7 The economic damage induced by sea level rise in the United States

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Changes in climate are expected to affect the ocean environment in a variety of ways. The potential effects of a temperature increase include thermal expansion and the melting of polar ice caps, both of which contribute to the causes of sea level rise. Increases in sea level can present problems to people living in coastal and low-lying areas, and can damage structures and beachfront property along the coast. Consequently, a sea level rise may impose economic costs on the United States – the costs of protecting coastal structures and the shoreline, or the lost value associated with abandoning such structures and property.

Early predictions of dramatic greenhouse gas-induced sea level rise have given way over the past decade to more modest expectations. High projections for the year 2100 reached more than 3.5 meters as late as 1983 (Hoffman *et al.*, 1983), but they dropped to 1.5 meters in 1990 (IPCC, 1990), and converged slightly more than 1 meter by 1992 (IPCC, 1992). The mid-range best guess now stands between 38 and 55 cm by 2100 (IPCC, 1996). One recent estimate is presented in Table 7.1 (Wigley, 1995; Wigley and Raper, 1992). The oceans would continue to rise for centuries, even if concentrations were stabilized in the interim. Despite this, the highest best guess reported for the year 2100 is 40 cm. One important contribution of this chapter is to present economic cost estimates for these new lower trajectories (less than 1 meter).

Another important contribution of this chapter is to illustrate the importance of including efficient adaptation. People can adjust to rising seas by constructing barriers and retreating. If these decisions are made rationally, the economic damages from rising seas fall dramatically. Economic damages are calculated as the sum of the value of lost property (valued at the time of loss, net of market-based adaptation that might mitigate against this cost, but including the cost of that adaptation) and the expense involved in protection. We model responses to sea level rise as though they are efficient. Because the efficient response of many protection measures involves cooperation among neighbors, this model implies a degree of public efficiency. Because

Table 7.1. *Sea level consequences of greenhouse gas concentrations*[a, b]

(1) Stabilization level (in ppm CO_2)	(2) Year of stabilization	(3) Sea level rise by the year 2100 (in cm)			(4) Sea level rise by the year 2400 (in cm)		
		Low	Middle	High	Low	Middle	High
350	2050	0	16	39	−18	19	77
450	2100	4	26	56	−10	52	157
550	2150	7	32	65	−3	77	216
650	2200	9	36	72	2	96	261
750	2250	11	40	78	7	112	300

Notes:

[a] Wigley, 1995 (Table 2) See citation for further elaboration of calculation and meaning of low, middle, and high designations.

[b] Sea level rise is measured in cm along scenarios that reach the stabilization levels recorded in column (1) by the date indicated in column (2).

public efficiency is by no means guaranteed, the results may be overly optimistic. Nonetheless, they do represent the lowest cost (smallest aggregate damage) of response to sea level change.

The first section of this chapter provides some context for this analysis by reviewing past estimates of the potential cost to the United States of sea level rise, and Section 7.2 offers a description of the assumptions and methods that frame this work. Section 7.3 provides an example site (Charleston, SC) to illustrate the methods and assumptions that are used in this analysis, as well as to demonstrate how the results were obtained and interpreted. Section 7.4 provides the results of the entire study, which examines the aggregate costs resulting from sea level rise over the entire United States, and Section 7.5 contains concluding remarks that return to the historical context to argue that currently accepted base-case estimates of the cost of sea level rise are much too high, and to discuss the implications of these overstated damage estimates.

Past estimates have been derived from sea level rise trajectories that exceed the upper range of the current scientific consensus. These earlier estimates have also underestimated adaptation. After correcting for both sources of error, estimates of the annual damages in 2060 from rising sea level are over an order of magnitude lower than the earlier estimates in the literature. A sea level rise of 33 cm by 2100 is expected to cause annual national damages of only $57 million in 2060.

7.1 Historical estimates of costs

Table 7.2 presents some of the cost estimates that have preceded this work. These studies are based upon estimates of economic vulnerability as opposed to true economic cost. Economic vulnerability measures the gross damages today if sea level rise suddenly occurred. It does not take into account adaptation or the fact that inland property would rise in value as it becomes shoreline property. Economic vulnerability is therefore not an accurate measure of net damages. The first cost estimate of sea level rise assumed a dramatic rise in the seas which in turn led to a tremendous damage of $450 billion (Schneider and Chen, 1980). Using a 1-meter rise by 2100 assumption, Nordhaus (1991) used the 1989 USEPA Report to Congress to predict a new estimate of $2.4 billion in lost land value (adjusted to 1990 for inflation) and $4.9 billion in annual protection costs in the year 2065. Several other authors have made similar estimates to the projections by Nordhaus.

The more recent assessments all roughly agree with the early Nordhaus projection. The consistency of these estimates should not be surprising. All of the estimates use the same USEPA report that was used by Nordhaus, and so they all build on the notion that $73–$111 billion in cumulative protection costs would be incurred up to the year 2100 for a 1-meter rise. They also tend to agree with Cline (1992) that something on the order of 6650 square miles of dry land valued at $4000 per acre would be abandoned, and that approximately 13 000 square miles of wetland valued at $10 000 per acre would be lost. In addition, and perhaps more importantly from an economic perspective, each cost estimate for sea level rise has been constructed from vulnerability measures of real estate losses. Each expresses the potential total cost of abandoning property. In other words, each estimate reflects the total, current value of the real estate that might be lost to a rise in sea level between now and the year 2100. This current value of real estate is computed by summing the constant annual values between now and the year 2100. This method by its very construction is static. It compares a snapshot of coastal property taken for the year 2100 with a snapshot of current development, but it expresses any differences between the two in terms of average annual changes. This procedure averages across a 110-year time span, and so it offers the same picture for the years 2050, 2075, or any other year in its range. Integrated assessments that need to calibrate costs at some point in the future would prefer to employ “transient costs” that are computed for that year, rather than rough averages across a century or so.

The data to which this averaging procedure has been applied were drawn from current conditions. Since total damage estimates were constructed from vulnerability estimates, they ignore future development and land appreciation that can be expected

Table 7.2. *Annualized cost at concentration doubling (billions of 1990$)*[a]

		Assumed changes		Economic damages (comprehensive annual costs)	
Source	Year	Temperature change (° C)	Sea level rise (m)	Sea level	Total
Schneider & Chen (1980)	2100	n/a	4.6	$450.0	n/a
Nordhaus (1991)	2065	3.0	1.0	$7.3	$8.7
Cline (1992)	2065	2.5	1.0	$7.0	$61.1
Titus (1992)	2065	4.0	1.0	$5.7	$139.2
Fankhauser (1994)	2065	2.5	1.0	$9.0	$69.5
Tol (1994)	2065	2.5	1.0	$8.5	$74.2

Notes:

[a] The Nordhaus estimates have been converted to 1990 dollars using the US Consumer Price Index; the Tol estimates include Canada and the United States.

even on vulnerable property in the intervening years. These total damage estimates miss any adaptation that might occur naturally within the market as new information emerges. They also miss any policies that might be enacted to protect or abandon property, and the cost of protection that must be applied to property that merits protection.

Correcting for most of these shortcomings can be expected to reduce the potential cost of sea level rise, since adaptation would not occur unless costs were reduced. There is, nonetheless, some ambiguity that must be explored. Adaptation could reduce the cost of abandoning property, but appreciation over the intervening years might increase the eventual cost of abandonment and thus increase the acceptable cost of protection. In addition, while optimal adaptive decisions that minimize the cost to society as a whole may be made with adequate and timely information, it is possible that society will choose high cost decisions (e.g. social decisions to protect current coastal dwellers regardless of costs). The work reported here presents a range of adaptation from perfect to imperfect foresight. However, social decisions to resist sea level rise could be even worse than the imperfect foresight scenario presented in this chapter. The next section describes the framework in detail.

7.2 Methods

Planning the response to rising seas along a developed coastline can be broken into two distinct decisions that are made in an effort to maximize discounted intertemporal welfare (the net benefits of any protection strategy minus the cost of its implementation). The first is a decision to protect the coastline starting at some time t_0 and the second is a decision to stop protection at some time T. The following subsections will discuss the benefits and costs associated with protection decisions.

Benefits of protection

The benefit side of a decision to protect a shoreline from time t_0 to time T can be modeled as the true opportunity cost of abandoning coastal property. This is calculated here as the economic damage that might be attributed to future sea level rise in the absence of any decision to protect threatened property. True opportunity cost is based on the value of that property at the (future) time of inundation, given any adaptation that might have occurred naturally and efficiently prior to flooding and abandonment. Satisfactory descriptions of how future development might affect coastline real estate values were derived from empirical market analyses of how property values might change as factors such as population and real income change. One estimate of these damages is:

$$d[\ln(P_t)] = \alpha_0 + \beta_L g_L + \beta_y g_y + \beta_{-1} d[\ln(P_{t-1})], \tag{7.1}$$

where g_L and g_y represent the rates of growth of population and per capita income, and P_k represents the real price of property in year k (Abraham and Hendershott, 1993). Constructing scenarios of how these "driving socio-economic variables" might move as the future unfolds, produced historically based portraits of how real property values might change over the same time frame (IPCC, 1992). Applied with care in the absence of any anticipated, fundamental structural change in the real estate marketplace, the resulting development trajectories offer reasonable portraits of the evolving context of the sea level rise problem.

Satisfactory descriptions of how real estate markets might respond on a smaller, local level in the face of threatened inundation from rising seas were more difficult to create. On the one hand, the value of the land lost to rising seas should be estimated on the basis of the value of land located inland from the ocean. Any price gradient which placed higher values on parcels of land in direct correlation with their proximity to the ocean would, in a very real sense, simply migrate inland as shoreline property disappeared under rising seas. Ignoring potential significant transfers of wealth, the true economic cost of inundation is the value of the land that will, in an economic sense, actually be lost – the interior land equal in area to the abandoned and inundated coastline property (Yohe, 1989). An exception to this rule would occur with barrier islands which must disappear altogether resulting in a net loss of coastal land.

The value of coastal structures, on the other hand, can be expected to depreciate over time as the threat of impending inundation and abandonment becomes known. Structures will be lost at the moment of inundation, and their true economic value at that point could be zero if markets were equipped with enough advanced warning and with a complete understanding that the property would, indeed, be abandoned. Despite stories of individuals' reluctance to abandon threatened property in, for example, flood plains, investigations into how markets react to low probability – high cost events strongly support the assertion that market-clearing real estate prices do indeed decline over time in response to the pending cost of a growing threat.[1]

True economic depreciation (TED), modeled to start at some fixed time prior to inundation and to finish just when inundation would occur, reflects the efficient market response to the known risk of future sea level rise (see Samuelson, 1964; Stiglitz, 1986).

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[1] Brookshire, Thayer, Tschirhart, and Schulze (1985) found evidence that real estate values did reflect earthquake risks. MacDonald, Murdoch, and White (1987) found homeowner behavior similarly affected in the face of the threat of flooding. Property prices should, over the long term, reflect the threat of gradually rising seas.

TED is, by definition, a representation of how the value of an asset declines over time as it moves toward its retirement from service. Structures are 30-year assets in the view of the Internal Revenue Service (IRS), so 30 years of (certain) advanced warning was deemed to be sufficient. The application of TED here supports the position that the true economic cost of structures lost to rising seas could be as low as zero.

Uncertain abandonment, caused by the uncertain rate of future sea level rise and/or a disbelief that existing property would actually be abandoned, would affect efficiency. Either a source of imperfect information or an incomplete reaction to the threat of rising seas could, for example, reduce the time period over which markets could react to this threat. The value of lost structures or shorelines under these conditions would not be zero; it would, instead, equal the remaining value of the structure or shoreline at the time of inundation. The worst case of imperfect information and uncertain abandonment would allow absolutely no warning and thus no time for any structural depreciation at all. This case takes the lack of information to an extreme, and is more likely to be caused by a sudden realization that the policy of abandonment would be followed, rather than a sudden realization that the oceans have risen; but it captures the situation in which the cost attributed to rising seas would be maximized, and it allows for the possibility that property that should have been abandoned (given maximum efficiency and perfect information) might actually be protected, instead.

Costs of protection

The cost of protection from time t_0 to time T was easier to frame – it was simply the time trajectory of protection costs along the specified sea level rise scenario. Seven published studies offer specific cost estimates for various protection structures.[2] For protection against a 1-meter rise in sea level, a review of these eight studies suggested that the fixed costs of constructing dikes/levees range from \$150 to \$800 per linear foot, while seawall and bulkhead construction costs range from \$150 to \$4000 per linear foot. Costs depend upon engineering and construction specifications, as well as design standards and geological characteristics. The baseline results reported in this analysis were derived from a central estimate of \$750 per linear foot for a generic hard structure, but their robustness was also tested in the extreme case where protection costs \$4000 per linear foot. Maintenance costs, modeled as the variable cost of protection, were also incorporated in these studies. Since the central fixed cost estimate was drawn from Gleick and Maurer, 1990, their representation of annual maintenance expenditure as a percentage of construction was also adopted. Four percent per year was chosen as the central estimate, but 10 percent was applied to hard

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[2] Weggel *et al.*, 1989; Sorenson *et al.*, 1984; Gleick and Maurer, 1990; URS Consultants, 1991; San Francisco BCDC, 1988; Leatherman, 1989; Leatherman, 1994.

structures that might be built along coastline open directly to the ocean (Weggel *et al.*, 1989; Sorenson *et al.*, 1984).

Structure and maintenance costs were changed for different scenarios, under the assumption that protection for the full measure of sea level rise expected to the year 2100 would be constructed when it was needed. Weggel *et al.* (1989) and Sorenson *et al.* (1984) both indicate that construction costs increase geometrically with height. Weggel *et al.* suggest a cost factor of 1.5 to reflect the geometric increase in cost with the height of the structure. Nichols, 1984 and Sorenson *et al.* offer more insight into the details of construction. They note that hard structures are typically trapezoidal in shape with 1 : 2 slopes on the sides and with the width of the crown on top matching the height. This information enabled us to compute a relationship between the cost of hard structures and their required height along 33 cm and 67 cm scenarios as fractions of the cost along a 100 cm scenario. Our results suggest a cost factor of nearly two to reflect the exponential increase in cost with the height of the structure. For example, at the Bridgeport, CT, site, the fixed cost of protection for 1 meter of sea level rise is \$0.619 million. A protection structure under a 67 cm sea level rise scenario, on the other hand, would cost \$0.272 million, and a protection structure under a 33 cm sea level rise scenario would cost \$0.068 million. These protection costs illustrate the geometric increase in cost with the height of the structure.

A different methodology from that used for coastal structures was employed to accurately characterize the cost of protecting beaches and beachfront property. The basic idea conveyed by experts in the field was that beach nourishment alone would suffice as a protection strategy, provided that nourishment were an ongoing operation from the very start, and as long as sea level rise did not exceed some threshold; 33 cm was chosen to be that threshold. The cost of nourishment was computed from estimates of the requisite volume and the expected (regional) price of sand.[3] Once the threshold was crossed, however, a hard structure constructed at the back of the beach was required both to preserve the nature of the beach and to protect interior property. The cost assumptions for coastal structures described above were then applied with 10 percent annual maintenance costs. Ten percent, as opposed to 4 percent, is used to account for the increased maintenance necessary at open ocean sites.

7.3 Charleston, SC: an application example

This section describes the results of a careful analysis of the economic costs of future sea level rise at a specific site – Charleston, South Carolina. This section

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[3] Private communication with Stephen Leatherman, Robert Hallermeier, and Dennis Dare.

should clarify the mechanics of how to apply the general structure of the benefit side of protection, as well as the specifics of the cost side, both of which are presented in the methods section above. Charleston was chosen because it was part of the sample which supported the earlier estimates of national vulnerability to sea level rise. Producing a time series of potential economic costs along a given sea level rise trajectory will allow a direct comparison with the vulnerability estimates derived from the previous Charleston analysis (Yohe, 1990). Moreover, the local geography of the Charleston site allowed the consideration of five distinct and qualitatively diverse "subsites": Downtown Charleston, Mount Pleasant, Avondale, Dorchester, and Sullivan's Island. The versatility of the model and its applicability across a range of sites and options was therefore adequately tested.

The first subsection describes the data and assumptions which frame both the Charleston site and the sea level rise trajectory (i.e. rate of sea level rise over time) to be considered. The second subsection presents results for each of the subsites; protection decisions are identified and supported. The descriptions of these protection decisions include their timing, which could minimize the discounted value of anticipated costs. The third subsection presents the ultimate result – a time profile of the cost of sea level rise along the given trajectory.

Background

We assume a quadratic sea level rise (SLR) scenario:

$$SLR(t) = bt^2. \tag{7.2}$$

For a 100 cm rise by the year 2100, $t = 110$ and SLR $(t) = 100$, yielding a value of b of approximately 0.008. The 100-cm trajectory certainly lies on the high side of the IPCC (1996) best estimates. It serves here, however, to support a diverse set of protection responses, and thus economic cost profiles, across the five Charleston subsites. It is also the middle trajectory in the national sample of vulnerability estimates completed in 1989 by Yohe (1990).

Inundation profiles along the 100-cm scenario over time for each subsite of Charleston are available from the computer-based mapping capability developed by Richard Park and his colleagues at the Holcomb Research Institute for the 1989 EPA Report to Congress (Park *et al.*, 1989). Each site in the Park sample, of which roughly one-third were used in the Yohe sample, represented a 30-minute cell provided by the US Geological Survey. The maps divide each site into 500-meter square partitions; and the mapping technology looks at how each partition changed over time for a specified sea level rise trajectory. If the seas were assumed to rise along, for example, the 100-cm scenario reflected in equation (7.2), then the Park maps would show snap-

Table 7.3. *Time series of inundated partitions for each of the Charleston subsites*[a] *(number of 500-m by 500-m blocks)*

Year	Charleston	Dorchester	Avondale	Mt Pleasant	Sullivan's Island
2000	0	0.5	0	0.5	0
2010	0	1.0	0	1.0	0
2020	0	1.5	0	0.5	0
2030	0	2	0	0.5	0
2040	0	0	0	0.5	0
2050	0	0	0	1.0	0
2060	0.5	0	0	1.0	0
2070	0.5	0	0	0	0
2080	0	0	0	0	0
2090	1.0	2.0	1.0	1.0	1.0
2100	0.5	1.0	0.5	0.5	2.0
Total	2.5	8.0	1.5	6.5	3.0

Notes:

[a] The number of 500-m by 500-m partitions deemed lost to rising seas along the 100-cm trajectory during the decade ending in the year noted. These values were judged from the Park *et al.*, 1989, mapping technology according to the following convention. Newly inundated partitions were noted for both of the 5-year intervals which comprised the period between one decade and the next; a partition is taken as inundated when more than 50 percent of its area would be under water during mean spring high tide. Any partition seen inundated in the first 5-year interval (say between 2040 and 2045) was assigned to the decade in question (the decade ending in 2050). Any partition disappearing in the second 5-year interval (say between 2045 and 2050) was shared 50 : 50 with the next decade (one-half to 2050 and one-half to 2060).

shots of seawater inundation and other land changes across all of the partitions in 5-year increments along that trajectory. Table 7.3 records, in decadal increments, the resulting time series of inundated partitions for each of the five Charleston subsites. The data in the table reflect the number of partitions deemed to be lost to the rising sea each decade. Applying estimates of how the value of the properties located in these threatened partitions might appreciate over time to the dynamic portraits of the physical impact of sea level rise produces estimates of (1) the potential benefit of protection, (2) the potential cost of abandonment, and/or (3) the cost of protection, all of which are statistics required to calculate the present value of the net benefit of protection. Together, the fixed cost and variable cost components define the cost side of the protection decision.

Table 7.4. *Characteristics of the Charleston subsites economic parameters*

	Charleston	Dorchester	Avondale	Mt Pleasant	Sullivan's Island
Initial land value[a]	8.6	0.8	1.9	6.0	10.3
Initial value of structure[a]	25.9	2.5	6.0	18.1	30.8
Fixed cost of protection[b]	11.6	23.2	7.7	27.1	0.3
Variable cost of protection[c]	0.05	0.10	0.03	0.12	0.024

Notes:

[a] Denominated in millions of dollars (1989) per 500-m by 500-m partition.

[b] Denominated in millions of dollars (1989).

[c] Denominated in millions of dollars (1989) per cm of sea level rise.

Table 7.4 reports the fixed and variable costs at each of the five Charleston subsites. They are extrapolated from a detailed estimate for building dikes and nourishing beaches (raising a barrier island), for Long Beach Island, NJ, as well as for a few other sites scattered around the country (Weggel, 1989). The relatively low fixed protection cost for Sullivan's Island corresponds to the small initial cost of preparing to raise the island and nourish its beaches with sand. Diking is simply not an option, so variable costs reflect an ongoing and increasing investment in sand along its entire length. A decision to protect the island would, in fact, really be a decision to begin protection in the year 1990, because delay is not possible. Irreversible, or at least problematical, erosion and inundation of beaches and dunes would begin immediately along a sea level rise trajectory unless some protective strategy were adopted. Nourishing the beach with sand is only viable up to a certain threshold. Once the sea rises beyond this threshold, which in this case was designated as 1 foot, a hard structure, such as a sea wall or dike, is necessary along with the nourishment strategy.

Dikes alone emerge as a potential option in the other four subsites. The lists of protection decisions for each are more complete and more complicated. Dikes can be constructed at any time, so questions of when to start construction must be confronted directly. The fixed cost of the initial construction plays a critical role here, but it should be noted explicitly that a dike would be constructed only along the limited coastline that merits protection. Dikes must be maintained and enlarged over time, though, so variable costs which depend upon the rate of sea level rise create the possibility that even limited protection might not be continued indefinitely. The question is when, if ever, to stop protection and to sacrifice previously protected land as well as new property that is subsequently threatened.

Table 7.4 also reports the initial values of land and structures (per 500-m^2 partition) that were employed to anchor the appreciation of property values in each subsite over time. Structure values were assumed to equal three times the land values (see Poterba, 1984). To preserve comparability, and in the absence of any other reasonable set of estimates, we use the average values for land and structures that supported the earlier Yohe, 1990 vulnerability estimates. Appreciation in the value of threatened property reflects the likely effect of future development – development that will be driven by future changes in real income and population. Abraham and Hendershott (1993) provide a regression result for housing prices, which could be interpolated for land value, assuming only that real construction costs and after-tax interest rates will be roughly stable over the very long term.[4] Given this assumed stability of relative prices, the best fit regression over their full sample is

$$d[\ln(P(t))] = -0.006 + 0.0313g_{\mathrm{L}} + 0.565g_{\mathrm{Y}} + 0.402[\ln(P(t-1))], \qquad (7.3)$$

where g_{L} and g_{Y} represent the rates of growth of population and real per capita income, respectively.[5] Equation (7.3) provides a means of proposing the P_t trajectory required to quantify the net benefit to society from protecting property from time t_0 to time T, given the anticipated population and (per capita) income scenarios. Given the income and population forecast for the next century (IPCC, 1992), one can forecast how real estate prices (adjusted for inflation) will increase over that time period.

The literature on property values offers only limited and somewhat contradictory evidence that coastal property values might change at a different rate from non-coastal property values. On the one hand, Frech and Lafferty (1984) and East (1990) have argued that policy factors, such as development moratoria, could constrain the future "supply" of coastal properties relative to other locations, and thereby inflate their relative price; historical data do not support this assertion, however. Parsons (1992) and Beaton (1988) note that the data seem to suggest that historical rates of growth over time for coastal and non-coastal property values are not significantly different. Note that rates of change were most important in drawing moving portraits of future development; differences in the initial (1990) valuation of property are reflected in the site-specific property value data. In the absence of more compelling evidence that rates of growth for coastal property should be different, rates of growth for property

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[4] The Poterba (1984) correlation, combined with the IRS convention of a fixed proportional relationship between land and structure values, supports the application of the Abraham and Hendershott (1993) results to land and structures taken separately.

[5] The income elasticity reflected here might appear high, but it is a long-term elasticity and represents a response to changes in real income per working age adult. The corresponding short-term elasticity corresponds well to the lower estimates offered by Peek and Wilcox (1991), Mankiw and Weil (1989), and Hendershott (1991).

values in general were used here; we did not distinguish between coastal and non-coastal property values.

Table 7.5 records the current values of property that would be lost to inundation in the absence of any protection along the trajectories described for each subsite in Table 7.3. This table is divided into two components. The first part (A) reflects the value of interior land equal in area to the coastal property which would be lost over succeeding decades, beginning in the year 2000. The data in the second part (B) reflect the potential cost that could be attributable to sea level rise if there were absolutely no anticipation of impending loss. The estimates combine the value of land with the value of appreciated structures, which have not been depreciated at all as a result of impending loss, but are located on the threatened land at the time of inundation. These estimates therefore reflect the cost of abandoning property to the rising sea level if the market did not adjust to the rising sea level or to a plan to abandon threatened property.

Some representative results

Table 7.6 displays an array of results for the Downtown Charleston subsite – the present values of beginning protection at time t_0 (indicated in the first column) and stopping at time T (indicated in the top row). Positive values appear only in the last column in which the property is never abandoned, at least not before the year 2100; and a present value of slightly more than $900 000 emerges as the highest value in the entire table. Notice that this maximum value corresponds to (1) planning to build the requisite protective dike in the year 2050, just before inundation losses would be felt, and (2) maintaining the dike beyond the year 2100. In terms of the notation described earlier, $t_0^* = 2050$ and $T^* > 2100$ for Downtown Charleston. Note that this is only the net benefit result for the inundation period starting in 2054. There are two other inundation periods that are also part of the Downtown Charleston subsite (see Table 7.3). All of these results are then aggregated to get the overall strategy and associated dollar value for the entire Downtown Charleston subsite.

Mount Pleasant is a subsite for which protection fails the net welfare test when threatened structures efficiently depreciate to worthlessness (or partially depreciate, given that the first inundation starts in the year 2000, which allows for only 10 years of depreciation), just before they are inundated by the rising water. The present values of all of the protection options are negative (the decision array is not presented here). If foresight were not perfect, and the undepreciated structure, as well as land, would be lost to inundation, a different decision could be made. For example, if residents and thus real estate markets simply did not believe that their property would be abandoned, then structures and land might continue to appreciate right up to the very end. The cost of abandonment would then be exaggerated by disregarding the threat of sea

Table 7.5. *Current value loss to sea level rise*[a] *(millions of dollars)*

	A. Perfect foresight[b]					B. No foresight[c]				
Year	Charleston	Dorchester	Avondale	Mt Pleasant	Sullivan's Island	Charleston	Dorchester	Avondale	Mt. Pleasant	Sullivan's Island
2000	0	1.6	0	17.5	0	0	1.7	0	24.5	0
2010	0	1.5	0	14.7	0	0	1.9	0	28.9	0
2020	0	1.3	0	3.3	0	0	5.1	0	12.5	0
2030	0	1.5	0	2.8	0	0	6.2	0	11.3	0
2040	0	0	0	7.4	0	0	0	0	28.9	0
2050	0	0	0	7.6	0	0	0	0	29.8	0
2060	7.6	0	0	6.3	0	30.3	0	0	30.3	0
2070	7.6	0	0	0	0	30.2	0	0	0	0
2080	0	0	0	0	0	0	0	0	0	0
2090	10.7	4.1	2.6	7.7	12.8	42.8	16.2	10.2	29.9	51.0
2100	11.7	1.6	2.8	8.4	31.7	46.9	6.5	11.2	32.7	126.9
Total	37.6	11.6	5.4	75.7	44.5	150.2	37.6	21.4	228.8	177.9

Notes:

[a] The value of land (A) or land plus structure (B) that would be lost in the decade indicated.

[b] The values of the lost land, appreciated up to 30 years short of the point of inundation. The 2000 and 2010 values included 20 and 10 years of undepreciated structure; true economic depreciation with a 3 percent discount rate was applied.

[c] No foresight implied no market reaction until the date of inundation.

Table 7.6. *Decision array for Downtown Charleston: the present value of the net benefits of protection alternatives with perfect foresight*[a]

T:	1990	2000	2010	2020	2030	2040	2050	2060	2070	2080	2090	2100	>2100
t_0													
1990	−11.61	−11.62	−11.69	−11.79	−11.89	−11.99	−12.08	−12.08	−11.70	−11.39	−11.01	−10.64	−9.26
2000		−8.60	−8.68	−8.78	−8.88	−8.97	−9.06	−9.07	−8.68	−8.38	−7.99	−7.63	−6.24
2010			−6.37	−6.47	−6.57	−6.67	−6.75	−6.76	−6.37	−6.07	−5.68	−5.32	−3.93
2020				−4.72	−4.82	−4.92	−5.00	−5.01	−4.63	−4.32	−3.94	−3.57	−2.18
2030					−3.50	−3.59	−3.68	−3.69	−3.30	−3.00	−2.61	−2.25	−0.86
2040						−2.59	−2.68	−2.68	−2.30	−2.00	−1.61	−1.24	0.14
2050							−1.92	−1.93	−1.54	−1.24	−0.85	−0.49	0.90
2060								−1.42	−1.28	−1.15	−0.90	−0.63	0.48
2070									−1.05	−1.11	−0.99	−0.82	0.01
2080										−0.78	−0.66	−0.49	0.34
2090											−0.58	−0.55	−0.12
2100												−0.43	−0.43

Notes:

[a] The present value of the benefit of beginning protection at the time t_0 (indicated in the first column) and stopping at the time *T* (indicated in the top row) net of the present value of the cost of that protection and the loss involved in abandoning previously protected property at time *T*. These values assume a quadratic trajectory for sea level rise ending at 100 cm in the year 2100. A discount rate of 3 percent was employed both in the present value calculations and in the definition of the time trajectory of structure depreciation.

level rise and any planned retreat in its wake. The decision array (not presented here) obtained using the resulting inflated property values derived under the assumption of absolutely no market foresight, shows that a decision to begin protection in the year 2000 and to continue past 2100 would be best.

The decision arrays for Dorchester and Sullivan's Island both reveal that threatened property should never be protected. The reasons for this differ for each site. Building protective dikes would have been the correct option for Dorchester, but at present their cost exceeds their value, primarily because prospective losses would be felt so far into the future that only interior land values support the benefit side of the calculations. Even discounting the cost of building a dike equally far into the future is not enough to support a positive difference between discounted benefits and costs. By way of contrast, beach nourishment (in effect, raising the island) would have been the correct option for Sullivan's Island, but any nourishment strategy must begin in 1990, even though the potential losses to sea level rise occur far in the future. Unfortunately for those whose relatively valuable properties are located on this barrier island, protection never results in a positive present value up to the year 2100, given a real discount rate of 3 percent. The trajectory of net benefits climbs towards zero as prospective stopping dates rise to 2100, though; so perhaps a longer time horizon would bring better news.

Avondale is a subsite for which a "partial" protection strategy results, meaning that certain blocks of land are not protected while others are. In the case of Avondale, the first inundation block started in the year 2080. The result was to forego protection. However, the next inundated block (actually half a block) occurred in 2090. At this point in time it was efficient to protect.

An intertemporal cost profile for Charleston

The middle five columns of Table 7.7 record the undiscounted incremental costs that are attributable in successive decades to sea level rise. These estimates incorporate perfect foresight and market adaptation (i.e. structure depreciation) along the 100-cm trajectory for each of the five subsites in the Charleston area. The last column shows the subsite costs across the whole area for each decade. The statistics displayed in the last column are expressed in current dollars (not discounted). These estimates include the cost of protection, when protection is deemed to be appropriate, and the cost of abandoned property when retreat from the rising seas is the better response. The present value of all of these costs, discounted at 3 percent, is nearly 37 million dollars – a sizable sum, to be sure, but certainly a small fraction of the total value of the metropolitan Charleston area.

Notice that over time, the current value cost statistics start high, fall quickly, and

Table 7.7. *Decadal economic cost estimates: the Charleston site*[a] *(in millions of 1989 dollars)*

Year	Dorchester	Avondale	Mount Pleasant	Sullivan's Island	Downtown Charleston	Total
2000	1.6	0	27.1	0	0	28.7
2010	1.5	0	0.1	0	0	1.6
2020	1.3	0	0.1	0	0	1.4
2030	1.5	0	0.2	0	0	1.7
2040	0	0	0.4	0	0	0.4
2050	0	0	0.6	0	14.4	15.0
2060	0	0	1.0	0	16.1	17.1
2070	0	0	1.5	0	18.3	19.8
2080	0	0	2.2	0	21.5	23.7
2090	4.1	2.6	3.2	12.8	25.8	48.5
2100	1.6	2.8	4.5	31.7	31.8	72.4
Total	11.6	5.4	40.9	44.5	127.9	230.3

Notes:

[a] These costs include the cost of protection for Mount Pleasant (beginning in 1990) and Charleston (beginning in 2050) as well as the value of lost property where abandoned (taken from Table 7.6). Optimal protection decisions and efficient adaptation with perfect information are both assumed given a 3 percent discount rate.

then gradually climb again. There are several reasons why this shape makes sense. Economic costs can start high because the cost of deciding not to protect property in the near term must include a significant proportion of the value of the structure since there is simply insufficient time to depreciate standing structures. Perfect foresight would allow all threatened structures to depreciate to zero after the year 2020, though, so this initial cost inflating effect eventually disappears. The cost of protection will eventually rise in the long run because the sea level is rising at a quadratic rate and the value of properties continues to rise over time.

7.4 National aggregate estimates

The results presented in this section were derived by applying the procedures outlined above for Charleston to the same national sample that supported the original vulnerability estimates (Yohe, 1990). The full sample is described in Table 7.8.

Table 7.8. *Subsample sites by region*

Region	Identification[a]	Major municipality	Northern latitude	Western longitude	Natural subsidence[b]
Northeast (NE)	MEROCKLA	Rockland	44 07 30	69 07 30	1.0
	MAWESTPO	Westport	41 37 30	71 07 30	1.5
	RIWATCHH	Watch Hill	41 22 30	71 52 30	0.6
	CTBRIDGE	Bridgeport	41 15 00	73 15 00	0.9
	NJLONGBE	Long Beach	39 45 00	74 15 00	2.7
	MDEASTON	Easton	38 52 30	76 07 30	2.4
	VABLOXOM	Bloxom	37 52 30	75 37 30	1.9
	VANEWPOR	Newport News	37 07 30	76 30 00	3.1
Southeast (SE)	NCLONGBA	Long Bay	35 00 00	76 30 00	0.6
	SCCHARLE	Charleston	30 00 00	80 00 00	2.2
	GASEAISL	Sea Island	31 22 30	81 22 30	1.8
	FLSTAUGU	St Augustine	30 07 30	81 30 00	1.8
	FLMIAMI	Miami	25 52 30	80 15 00	1.1
	FLKEYWES	Key West	24 37 30	81 52 30	1.0
	FLPORTRI	Port Richey	28 30 00	83 45 00	0.7
Gulf Coast (Gulf)					
	FLAPALAC	Apalachicola	29 45 00	85 07 30	1.2
	FLSTJOSE	St Joseph	29 52 30	85 30 00	0.7
	MSPASSCH	Pass Christian	30 22 30	89 15 00	1.2
	TXPALACI	Palacios	28 45 00	96 15 00	2.8
	TXPORTLA	Portland	27 52 30	97 22 00	2.8
	TXGREENI	Green Island	26 30 00	97 22 00	3.9
	LAMAINPA	Main Pass	29 22 30	89 15 00	9.3
	LABARATA	Barataria	29 45 00	90 22 30	9.3
	LAGRANDC	Grand Chenier	29 52 30	93 00 00	8.5
West Coast (West)					
	CAALBION	Albion	39 15 00	123 52 30	0.0
	CAPTSAL	Point Sal	35 00 00	120 45 00	0.0
	CASANQUE	San Quentin	38 00 00	122 30 00	0.1
	ORYAQUIN	Yaquina	44 45 00	124 07 30	−1.0
	WAANACOR	Anacortes	48 45 00	122 45 00	0.2
	WATACOMA	Tacoma	47 30 00	122 30 00	0.8

Notes:

[a] Site identification codes reflect the state abbreviation in their first two letters and the major municipality in their last six letters.

[b] Rate of shoreline subsidence in mm per year.

For each site, the same computer-based mapping technique was applied as in Charleston to interpolate inundation effects for each sea level rise scenario.[6] In those maps, each site was partitioned into square cells usually measuring 500 meters on each side. A computer run for each cell provided specific effects in 5-year increments for designated sea level scenarios. These scenarios were defined by an assumed contribution from greenhouse warming, as well as by a site-specific rate of natural subsidence. Sea level rise in year t upon the shoreline of any site J along sea level rise trajectory K was, more specifically, expressed by:

$$SLR_{JK}(t) = S_J(t - t_J) + GH_K(t - t_J)^2, \tag{7.4}$$

where t_J represents the year of initialization for site J, S_J represents the rate of local subsidence for site J, and GH_K represents a greenhouse warming coefficient intended to produce the chosen cumulative rise to the year 2100.

Time series of the economic cost of future sea level rise at each site were constructed as the sum of protection costs and abandonment losses, under the assumption that decisions to protect were made on a cell-by-cell basis within each sample site. The size of these cells may or may not fit protection strategies for every site, as these must conform to the contours of the land. However, the units are sufficiently small to judge the economic strategy which fits this problem most closely. Further research may indicate slight improvements in decision making with alternative units but is unlikely to uncover a large bias. Abandonment losses, given property appreciation and market adaptation, were derived by applying the procedures described above in the Charleston example to the same property value data that supported the original vulnerability estimates (Yohe, 1990). The resulting series therefore include the expense of protection or the cost (net of adaptation) of abandonment, applicable not only to each specific sample site, but also to specific regions and areas within that site. There was, for example, no reason to require protection for all of the cells in any site that might eventually be threatened by rising seas, as soon as rising seas reached the first one or two cells. For each cell that might be threatened at some time t, in fact, a decision to protect or not was made on the basis of maximizing the present value of the total (net) benefit of protection with respect to t_0, the time when protection might start, and with respect to $T > t_0$, the time when protection might end. The cost trajectories reported here, therefore, include the cost of protection only during times when protection is warranted on a cell-by-cell basis; and the cost trajectories include the (net) cost of abandonment only at the time of that abandonment.

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[6] The mapping technology allows 50-, 100-, 150-, 200-, 250- and 300-cm scenarios to be applied to each of 98 sites chosen systematically from the 980 USGS half degree sites that have some coastline around the United States (Park *et al.*, 1989). The work reported here interpolates from these scenarios to get data for the 33-cm and 67-cm trajectories.

Table 7.9 reports the results for each site under the baseline cost assumptions, with and without foresight, given a 3 percent discount rate along three alternative sea level scenarios.[7] Table 7.10 and Figure 7.1 reflect summary estimates that emerge from these data for the United States, which are based upon the best available estimates of property value appreciation, market adaptation, and protection costs for three sea level trajectories under a variety of circumstances. Estimates of the present value of the true economic cost of the indicated sea level rise trajectories are recorded in column (1). They behave appropriately across the cases, showing larger estimates both for steeper sea level rise trajectories and for circumstances of absolutely no foresight. Perfect foresight is, however, not as valuable as one might think. The small increase in damages associated with imperfect foresight is easy to explain. First, a majority of the property is protected even when the maximum efficiency (minimum abandonment cost) implications of perfect foresight are imposed; improved information has, in these cases, no effect on the ultimate decision of whether or not to protect, and it has no effect on the cost of protection. Second, protection costs limit the value of information, because they cap economic costs for the cells that would not be protected with perfect foresight but that would be protected if the decision were made at the time of inundation, with no advanced adaptation or market response. Finally, most of the protection decisions are made well into the future and so differences in the discounted values of different decisions are small.

Columns (2) and (3) are the most easy to compare with previous estimates. For example, with the 100-cm sea level rise scenario, the annuitized costs run between $100 and $200 million (1990 dollars) – not even 20 percent of the estimated $1.1 billion in annual protection costs projected by earlier studies. The transient cost estimates for the year 2065 of $333 and $384 million are larger; but they, too, fail to cover more than one-third of the previous estimates. Fankhauser (1994) has produced the most comparable evaluation of the cost of sea level rise for the United States. It projects a benchmark protection cost that is in line with the established wisdom. The analysis is based upon smooth inundation patterns that are proportional in area to the assumed rates of sea level rise. Proportional inundation, however, is an oversimplification for any rugged coastline, and could easily produce overestimates of the area of land that is actually threatened. While the accuracy of smooth inundation patterns may be an open question, careful review of Table 7.9 shows no discernible patterns of inundation or protection decisions, and so casts some doubt on the Fankhauser results. His widely applicable systematic analysis, nonetheless, offers an estimate of $104.8 billion for the cumulative cost of protecting the United States from a 100-cm higher sea level, given a 3 percent discount rate.

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[7] The results, given a 5 percent discount rate, are not reported here. The underlying data and spreadsheet-based methodology are available from the authors of this chapter.

Table 7.9. *National and regional estimates for coastal protection strategy costs (in millions of dollars)*

		100-cm SLR scenario			67-cm SLR scenario			33-cm SLR scenario		
Region	Site name	30 Years foresight	0 Years foresight	Protect?	30 Years foresight	0 Years foresight	Protect?	30 Years foresight	0 Years foresight	Protect?
Northeast	Rockland, ME	1.083	1.083	yes	0.477	0.477	yes	0.119	0.119	yes
	Westport, MA	3.829	3.829	yes	1.386	1.386	yes	0.244	0.244	yes
	Watch Hill, RI	9.259	9.259	yes	3.715	3.715	yes	0.768	0.768	yes
	Bridgeport, CT	6.213	7.598	partial protect (30 yrs) yes (0 yrs)	2.849	2.849	yes	0.477	0.477	yes
	Long Beach Island, NJ[bc]	27.708	27.708	yes	18.331	18.331	yes	8.945	8.945	yes
	Easton, MD	6.102	6.102	yes	2.263	2.263	yes	0.264	0.264	yes
	Bloxom, VA	0	0	zero inundation	0	0	zero inundation	0	0	zero inundation
	Newport News, VA[a]	32.626	33.817	–	12.687	12.687	–	2.374	2.374	–
	Suffolk	0.254	0.445	no (30 yrs) yes (0 yrs)	0.138	0.138	yes	0.009	0.009	yes
	Hampton	22.322	22.322	yes	8.802	8.802	partial protect	1.693	1.693	yes
	Norfolk	6.477	6.477	yes	2.355	2.355	yes	0.353	0.353	yes
	Portsmouth	3.573	3.573	yes	1.392	1.392	partial protect	0.319	0.319	yes
Southeast	Long Bay, NC	1.282	4.762	no	0.877	2.785	no (30 yrs)[d] partial protect (0 yrs)[d]	0.245	0.246	partial protect (30 yrs) yes (0 yrs)
	Charleston, SC[a]	8.971	18.146	–	3.475	4.215	–	0.952	1.233	–
	Charleston City	1.101	1.214	partial protect (30 yrs)[d] yes (0 yrs)	0.261	0.261	yes	0	0	zero inundation

	Mt Pleasant	4.057	6.287	no (30 yrs) yes (0 yrs)	2.410	2.550	partial protect (30yrs)[d] yes (0 yrs)	0.498	0.498	yes
	Avondale	0.176	0.185	partial protect (30 yrs)[d] yes (0 yrs)	0	0	zero inundation	0	0	zero inundation
	Dorchester	0.962	1.615	no yes (0 yrs)	0.804	1.404	no	0.454	0.735	no (30 yrs)
	Sullivan's Island[bc]	2.675	8.845	no	0	0	zero inundation	0	0	zero inundation
	Sea Island, GA[bc]	7.182	7.182	yes	4.579	4.579	yes	2.171	2.171	yes
	St. Augustine, GA[bc]	2.236	2.801	no	1.700	2.322	no	0.805	1.580	no
	Miami, FL[bc]	15.675	15.675	yes	10.386	10.386	yes	5.068	5.068	yes
	Key West, FL[c]	11.636	11.636	yes	2.906	2.906	yes	0.528	0.528	yes
	Port Richey, FL[c]	5.874	8.422	no	5.023	7.855	no	2.329	2.329	yes
Gulf Coast	Apalachicola, FL	0.081	0.230	no (30 yrs) yes (0 yrs)	0	0	zero inundation	0	0	zero inundation
	St. Joseph, FL	0	0	zero inundation	0	0	zero inundation	0	0	zero inundation
	Pass Christian, MS	1.325	1.900	no[d]	0.955	0.955	yes	0.239	0.239	yes
	Palacios, TX	0.106	0.396	no ([d] 0 yrs)	0.078	0.197	no (30 yrs) yes (0 yrs)	0.024	0.024	yes
	Portland, TX	0	0	zero inundation	0	0	zero inundation	0	0	zero inundation
	Green Island, TX	0	0	zero inundation	0	0	zero inundation	0	0	zero inundation
	Main Pass, LA	0	0	zero inundation	0	0	zero inundation	0	0	zero inundation
	Barataria, LA	11.412	16.623	no ([d] 0 yrs)	9.016	8.174	no (30 yrs) yes (0 yrs)	2.044	2.044	yes
	Grand Chenier, LA	2.662	7.813	no	2.001	5.115	no (30 yrs) yes (0 yrs)	0.700	0.700	yes
West Coast	Albion, CA	0	0	zero inundation	0	0	zero inundation	0	0	zero inundation
	Point Sal, CA	0	0	zero inundation	0	0	zero inundation	0	0	zero inundation

Table 7.9. (*cont.*)

		100-cm SLR scenario			67-cm SLR scenario			33-cm SLR scenario		
Region	Site name	30 Years foresight	0 Years foresight	Protect?	30 Years foresight	0 Years foresight	Protect?	30 Years foresight	0 Years foresight	Protect?
	San Quentin, CA	4.321	5.335	partial protect (30 yrs)[d] yes (0 yrs)	2.055	2.055	yes	0.324	0.324	yes
	Yaquina, OR	1.903	1.903	yes	0.600	0.600	yes	0.075	0.075	yes
	Anacortes, WA	2.373	4.054	no (30 yrs) yes (0 yrs)	1.412	1.484	partial protect (30 yrs) yes (0 yrs)	0.222	0.222	yes
	Tacoma, WA	5.324	5.343	partial protect (30 yrs)[d] yes (0 yrs)	2.274	2.274	yes	0.389	0.389	yes
Regional estimates	Northeast	$2836	$2920		$1362	$1362		$431	$431	
	Southeast	$1665	$2096		$839	$945		$333	$368	
	Gulf Coast	$509	$881		$394	$472		$98	$98	
	West Coast	$455	$543		$207	$209		$33	$33	
National estimates		$5465	$6440		$2802	$2988		$895	$930	

Notes:

National and Regional estimates are calculated by applying a weight of 32.667 (980/30) to each site.

All values assume a rate of 4 percent was used for variable costs of protection, unless otherwise specified.

[a] Values are taken as a sum of all subsites analyzed at that site.

[b] A site involving a beach nourishment strategy.

[c] A site using 10 percent variable protection cost instead of 4 percent.

[d] Using a 1 percent variable protection cost induced a protect strategy.

Table 7.10. *Economic damage from sea level rise[a] (millions of 1990$; 3 percent discount rate)*

Scenario	(1) Present value	(2) Annuitized annual cost	(3) Transient cost (2065)	(4) Percent protected
100 cm (perfect)	5465	164	333	40
100 cm (none)	6440	193	384	70
67 cm (perfect)	2802	84	170	60
67 cm (none)	2988	90	195	78
33 cm (perfect)	895	27	57	88
33 cm (none)	930	28	57	96

Notes:

[a] Annuitized costs are annual costs that produce the same discounted value as the cumulative calculation. Transient costs are actual costs incurred in the year indicated along the sea level trajectory indicated.

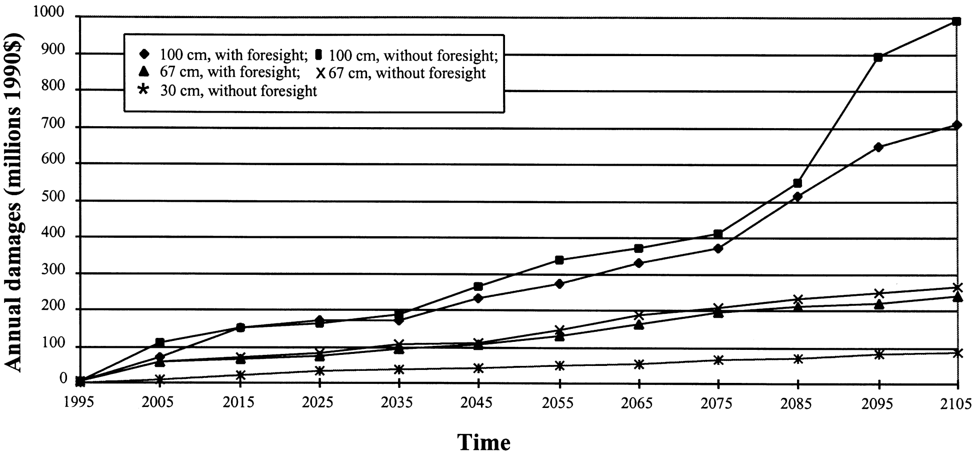

Figure 7.1 Trajectory of estimated annual damages.

Averaging this total over roughly 100 years would put annual costs around $1 billion, and would place him at the upper end of the early Titus and Green (1989) estimates.

The Fankhauser work also suggests that 84 percent of open coastline and 99 percent of US cities would be protected. This level of protection is significantly larger than results indicated in this chapter. Apparently the geographically specific dynamic adaptation modeled in this current analysis reduces the likelihood of protection by deflating the benefit side of any protection decision. It is important to recognize, however, that differences in the frequency of protection do not completely explain the

Table 7.11. *Economic damages with high protection costs*[a] *(millions of 1990$; 3% discount rate)*

Scenario	(1) Present value	(2) Annuitized annual cost	(3) Transient cost (2065)	(4) Percent protected
33-cm trajectory				
Perfect; × 5.33	1922	57	103	54
None; × 5.33	2289	69	110	73
67-cm trajectory				
Perfect; × 5.33	5411	162	324	11
None; × 5.33	7966	238	524	37

Notes:

[a] Damages are calculated based on construction costs equal to $4000 per linear foot; increasing both fixed and variable cost by a multiplicative factor of 5.33.

reported differences in cost. The statistics recorded in Table 7.10 and depicted in Figure 7.1 include not only the expense involved in protection when it is warranted, but also the value of abandoned property when it is lost. Of the $333 million in transient cost recorded in Table 7.10 for the 100-cm sea level rise scenario in the year 2065 under the assumption of perfect foresight, in fact, only about $200 million reflect protection expenditure. The appropriate "apples to apples" comparison shows that the estimate of transient cost reaches only approximately 20 percent of the comparable $1 billion average produced from Fankhauser's cumulative cost calculations.

The results are even more striking along the more likely 33-cm scenario. Annuitized estimates of average cost run from $27 to $28 million per year, and transient costs for the year 2065 round off to $57 million, given a 3 percent discount rate. These are 3 percent and 6 percent of contemporary (100 cm) protection cost estimates, respectively. The 67-cm scenario paints an intermediate case, of course, with transient costs reaching $195 million, given a 3 percent discount rate and zero foresight. With the best guess sea level trajectory somewhere in between these two cases, it would therefore seem that previous estimates were over one order of magnitude too high.

The results presented in this section hinge on protection cost. In Table 7.11 we explore the implications of using the highest protection cost estimate available – $4 000 per linear foot estimated for a project in San Francisco Bay (Gleick and Maurer, 1990). New estimates are registered for three sea level trajectories and the summary statistics are reported in Table 7.11 for the 33-cm and 67-cm scenarios. These estimates reflect efficient protection decisions made on a cell-by-cell basis with and without foresight when the fixed and variable costs of protection are 5.33 times higher than the baseline case. This cost factor is derived by dividing $4 000 (the highest per linear foot protection cost estimate available), by $750 (the central per linear foot protection cost estimate used in baseline case results). The percentage of sites that are protected falls dramatically in all cases, and that moving from foresight to no foresight makes a big difference in damages. Annuitized and transient cost estimates also rise, but by less than a factor of 5.33. The value of threatened land and, in the case of no foresight, structures, now cap the cost estimates.

The largest transient cost recorded in Table 7.11 is $524 million, which is associated with no foresight along the 67-cm trajectory. Although it is the largest transient cost in the table, it is still less than 50 percent of the current benchmark protection cost estimate. In addition, it corresponds to a sea level trajectory that is on the high side of current expectations.

7.5 Conclusions

The results reported here are most striking when they are compared with the currently accepted estimates of the potential cost to the United States of greenhouse gas-induced sea level rise, which are recorded in Table 7.2. The results of this current analysis suggest that estimates of the cost of protecting coastal properties against rising seas are about an order of magnitude too high. Earlier estimates miss the cost-reducing potential of natural, market-based adaptation in anticipation of the threat of rising seas and/or the likely decisions to protect or not to protect property on the basis of economic merit. It is difficult to determine what effect these omissions in the modeling of protection decisions for developed property have on the likely total cost of sea level rise. Some thought experiments designed to account for lower sea level trajectories certainly support the qualitative conclusion that current estimates are much too high.

Take, for example, the transient protection and abandonment cost estimate reported here for the year 2065 along the 33-cm linear sea level trajectory; it is $57 million per year with no foresight. This scenario is closest to the most recent IPCC estimates. If we were to proportionately scale current estimates for cumulative dry land and wetland losses expected along a one-meter trajectory, we should add $370 million and $893 million to the estimate, respectively, for a total of about $1.3 billion.[8] This sum clearly falls well short of the accepted $7 to $9 billion range.

[8] This scaling process has limitations, because adaptation mechanisms and inundation patterns may differ between wetlands and dry lands. Therefore, using the same scaling factor for both may lead to over- or under-stating protection and abandonment cost estimates.

Because currently accepted cost estimates of protection against greenhouse gas-induced sea level rise appear to be an order of magnitude too high, we should concentrate our efforts on perfecting analytical methods to generate more accurate results. The methodology presented here should be used to conduct more studies on the economic impact of potential sea level rise damages. Ultimately, these results, which must incorporate the cost reducing potential of natural, market-based adaptation in anticipation of the threat of rising seas, as well as the likelihood that decisions to protect or not to protect will be made on the basis of economic merit, should replace earlier cost estimates. In turn, these new results may be used as the basis for specific protection decisions.

There are, finally, many lessons to be drawn from this work – some specific to estimating the cost of greenhouse gas-induced sea level rise, and others that can be applied more generally to impact assessment. It is, first of all, critically important to realize that none of the damage estimates associated with sea level rise, including these, take account of storms and other stochastic events that affect the coastline. The usual response to this criticism is that the jury is still out about whether or not warming will spawn more storms with larger intensities. A second response is that higher seas do not necessarily translate ubiquitously into larger storm surges and thus increased damage. However, a recent and preliminary case study produced by researchers at Carnegie Mellon's Center for Integrated Study of the Human Dimensions of Global Change suggests that storms can be impediments to the orderly market adaptation to rising seas that is embodied in these results (West *et al.*, 1996). Their careful analysis shows that decisions made at the individual level, including decisions to rebuild damaged structures after a storm, can influence the cost of inundation when it finally occurs. Some of the damage simply occurs earlier than envisioned here so that depreciation has not been completed; it thereby increases the present value of cost, but seldom by more than the no foresight case reported above. Costs can, however, also be amplified by individuals' rebuilding structures that should and will be abandoned within the planning horizon. These individual decisions produce a double-cost effect that is not captured in the present analysis but which might, at least according to the mean estimate reported in the case study, nearly triple the cost of abandonment in comparison with the perfect foresight case reported here. Applying this factor to the national estimate would not bring the total cost attributable to sea level rise along the 33- or 67-cm trajectories, even in their transient form, up to the levels of past estimates; but it is certainly enough to warrant further investigation across a wider sample of sites to see if the result can be generalized.

It should also be noted that none of the cost assessments for sea level rise have tracked distributional effects very closely. The method of benefit–cost analysis looks for net effects, assuming implicitly that transfers from "winners" to "losers" are made so that a positive benefit–cost ratio can be pareto improving. These transfers hardly ever happen, though; and severe costs concentrated on a specific group of people can produce pressure to oppose the efficient adaptation envisioned here. Once again, the no foresight case bounds damages estimates on the high side except when that pressure is sufficient to force the protection of property and structure when costs exceed benefits. The Army Corps of Engineers uses benefit–cost calculations to evaluate coastal projects in the United States, and so this might be a small concern for these estimates. Application of the methods described here to coastal zones lying outside the borders of the United States might be more problematic.

The more general lessons to be drawn from these developments can be used to frame the course of impact assessment applied well beyond the coastal zone and beyond the United States. The early impact assessments for sea level rise produced relatively high costs that have been reduced substantially by second round assessments that include adaptation. Adaptation models have usually been constructed within sound and consistent theoretical models of how the world can be expected to work on a tractable micro-level, and so they are the appropriate second steps. Now that they have been completed, third and fourth steps can be expected in two directions. On the one hand, a third step in the evolution of impact assessment should involve application of results to countries where data are more scarce than they are in the United States. One method currently under investigation attempts to produce reduced form estimates of cost functions for the United States that (1) capture a reasonable amount of the variation associated with the adaptation "correction" to vulnerability estimates from a minimal set of data and (2) can support reasonable application to adaptation that will be possible elsewhere around the world as the next century unfolds. Yohe and Schlesinger (1997) have made a first attempt in this direction for US cost estimates tied to specific greenhouse gas-emissions trajectories under a variety of sulfate alternatives. The point here is not to look at conditions today, but rather to try to envision what will exist in a globally integrated world in, say, the year 2050.

On the other hand, a fourth step should look carefully at the modeling assumptions which frame current views of adaptation in the United States to determine if they are sufficiently descriptive of what is possible. In some cases, more potential may exist; in others, informational and institutional impediments may limit adaptation and its ability to reduce costs. In either case, work along these lines will be very data intensive and will certainly not produce modeling candidates for wide application. Moreover, cost estimates depend upon local institutions that can either help or hinder market-based adaptation. In the United States, banks that hold mortgages require insurance coverage; and insurance companies certainly increase premiums as the risk of loss to storms and/or sea level rise climbs. Combining the workings of these two institutions certainly facilitates market depreciation of the value of insured structures even in areas where actual markets are thin. Would this story in support of market-based depreciation apply elsewhere? Nobody will know without careful and expensive analysis on a case-by-case basis. Care should thus be taken to determine when greater detail makes a difference; and efforts should be made to frame significant results in terms of defensible scaling factors (constants or values dependent upon easily perceived parameters) that can be used to increase or decrease aggregate measures of cost.

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