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The Economic Value of Delaying Adaptation to Sea-Level Rise: An Application to Coastal Properties in Connecticut

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ABSTRACT

The magnitude and frequency of coastal storms are expected to increase with rising global sea levels, which necessitates evaluating coastal flood adaptation measures. This study examines an important issue in the context of coastal flood protection, namely, the decision when to adopt protection measures. For any given coastal region, our benefit-cost framework allows us to determine the optimal timing of initiating protection that maximizes expected net benefits. We present an application of this framework to a coastal area in Connecticut. Our results suggest that the optimal timing of adopting protection may vary across different census blocks within the study area. We find that using a relatively low discount rate in the benefit-cost analysis implies greater heterogeneity in the timing decisions and earlier overall adoption, whereas, with higher discount rates, the timing decisions are reduced to a choice between early protection and no protection at all. If possible negative environmental and aesthetic impacts of sea barriers are taken into account, delaying protection would become more desirable, with the extent of delay being sensitive to the relative magnitude of one-time costs (e.g., loss of ocean view and recreational opportunities) vs. continuous costs (e.g., shoreline erosion and loss of wetlands).

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 true expected flood losses (King 2011; Landry and Jahan-Parvar 2011). 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 U.S. Coastal Zone Management Act (CZMA) of 1972[2] and have been used in almost all

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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).

[2] See http://coastalmanagement.noaa.gov/about/czma.html#section303.

coastal states.[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 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 protecting the shoreline with "hard" structures, such as seawalls and levees (e.g., Kirshen *et al*. 2006). These structures need to be maintained and expanded periodically in order to cope with the rising sea levels. Alternatively, residential properties in 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 considers coastal protection via "hard" structures as a potential complement to zoning restrictions and examines an important issue in the context of flood protection, namely, the decision *when* to adopt flood protection measures. Since our focus is on the optimal timing of protection and not on whether protection is the optimal adaptation response, retreat and 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. For any given coastal region, our benefit-cost framework allows

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[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 http://coastalmanagement.noaa.gov/ mystate/welcome.html.

us to determine the optimal timing of initiating protection that maximizes expected net benefits. This framework follows the tradition of benefit-cost analyses under uncertainty regarding the implementation of a potentially irreversible project (or one with prohibitively high disinvestment costs), which dates back to seminal papers by Arrow (1968), Arrow and Fisher (1974), and Graham (1981), and recognizes the role of project irreversibility and the value of delaying investment.[4]

We extend the above notions to the context of flood protection. While a number of other shoreline protection studies have adopted a similar site-specific approach in their benefit-cost analyses (e.g., recent works by Neumann *et al.* (2011) on protecting against tidal inundation and Kirshen *et al.* (2012) on adaptation to episodic coastal floods), our contribution to the literature on coastal flood protection lies in incorporating the option to delay protection in time. Such option has been considered by some studies on protection against gradual coastal property inundation (e.g., Yohe *et al.* 1995; Yohe and Schlesinger 1998; Neumann *et al.* 2011), but, to our knowledge, no similar framework has been implemented in evaluating protection against stochastic flood events, as previous analyses of coastal flood protection (e.g., Nicholls and Tol 2006; Kirshen *et al.* 2006; Heberger *et al.* 2009) consider only a policy decision of the type “protect today or abandon forever.”

We present an application of our benefit-cost framework to a coastal region in Fairfield County, Connecticut. Although Connecticut is not among the states historically prone to coastal flooding, recent storms Irene in 2011 and Sandy in 2012, which resulted in storm surges of up to 13 feet (4 meters) and widespread flooding along the coastline (e.g., Chamoff 2011; O’Leary 2012), may indicate that this trend has already started to change. Furthermore, flood risk in the area is expected to increase substantially by the end of this

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[4] The concepts of quasi-option value and option value, which emerge from the work of Arrow and Fisher (1974) and Graham (1981), have subsequently been adapted 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).

century due to sea-level rise (Gornitz *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 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 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^{min} and R^{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:

$$ED_{jt}\left(R^{min}, R^{max}\right) = \int_{R^{min}}^{R^{max}} D_{jt}(R) f_t(R) dR. \tag{1}$$

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

$$PV\left(ED_{j,t_0}\right) = \int_{t_0}^{t_T} e^{-r(t-t_0)} ED_{jt}\left(R^{min}, R^{max}\right) dt, \tag{2}$$

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:

$$PV\left(EB_{j,t_A}\right) = \int_{t_A}^{t_T} e^{-r(t-t_0)} ED_{jt}\left(R^{min}, \bar{R}\right) dt, \tag{3}$$

where $\bar{R} \in \left[R^{min}, R^{max}\right]$ 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 variable costs m, incurred in subsequent time periods.[5] Both c and m can incorporate market costs (e.g., infrastructural or relocation costs), as well as additional social costs (e.g., environmental or amenity costs).[6] Thus, total discounted adaptation costs are:

$$PV\left(C_{j,t_A}\right) = e^{-r(t-t_0)} c_{jt_A} + \int_{t_A}^{t_T} e^{-r(t-t_0)} m_{jt} dt. \tag{4}$$

Note that initial costs can be expressed as a continuous stream of per-period costs *N*, i.e.,

$$c_{jt_A} = \int_{t_A}^{\infty} e^{-r(t-t_0)} N_j dt = e^{-r(t_A-t_0)} \frac{N_j}{r}. \tag{5}$$

Any empirical implementation of this framework necessitates the use of a finite time horizon. In that case, $t_T < \infty$ and only the expected benefits up to period t_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 are:

$$\tilde{c}_{jt_A} = \int_{t_A}^{t_T} e^{-r(t-t_0)} N_j dt = \left(e^{-r(t_A-t_0)} - e^{-r(t_T-t_0)}\right) \frac{N_j}{r}. \tag{6}$$

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

$$\tilde{c}_{jt_A} = \left(1 - e^{-r(t_T-t_A)}\right) c_{jt_A}, \tag{7}$$

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[5] In the case of managed retreat variable costs are zero.

[6] See Section 2.2 for a more detailed discussion of social costs in the case of sea barriers.

[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_T the approximation error would be of small magnitude.

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

Assuming risk-neutrality, a policy-maker solves:

$$t^* = \text{argmax}_{t_A}\left[PV\left(EB_{j,t_A}\right) - PV\left(C_{j,t_A}\right)\right] \quad s.t.\ t_A \in [t_0, t_T] \qquad (8)$$

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

The above model is dynamic due to sea-level rise. As sea rises over time, coastal floods generate larger damages, resulting in greater benefits of adaptation. On the other hand, costs of adaptation may also increase with sea level. If the strategy considered is protection with “hard” structures, both height and length of structures necessary to provide adequate protection could increase. 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 Fairfield County, Connecticut. Fig. 1 illustrates how the iterative decision-making process explained at the end of section 2.1 is applied to problem of when to initiate such protection (that would be maintained and progressively strengthened as needed). Our study considers a 100-year time horizon. 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

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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.

probability of exceedance in a given year. Mathematically, exceedance probability is simply the reciprocal of the recurrence period (e.g., a 100-year flood has 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 (Stedinger *et al*. 1993). Given this assumption, we can re-write equation (1) to express expected damages in census block *j* for year *t* as follows:

$$ED_{jt}(1, R^{max}) = \int_1^{R^{max}} D_{jt}(R)f(R)dR\,, \qquad t = 1, \ldots, 100, \qquad (9)$$

where R now denotes the flood recurrence interval.[9]

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 (2013), 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 $f(R) = {}^{1}/_{R^2}$.

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

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[9] This framework assumes that a one-year flood, which is equaled or exceeded with certainty every year, generates no damages, i.e., $D(1) = 0$.

[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.

assumed to be the same as in the absence of protection.[11] Therefore, we set $\bar{R} = 100$ and use the discrete-time version of equation (3) in order to derive the discounted expected benefits of protection.

As discussed in Section 2.1, the costs of protection incorporate both infrastructural and social costs. Infrastructural costs can be broken down into initial construction costs, maintenance costs incurred over time, and costs of future retrofitting. In addition, “hard” 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). Some of these negative impacts, such as loss of recreational space and view, are an immediate result of the presence of sea barriers and can be accounted for as part of the initial costs and the costs of expanding the structures. On the other hand, erosion and loss of wetland, which are generally slow and continuous processes, can be viewed as a variable cost component.

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] Suppose 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, initial 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:

$$PV\left(C_{j,t_0}\right) = e^{-r(t_1-t_0)}\tilde{c}_{jt_1} + \int_{t_1}^{100} e^{-r(t-t_1)} m_{jt} dt$$

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[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 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.

$$+e^{-r(t_2-t_0)}\tilde{c}_{jt_2} + \int_{t_2}^{100} e^{-r(t-t_2)} m'_{jt} dt, \tag{10}$$

where m'_{jt} are the additional maintenance (and environmental) 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 1 meter by the end of our 100-year study period. A 1-meter increase has been considered a relatively reasonable prediction by recent studies (e.g., Kirshen *et al*. 2006; Michael 2007; Heberger *et al*. 2009). In fact, rapid ice-melt scenarios predict sea-level rise for the area to reach 55 inches (1.4 meters) 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 0.1-meter increase every decade. The implications of using alternative rates of sea-level rise are discussed in Section 4.

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 2009a). The Flood Module within HAZUS combines census data and user-supplied information on stillwater elevation, shore type, wave exposure, and flood magnitude to produce an estimate of the monetary value of flood-related direct economic losses. These losses are provided in 2006 dollars and include:

(i) Repair and replacement costs for damaged buildings[13]

(ii) Building content losses

(iii) Building inventory losses

(iv) Relocation expenses for businesses and institutions

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[13] Inbuilt in the Flood Module is the assumption that damaged buildings are repaired or replaced (if damages exceed 50%) following the flood event (Scawthorn *et al*. 2006b).

(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.[14]

Our study area, shown in Fig. 2, consists of four census tracts in southwest Fairfield County adjacent to the shoreline. The census tracts, with FIPS[15] 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 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. 3. There is considerable heterogeneity across census blocks in terms of the building count, with numbers in most blocks ranging between 6 and 50. The sample also features a few more densely populated outliers where the building count exceeds 70.

The HAZUS coastal flood modeling process requires the input of a value for the local 100-year flood stillwater elevation. This parameter represents water elevation due to tides and storm surge during a 100-year event.[16] We obtain data on current elevations from local

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[14] 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.

[15] 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.

[16] HAZUS requires data only on 100-year flood stillwater elevation. The Flood Module then computes values for elevations for other flood events based on the 100-year value and default flood elevation ratios (FEMA 2009b).

flood insurance studies[17] and then follow Wake *et al*. (2011) to derive stillwater elevations in future years by linearly adding sea-level rise to the current elevation. Based on each stillwater elevation value, HAZUS computes the significant wave height (i.e., average of the highest one third of wave heights encountered in a given region) at the shoreline and then uses a wave height regeneration algorithm for waves reaching the interior. Then, using information on local peak wave periods, average slope, and significant wave height, the Module calculates wave runup (i.e., the height above stillwater level reached by waves after breaking). Once wave height and runup hazard zones are identified, flood damages are assessed using census data (FEMA 2009b).

In order to obtain $D_{jt}(R)$, we run the HAZUS Flood Module at various stillwater elevations for each census block under five flood events: 10, 50, 100, 200, and 500 years.[18] 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.[19] 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.[20] The expected damages from equation (9) can then be obtained by solving:

$$ED_{jt}(1, R^{max}) = \int_1^{R^{max}} exp(\alpha_{jt}) R^{\beta_{jt}} \frac{1}{R^2} dR = \frac{exp(\alpha_{jt})}{\beta_{jt-1}} \left((R^{max})^{\beta_{jt-1}} - 1\right),$$

$$t = 1, \dots, 100. \tag{11}$$

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[17] Local flood insurance studies can be found at http://store.msc.fema.gov.

[18] 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.

[19] Other functional forms (linear, log-linear, and polynomial) were also fitted through the data, but showed worse fits relative to the log-log form.

[20] A list of all α_{jt} and β_{jt} values obtained from the interpolation is available from the authors upon request.

Using equation (11), we calculate $ED_{jt}(1, R^{max} = 100)$ 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 protection in year t.[21]

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 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.[22] 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 1 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.[23]

To place our cost figures in the context of recent literature, note that we obtain construction costs of approximately $10,000 per linear meter for a 5.2-meter (17 ft) high seawall. Casselman (2009) presents cost estimates for a 17-ft seawall in Galveston Bay starting from $2 billion for the 96 km (60 miles) involved. This translates approximately into

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[21] 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 $R < 2$.

[22] Other functional forms (linear, log-linear, and log-log) were also fitted through the report's estimates. The polynomial form gave the best fit (R^2 = 0.994) and is therefore the one we use in our final analysis.

[23] 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 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.

$20,000/lm, measured in year 2006 dollars. Kanak (2008) reports $1,600/lf (approximately $5,000/lm 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 annual maintenance costs in year *t* are a constant fraction of the total construction cost incurred up to year *t*. Previous studies (e.g., Gleick and Maurer 1990; Yohe and Schlesinger 1998; Heberger *et al*. 2009) take this fraction to be 10% for levees and 1% – 4% for seawalls. We choose a medium value of 6% 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).[24] 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.[25]

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 (0.3 m) above the level reached by the one-percent wave.[26] Hence, we add 0.3 m 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

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[24] See http://seamless.usgs.gov.

[25] See the Appendix for more details.

[26] 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.

length and height of coastal structures 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 annual expected damages remain constant within any given decade. Over the course of each 10-year period, however, sea-level rise eventually becomes substantial enough to affect flood damages. Hence, we run a loss estimate in HAZUS once for each decade, incorporating a 0.1-meter rise in stillwater elevation compared to the preceding decade, and conduct the benefit-cost analysis of coastal protection on a decadal basis.[27] Our results will therefore indicate that it is optimal to either initiate protection of a given region from the start of a particular decade, i.e., from year $t = \{1, 11, 21, \ldots, 91\}$, or not protect the region at all.

4. Results

We use a base discount rate of 3%, following the general recommendations of the U.S. Environmental Protection Agency with regards to discounting benefits and costs over the longer time horizon relevant for climate change policies (EPA 2008, p. 9). A 3% rate has also been adopted by other recent climate-related studies conducting assessments over a 100-year horizon (Dorbian *et al.* 2011; Neumann *et al.* 2011; Azar and Johansson 2012). Thus, using a discount rate of 3% and the discrete-time equivalent of equation (3), 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. Recall that we assume that a protective structure would need to

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[27] Other papers studying the impacts of gradual sea-level rise over the course of the next century (e.g., Yohe *et al.* 1995; Pendleton *et al.* 2011; Kirshen *et al.* 2012; Pendleton *et al.* 2012) have also conducted their analyses on a decadal (or longer-period) basis.

be maintained and kept at the appropriate height in all subsequent years $\tau \geq t_A$. This implies that, once made, the decision to implement coastal protection is "binding" and is not planned on being reversed in the following decades. Hence, $PV\left(C_{jt_A}\right)$ incorporates all future structural retrofitting costs and higher maintenance expenses that result from accommodating the rising sea level.

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, which can be interpreted as the "cost of waiting." Adopting protection becomes optimal once the cost of waiting begins to exceed the benefits of delaying protection. Due to the finite study period, if initiating protection is optimal at year $t > 100$, we report the respective coastal area as unprotected.

The baseline results of our benefit-cost analysis are displayed in the first column of Table 2. For one third of the sample, our estimates suggest that initiating protection is optimal during the first two decades of the study period. In four census blocks, it is most efficient to delay the construction of sea barriers by at least 60 years, as the benefits of delaying protection outweigh the costs of waiting in the initial periods, but eventually protection 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.

We test the sensitivity of our results to changes in the discount rate. 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 $\tilde{c}_{jt}$ terms, as seen in equation (7). While in theory the net effect is ambiguous, we found that a marginal reduction in the discount rate for our dataset leads to an increase in $PV\left(C_{jt}\right)$. The exact opposite outcome is observed when the discount rate increases.

With both $PV(EB)$ and $PV(C)$ curves shifting in the same direction in response to a change in the discount rate, the overall impact on the protection decision is ambiguous and region-specific. For our sample, we find that lowering the discount rate from 3% to 1% encourages protection in some census blocks, while discouraging it in others, but the overall trend is for protection to occur earlier. As shown in the second column of Table 2, the number of census blocks that remain unprotected during the 100-year period is reduced, while there are more blocks adopting protection during the last 60 years of the study period. On the other hand, raising the discount rate from 3% to 5% also has a varying impact across regions, but the overall pattern suggests polarization, as regions that protect tend to initiate protection either at the very beginning or the very end of the study period. Intuitively, increasing the discount rate puts more weight on net benefits in earlier periods and eventually, for sufficiently high rates, would reduce the dynamic model to a static one. To explore this pattern further, we also run our estimates with a discount rate of 10% and obtain results consistent with strong polarization: all blocks' decisions are either to begin protection within the first two decades or not to protect at all.

In addition, we check the sensitivity of the baseline results to a rise in maintenance costs. Increasing maintenance costs, while leaving benefits unchanged, clearly discourages protection. Thus, if the maintenance cost value used is too low, our estimates may overstate the gains from early protection. We explore this by adopting a value equal to 10% of total construction costs, almost twice as high as our base value. As expected, the number of blocks adopting early protection is reduced dramatically. Furthermore, as shown in the fifth column of Table 2, more than 75% of the regions in our sample now delay protection beyond the 100-year study period.

There also exist additional social costs of protection, discussed in Section 2, which are not accounted for in our baseline analysis. One important question to explore is whether the inclusion of fixed social costs into the analysis would have a different implication for the timing decision when compared with the inclusion of variable social costs. While theoretically both will result in higher total costs of protection, thus encouraging delay of adoption, their impacts may be of different magnitudes. In order to obtain a sense of these potentially different magnitudes, we conduct separate sensitivity estimates. Koch (2010) suggests that environmental and amenity losses resulting from sea barriers may increase cost estimates by up to 25%. Hence, we first augment our data by adding 25% to the costs of construction and retrofitting, while using the base maintenance cost values. We then re-do our analysis with the base construction and retrofitting costs, but adding 25% to the maintenance costs. Finally, we also repeat our simulations adding 25% to all costs.

As seen in Table 2, the impact of including fixed social costs (e.g., loss of view and recreational space) on the decision to delay protection appears to be of a smaller magnitude relative to the inclusion of variable social costs (e.g., beach erosion and loss of wetland). Intuitively, delaying protection reduces the total variable costs by an amount equal to the variable costs that would have been incurred during the delay period. On the other hand, the same delay would result in only modest savings from avoiding instances of future retrofitting, as fixed setup costs would have to be incurred regardless of the time when protection is initiated. Thus, an increase in variable costs, resulting from the inclusion of environmental costs, is more likely to cause delay than a corresponding increase in fixed costs. Furthermore, we find, as expected, that the presence of both fixed and variable social costs (i.e., a 25% increase of all protection costs) leads to a quite pronounced delay of protection, with only a quarter of the sample initiating protection during the first two decades.

While the main purpose of our analysis is to highlight the role of optimal timing as part of the coastal adaptation process, our results also allow us to draw inferences about the potential impact of alternative rates of sea-level rise (e.g., accelerating rate over time due to rapid ice melt) on the protection decision. Although the impact of sea-level rise on benefits and costs of protection is non-linear and region-specific, our results[28] imply that it is not necessarily the case that increasing the rate of sea-level rise in some periods would encourage the adoption of protection. For instance, if a particular region has minimal storm surge exposure due to natural barriers (e.g., hills or higher overall elevation), its optimal timing decision would be relatively robust to the use of a different rate of sea-level rise. Alternatively, depending on topography and building location, it may also be possible that a modest initial increase in sea level results in substantial flood damages (e.g., due to lack of natural barriers and development being concentrated close to the shore), while additional sea-level rise does not lead to a significant increase in damages. In that case, an increase in the rate of sea-level rise only results in higher costs of protection and in fact discourages protection. Finally, in regions where property location is such that higher sea level puts an increasingly larger number of properties at risk of flooding, a rise in sea level leads to a larger increase in benefits of protection relative to costs. Given these trends, we anticipate that, although the regional timing decisions are likely to change under alternative rates of sea-level rise, they would remain relatively heterogeneous across our sample.

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[28] Complete output (optimal height and length of the protective structure, HAZUS-generated flood damage data for five return periods, costs and benefits of protection, and timing of protection) for each census block at various discount rates and costs is available from the authors upon request.

5. Conclusion

In this paper, we model the decision to adopt coastal protection against stochastic flood events and explicitly account for the choice of optimal timing of adoption, recognizing that sea-level rise affects both benefits and costs of protection over time. In an application to a study area of 57 census blocks along the western coastline of Connecticut, we find that the optimal timing of initiating protection measures could vary across regions and that the exact timing pattern may be sensitive to discounting, maintenance costs, as well as additional social costs, such as environmental and amenity losses resulting from the presence of “hard” structures. In particular, we find that using a relatively low discount rate in the benefit-cost analysis implies greater heterogeneity in the timing decisions and earlier overall adoption, whereas, with higher discount rates, the timing decisions are reduced to a choice between early protection and no protection at all. Furthermore, higher maintenance costs clearly discourage protection. Finally, if possible negative environmental and aesthetic impacts of sea barriers are taken into account, delaying protection would become more desirable, with the extent of delay being sensitive to the relative magnitude of one-time costs (e.g., loss of ocean view and recreational opportunities) vs. continuous costs (e.g., shoreline erosion and loss of wetlands).

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, do not account for possible changes in human behavior over time (e.g., changing the timing of protection could lead to changes in expected property values over time, which would in turn impact expected damage estimates), consider a constant rate of sea-level rise, and assume that protection does not mitigate the damages resulting from floods greater than a 100-year event. Future extensions of our work could relax these assumptions by providing more precise estimates of the benefits and costs of coastal protection and introducing variation in housing units, values, and population over time. Additional extensions would include (i) modeling uncertainty in the rate of sea-level rise, (ii) considering a wider variety of sea-level rise scenarios, (iii) integrating risk-aversion into the model, (iv) introducing additional adaptation strategies, and (v) incorporating more precise data on environmental costs into the numerical analysis. While these extensions would allow for a more realistic depiction of the coastal flooding problem, we do not expect them to affect our fundamental result that, when the temporal variation of expected benefits and costs of adaptation is accounted for, it would most likely be optimal for coastal regions to change the timing of adaptation measures.

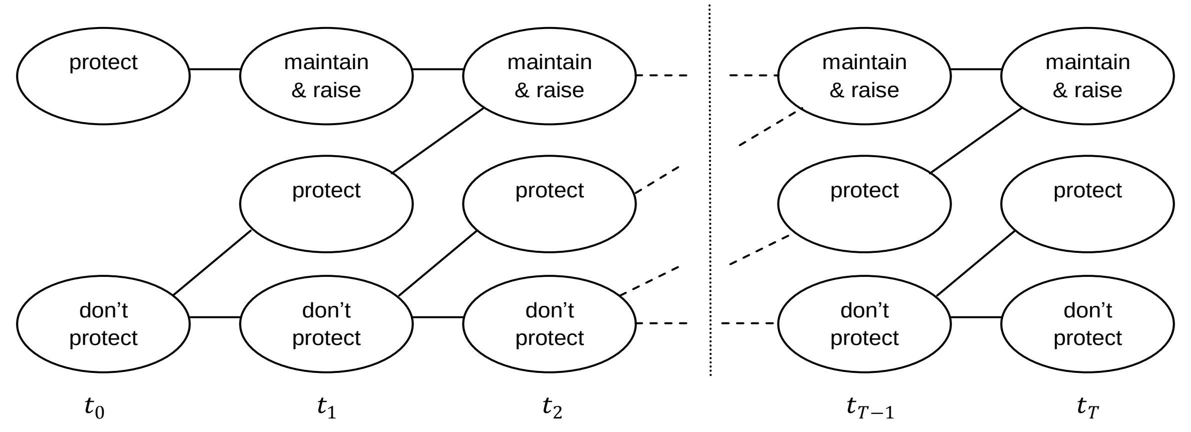

Fig. 1 Iterative Decision-Making Process for Coastal Protection

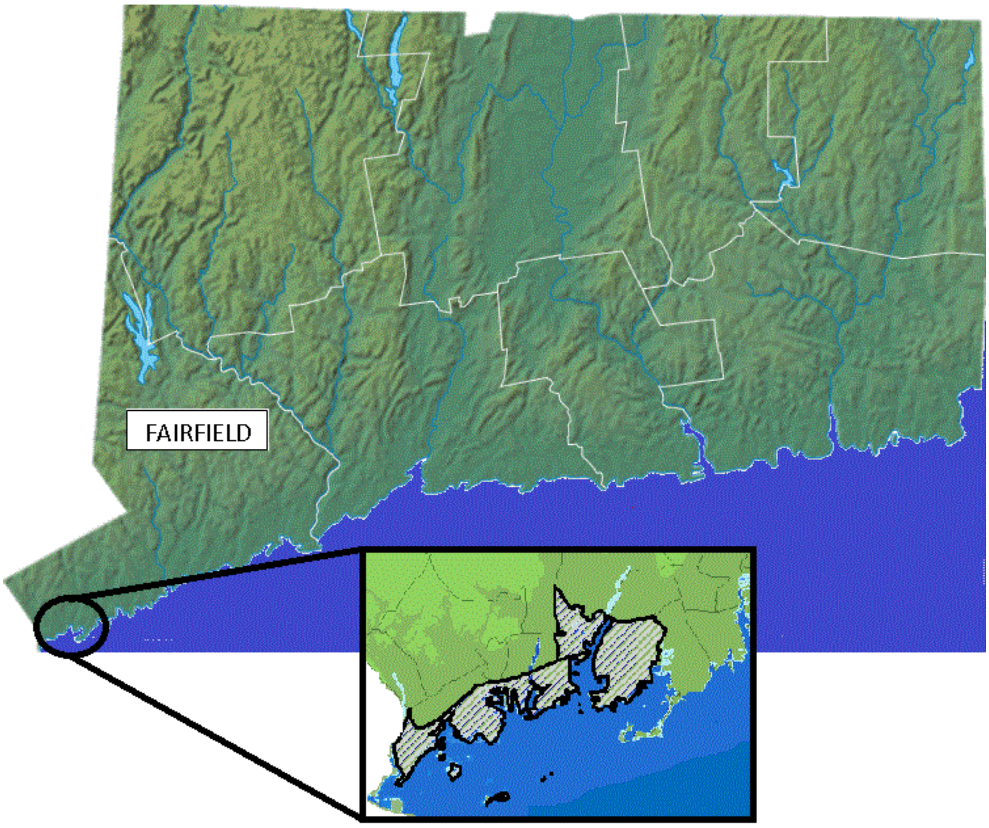

Fig. 2 Location of the study area within Fairfield County, Connecticut

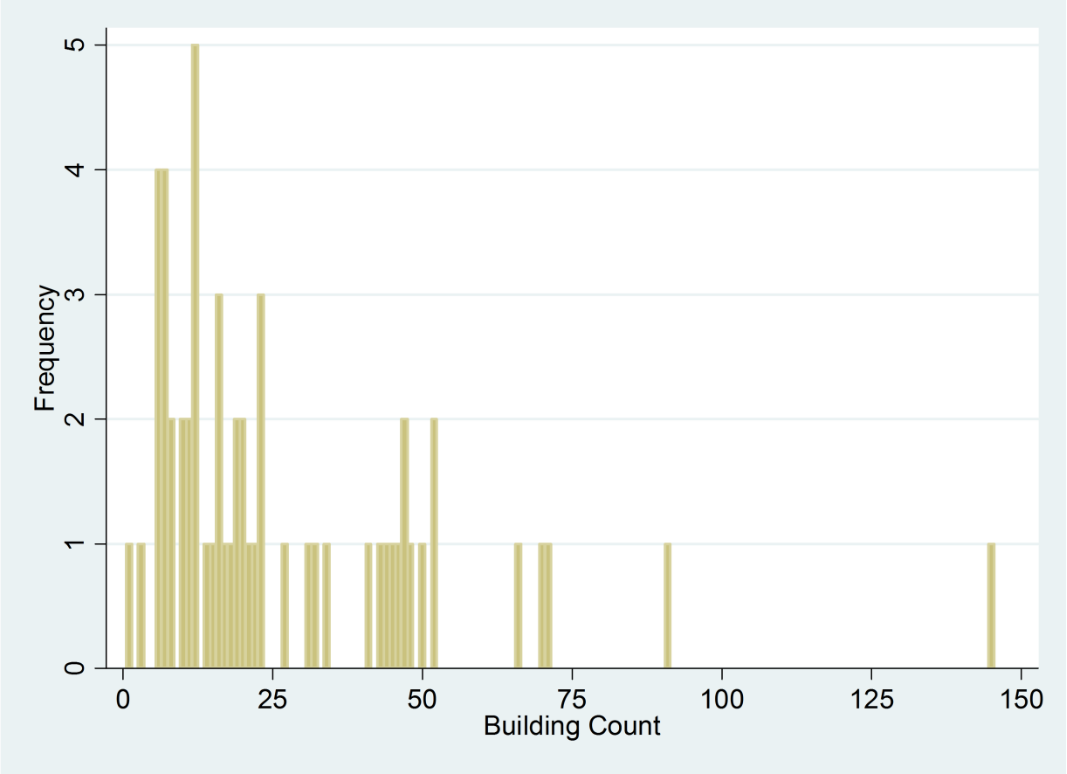

Fig. 3 Distribution of building count by census blocks

Table 1 Predicted Construction Costs

Design Height (ft)	Design Height (m)	Cost per linear m (2006 USD)
17.0	5.2	$9,857
20.7	6.3	$13,936
21.2	6.5	$14,491
21.8	6.6	$15,252
22.2	6.8	$15,834
22.8	6.9	$16,631
23.3	7.1	$17,240
23.9	7.3	$18,074
24.3	7.4	$18,710
24.9	7.6	$19,580
25.4	7.7	$20,243

Table 2 Results

	Baseline	Sensitivity tests						
Discount rate	3%	1%	5%	10%	3%	3%	3%	3%
Maintenance costs	6%	6%	6%	6%	10%	6%	6%	6%
Fixed social costs	no	no	no	no	no	yes	no	no
Variable social costs	no	no	no	no	no	no	yes	no
Fixed & variable social costs	no	no	no	no	no	no	no	yes
Optimal timing of protection (number of census blocks)								
Between years 1 and 20	19	19	20	19	11	18	17	14
Between years 21 and 40	0	0	0	0	0	0	0	0
Between years 41 and 60	0	1	0	0	0	0	0	0
Between years 61 and 80	2	2	0	0	0	1	1	0
Between years 81 and 100	2	4	4	0	3	3	4	5
No protection	34	31	33	38	43	35	35	38

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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[29] 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 2009).

Longuet-Higgins (1952) demonstrates that wave heights follow approximately a Rayleigh distribution (Fig. A-1). 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, p. 262-263) 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^*, $0.01 = e^{-\frac{(H^*)^2}{2\sigma^2}}$, i.e.,

$$H^* = \sigma\sqrt{-[2\ln(0.01)]}. \qquad \text{(A.1)}$$

Let H_p denote the mean of the highest $1/p^{th}$ waves. Goda (2010) shows that if wave height follows the Rayleigh distribution,

$$\frac{H_p}{\sigma\sqrt{2}} = \sqrt{\ln(p)} + \frac{p\sqrt{\pi}}{2} erfc(\sqrt{\ln(p)}), \qquad \text{(A.2)}$$

Where $erfc(x)$ is the complementary error function defined as $erfc(x) = \int_x^\infty e^{-t^2} dt$.

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[29] 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.

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

$$H^* \approx 1.52 H_S. \tag{A.3}$$

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.

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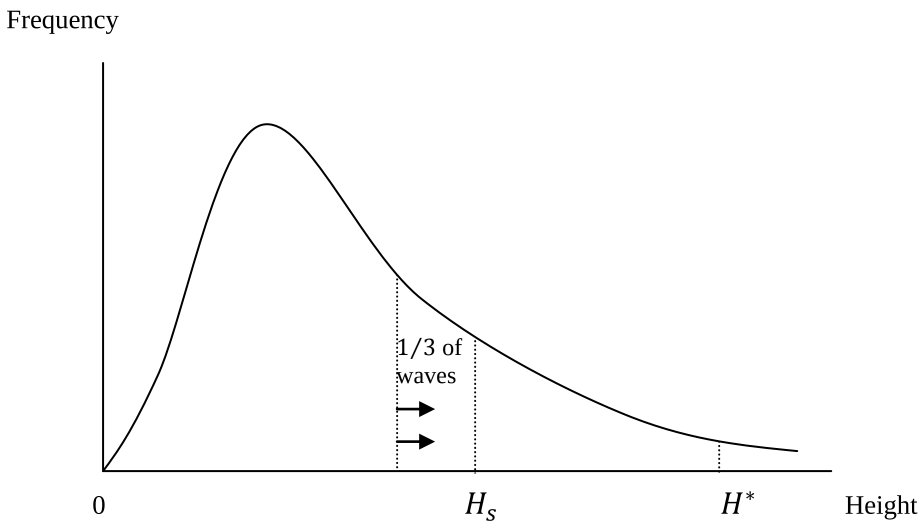

Fig. A-1 Rayleigh distribution of wave heights