, the benefits of delaying protection outweigh the costs of waiting in the initial periods, but eventually protecting becomes economically viable. Finally, for the rest of the dataset, the benefits of delaying protection are higher than the costs of waiting throughout the entire 100-year period. Hence, in those remaining 33 regions, “no protection” is the optimal strategy.

We quantify the welfare gains from coastal armoring by estimating the policy-induced reduction in flood-related costs for the study area, accounting for sea-level rise. In the absence of protection, flood-related costs are equal to the present value of expected flood damages (with $R^{\text{max}} = 500$) during the entire study period. Next, we derive total discounted flood costs with flood protection implemented in regions where the net benefits from it are positive. For unprotected areas, these costs are the same as in the absence of policy intervention. For areas where protection is implemented throughout the entire 100-year period.

Note that each curve passes through 10 data points, since the benefit-cost analysis is conducted at the beginning of each decade.
period, discounted costs are equal to the sum of construction and maintenance costs and expected damages from events larger than a 100-year flood. Finally, in census blocks where protective structures are built in period $\tau > 1$, discounted costs are obtained by adding up foregone expected benefits due to delayed protection $PV(EB_{t+1}) - PV(EB_{t})$, construction and maintenance costs, and expected damages from floods with recurrence intervals $R > 100$. From the cost figures with and without the policy, we estimate the percentage cost reduction in our sample due to flood protection. As shown in the first column of Table 3, optimal policy leads to approximately 41% reduction in flood-related costs for the study area.

We test the sensitivity of our results to ceteris paribus changes in the discount rate and maintenance costs. In general, a project involving large upfront costs and benefits that are dispersed across time tends to become more attractive once a relatively low discount rate is used in its benefit-cost evaluation. However, the effects of the discount rate value in our model are more complicated. From equation (3), it is clear that a reduction in $r$ leads to an unambiguous increase in expected benefits. However, it has two opposite effects on costs. A lower $r$ leads to an increase in the discounted stream of maintenance costs and costs of raising the protective structure, but also reduces all $\bar{c}_{jt}$ terms, as seen in equation (7). While in theory the net effect is ambiguous, we found that a marginal reduction in $r$ for our dataset leads to an increase in $PV(C_{jt})$. The exact opposite outcome is observed when $r$ increases.

With both $PV(EB)$ and $PV(C)$ curves shifting in the same direction in response to a change in $r$, the overall impact on the protection decision is ambiguous and region-specific. We find that lowering the discount rate from 5% to 1% encourages protection in some census blocks, while discouraging it in others. As shown in the second column of Table 3, total cost savings from coastal armoring are almost unchanged compared to the base case. On the other hand, raising the discount rate from 5% to 10% discourages protection in most regions (except for one) and results in cost savings of about 39%. Overall, changing the discount rate
does not impact the total cost reduction estimates substantially, indicating that the outcome of
our benefit-cost analysis is quite robust to varying discount rate values.

In addition, we check the sensitivity of the baseline results to a rise in maintenance
costs. Higher value for $\alpha$ increases protection costs, while leaving benefits unchanged, which
discourages protection. Thus, if the maintenance cost value used is too low, our estimates
may overstate the gains from protection. We test this by adopting a value of 0.1, almost
twice as high as our base value. As shown in the fourth column of Table 3, the magnitude of
the cost reduction under the protection policy changes by less than 10%, which again
underscores the relative robustness of our baseline results.

Finally, we derive an approximate lower bound for the gains from protection by
simulating the most “pessimistic” protection scenario. We set the maintenance cost
parameter $\alpha$ to 0.1. Furthermore, there are debates in the literature regarding the appropriate
discount rate that should be used in evaluating environmental projects (Carson and Tran
2009). While the U.S. Office of Management and Budget mandates that a real discount rate
of 7% be applied in the benefit-costs analyses of governmental regulations, there are no
established guidelines regarding the appropriate discounting of projects with long time
horizons (50 years or more). We thus consider a relatively high discount rate of 10%.
Finally, our baseline analysis does not account for environmental degradation and amenity
losses that may result from the presence of “hard” structures. These structures are known to
cause damages to the surrounding area, which include loss of wetland, ocean view, and
recreational space (Koch 2010), as well as shoreline erosion (Kelly 2000). Koch (2010)
suggests that environmental and amenity losses resulting from sea barriers may increase cost
estimates by up to 25%. Hence, we augment our data by adding 25% to the total fixed and
variable costs of protection. We re-do our benefit-cost analysis and obtain a cost-savings
estimate of almost 27%, as shown in the fifth column of Table 3.
5. Conclusion

In this paper, we evaluate protection against stochastic flood events and link policy decisions to sea-level rise. We develop a relatively simple and tractable framework for analyzing the expected benefits and costs of installing hard structures and apply it to a study area of 57 census blocks along the western coastline of Fairfield County, Connecticut. Our results suggest that when coastal armoring is introduced in regions where protection is justified from a benefit-cost perspective, it can substantially alleviate the burden of total flood-related costs in the study area. Our estimates of the present value of cost savings under this policy (relative to no protection) over the next century amount to more than 26% with moderately high (physical, environmental, and amenity) costs and discount rate and range up to 41% under more conservative assumptions on the model parameters. Furthermore, the results we obtain imply that optimal timing of protection may vary across different coastal regions.

When interpreting these results, one should bear in mind that our analysis considers the benefits and costs of coastal armoring, while excluding some other flood adaptation strategies, such as managed retreat or structural floodproofing and retrofitting. While our conclusions appear to favor the construction of “hard” structures in a number of regions within the study area, it may also be the case that, when compared to the costs of other adaptation responses, armoring is a suboptimal strategy. However, what our results clearly suggest is that installing protective structures is preferred over leaving all areas unprotected while kept under existing uses.

Our analysis relies on some simplifying assumptions. We exclude loss of lives and health effects of potential floods from the benefit-cost calculations, abstract from building stock dynamics by including zoning restrictions, and assume that protection does not affect the outcome of floods greater than a 100-year event. Yet, if we accept the argument that the
presence of a flood barrier would rather have a mitigating than aggravating role in case of
overtopping, the above assumptions may in fact lead to understating the gains from
protection. Future extensions of our work will relax these assumptions by providing more
precise estimates of the benefits and costs of coastal armoring and allowing variation in
housing units and population over time. Additional model extensions will include (i)
incorporating uncertainty in the rate of sea-level rise, which will allow the regulator to update
her expectation of flood damages and will result in a positive quasi-option value of
investment, (ii) introducing risk-aversion in the model, and (iii) considering alternative
adaptation strategies. While these extensions will allow for a more realistic representation of
the coastal flooding problem, we do not expect them to affect the implication of our model
that with expected benefits and costs of adaptation varying over time it may be optimal to
delay adaptation measures. Upon introducing these enhancements to our framework, a
subsequent step will also involve applying the model to other geographical areas, which
would serve as a more complete test of its validity.
Fig. 1 Location of the study area within Fairfield County
Fig. 2 Distribution of building count by census blocks
Fig. 3 Present value of expected benefits and costs of protection for census block #108-4005
Fig. 4 Rayleigh distribution of wave heights
<table>
<thead>
<tr>
<th>Tract</th>
<th>Observations</th>
<th>Mean</th>
<th>St Dev</th>
<th>Min</th>
<th>Max</th>
</tr>
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<tr>
<td>#108</td>
<td>17</td>
<td>26.06</td>
<td>16.03</td>
<td>7</td>
<td>52</td>
</tr>
<tr>
<td>#111</td>
<td>16</td>
<td>31.19</td>
<td>39.11</td>
<td>3</td>
<td>145</td>
</tr>
<tr>
<td>#112</td>
<td>19</td>
<td>24.95</td>
<td>20.42</td>
<td>1</td>
<td>71</td>
</tr>
<tr>
<td>#113</td>
<td>5</td>
<td>28.40</td>
<td>20.42</td>
<td>6</td>
<td>52</td>
</tr>
<tr>
<td>Total</td>
<td>57</td>
<td>27.33</td>
<td>25.57</td>
<td>1</td>
<td>145</td>
</tr>
</tbody>
</table>

**Table 1** Building Count: Summary Statistics
<table>
<thead>
<tr>
<th>Design Height (ft.)</th>
<th>Cost per linear ft. (2006 USD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>17.0</td>
<td>$3,004</td>
</tr>
<tr>
<td>20.7</td>
<td>$4,248</td>
</tr>
<tr>
<td>21.2</td>
<td>$4,417</td>
</tr>
<tr>
<td>21.8</td>
<td>$4,649</td>
</tr>
<tr>
<td>22.2</td>
<td>$4,826</td>
</tr>
<tr>
<td>22.8</td>
<td>$5,069</td>
</tr>
<tr>
<td>23.3</td>
<td>$5,255</td>
</tr>
<tr>
<td>23.9</td>
<td>$5,509</td>
</tr>
<tr>
<td>24.3</td>
<td>$5,703</td>
</tr>
<tr>
<td>24.9</td>
<td>$5,968</td>
</tr>
<tr>
<td>25.4</td>
<td>$6,170</td>
</tr>
</tbody>
</table>

*Table 2 Predicted Construction Costs*
<table>
<thead>
<tr>
<th></th>
<th>Baseline</th>
<th>Sensitivity tests</th>
<th>&quot;Pessimistic&quot;</th>
</tr>
</thead>
<tbody>
<tr>
<td>Discount rate</td>
<td>5%</td>
<td>1%</td>
<td>10%</td>
</tr>
<tr>
<td>Maintenance costs</td>
<td>0.06</td>
<td>0.06</td>
<td>0.06</td>
</tr>
<tr>
<td>Nonmarket costs (+25%)</td>
<td>no</td>
<td>no</td>
<td>no</td>
</tr>
</tbody>
</table>

Regional statistics (number of census blocks)

<table>
<thead>
<tr>
<th></th>
<th>No Protection</th>
<th>Protection from year 1</th>
<th>Protection from later year</th>
</tr>
</thead>
<tbody>
<tr>
<td>No Protection</td>
<td>33</td>
<td>31</td>
<td>38</td>
</tr>
<tr>
<td>Protection from year 1</td>
<td>20</td>
<td>17</td>
<td>18</td>
</tr>
<tr>
<td>Protection from later year</td>
<td>4</td>
<td>9</td>
<td>1</td>
</tr>
</tbody>
</table>

Cost summary

<table>
<thead>
<tr>
<th></th>
<th>$595,544,232</th>
<th>$1,958,082,960</th>
<th>$301,801,555</th>
<th>$595,544,232</th>
<th>$301,801,555</th>
</tr>
</thead>
<tbody>
<tr>
<td>PV Flood costs (No protection)</td>
<td>$351,268,960</td>
<td>$1,161,214,576</td>
<td>$184,145,040</td>
<td>$406,791,092</td>
<td>$221,008,391</td>
</tr>
<tr>
<td>Cost reduction</td>
<td>41.02%</td>
<td>40.70%</td>
<td>38.98%</td>
<td>31.69%</td>
<td>26.96%</td>
</tr>
</tbody>
</table>

**Table 3 Results**
APPENDIX: Determining the Optimal Length of Protective Structures

Following federal standards, we assume that an elevation is in danger of flooding during a 100-year event if it lies below the level reached or exceeded with one percent probability by the storm waters of that event (44 CFR Part 65 2010). Any strip of coastal land located below this level would need protection. This necessitates that we compute the one-percent wave height of a 100-year flood (i.e., the wave height at the shore that could be either reached or exceeded with a 1% probability) given the local conditions and sea level. HAZUS does not provide this number directly. Instead, it combines shoreline characteristics with user-supplied 100-year stillwater elevation data\(^{26}\) to produce estimates of the significant wave height at the shoreline. Significant wave height, denoted \(H_s\), is the average of the highest 1/3 of wave heights encountered in a given region (FEMA 2009b).

Longuet-Higgins (1952) demonstrates that wave heights follow approximately a Rayleigh distribution (Fig. 4). A Rayleigh distribution with parameter \(\sigma > 0\) has a cumulative distribution function

\[
F(x) = 1 - e^{-\frac{x^2}{2\sigma^2}}
\]

Thus, the exceedance probability is given by

\[
1 - F(x) = e^{-\frac{x^2}{2\sigma^2}}
\]

We follow the method described by Goda (2010) in order to transform \(H_s\) obtained from HAZUS into a corresponding one-percent wave height.

Note that, for the one-percent wave height \(H^*\),

\[
0.01 = e^{-\frac{(H^*)^2}{2\sigma^2}}
\]

Let \(H_s\) denote the mean of the highest \(1/p\) waves. Goda (2010) shows that if wave height follows the Rayleigh distribution,

\[
\frac{H_p}{\sigma\sqrt{2}} = \sqrt{\ln (p)} + \frac{\sqrt{\pi}}{2} \text{erfc} \left(\sqrt{\ln (p)}\right),
\]

where \(\text{erfc}(x)\) is the complementary error function defined as

\[
\text{erfc}(x) = \int_x^\infty e^{-t^2} dt.
\]

In this notation, the significant wave height is \(H_s = H_3\). Hence, plugging \(p = 3\) into equation (A.2), we obtain \(H_s \approx 1.42\sigma\sqrt{3}\). We can now re-write \(\sigma\) as a function of \(H_s\). Then, plugging the expression into equation (A.1) allows us to transform \(H_s\) directly into \(H^*\):

\[
H^* \approx 1.52H_s.
\]

Note that, for the one-percent wave height \(H^*\),

\[
0.01 = e^{-\frac{(H^*)^2}{2\sigma^2}}, \text{ i.e.,}
\]

\[
H^* = \sigma\sqrt{-[2\ln (0.01)]}.
\]

Let \(H_s\) denote the mean of the highest \(1/p\) waves. Goda (2010) shows that if wave height follows the Rayleigh distribution,

\[
\frac{H_p}{\sigma\sqrt{2}} = \sqrt{\ln (p)} + \frac{\sqrt{\pi}}{2} \text{erfc} \left(\sqrt{\ln (p)}\right),
\]

where \(\text{erfc}(x)\) is the complementary error function defined as

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\[
H^* \approx 1.52H_s.
\]

Next, we add the value for 100-year flood stillwater elevation to the one-percent wave height and obtain the total height that can be reached or exceeded by storm waters with a one-percent chance. Equipped with data on this height for every region at each point in time, we turn to the digital elevation maps. For each area lying below the one percent elevation level, we determine the optimal location and length of hard structures that would prevent surge waters from entering the area. Thus, our analysis provides us with the total length of structures needed to protect a given census block against a 100-year flood event.

\(^{26}\) The data are obtained from flood insurance studies that are available at the Federal Emergence Management Agency (FEMA) map store at http://store.msc.fema.gov.
REFERENCES:


