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Climate change and coastal flooding in Metro Boston: impacts and adaptation strategies

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Abstract Sea level rise (SLR) due to climate change will increase storm surge height along the 825 km long coastline of Metro Boston, USA. Land at risk consists of urban waterfront with piers and armoring, residential areas with and without seawalls and revetments, and undeveloped land with either rock coasts or gently sloping beachfront and low-lying coastal marshes. Risk-based analysis shows that the cumulative 100 year economic impacts on developed areas from increased storm surge flooding depend heavily upon the adaptation response, location, and estimated sea level rise. Generally it is found that it is advantageous to use expensive structural protection in areas that are highly developed and less structural approaches such as floodproofing and limiting or removing development in less developed or environmentally sensitive areas.

1 Introduction

The Intergovernmental Panel on Climate Change (IPCC 2007, p 10) states that, "Discernible human influences (due to observed increases in globally averaged temperatures very likely due to the observed increase in anthropogenic greenhouse gas concentrations) now extend to other aspects of climate, including ocean warming, continental-average temperatures, temperature extremes and wind patterns" One of the impacts has been an increase in sea level because of the melting of ice on land and thermal

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expansion of the ocean as it is warmed (the sum of both is eustatic sea level rise, Pugh 2004). IPCC (2007) reports that the historic eustatic rate over the period 1961 to 2003 is 1.8± 0.5 mm/year with an increase to 3.1±0.7 mm/year from 1993 to 2003. Sea level elevation relative to land is also related to processes that affect a specific region, including tectonic uplift and down dropping, isostatic rebound and depression, land surface changes due to compaction, dewatering, fluid extraction, and diagenetic processes. For example in coastal Boston in the northeastern United States (USA), land subsidence is estimated to have been 1.5 mm/year or 0.15 m in the last 100 years (Nucci Vine Associates, Inc. 1992). An estimate of 2 mm/year for historical subsidence in Revere, nearby to the north of Boston, was reported in Clark et al. (1998). Eustatic sea level rise (SLR) combined with land subsidence is referred to as relative SLR. The effects of SLR in the coastal zone include displacement and loss of wetlands, inundation of low-lying property, increased erosion of the shoreline, change in the extent of flood zones, changing water circulation patterns, and more salt water intrusion into groundwater. It is also possible that due to climate change there could be changes in coastal storm patterns that alter the frequency and intensity of coastal flooding, for example, see Emanuel (2005).

Most experts (IPCC 2001; Natural Resources Canada 2002) agree with the IPCC (1990) formulation that adaptation responses to SLR include protection, accommodation, and retreat. Protection attempts to manage the hazard with “hard” structures such as seawalls and groins or “soft” measures such as beach nourishment. Accommodation allows human activities and the hazard to coexist through actions such as flood proofing. Retreat removes human activity from the hazard area which generally is accomplished by abandoning land as the sea rises. Each of these strategies has different economic, social, and environmental impacts and policy implications that are highly site dependent.

In the Boston research, we examine periodic losses from flooding quantified by areas at-risk and cost of likely damages and adaptation actions under four possible adaptation strategies. This research expands the coastal flooding section of the Climate’s Long-term Impacts on Metro Boston (CLIMB) research project which examined the integrated, multi-sector impacts of climate change upon the region's infrastructure services. The CLIMB project was conducted from 1999 to 2004 by a multidisciplinary research team from Tufts University, University of Maryland, and Boston University with assistance from the Metropolitan Area Planning Council (MAPC) and a Stakeholder Advisory Committee composed of representatives of government and other interest groups and infrastructure and planning experts. The methodology and results are summarized in Ruth and Kirshen (2001) and Kirshen et al. (2008a, b), and are available in full in Kirshen et al. (2004). The CLIMB region or Metro Boston, which is located in the northeastern USA, is shown in Fig. 1 and includes the major cities of Boston and Cambridge and the other 99 municipalities within approximately 20 miles of Boston. The area is bordered on the east by Boston Harbor (the confluence of three major rivers) and on the south, west, and north approximately by the circumferential Route 495, covering an area of 3,683 km^2. Metro Boston’s population is approximately 3.2 million and is expected to increase to 4.0 million by 2050. Land use varies from densely populated urban areas in the east, suburbs in the center, and undeveloped farmland and some urban “sprawl” on the fringes. It is the heart of the New England economy and provides its major airport, and seaport facilities. The region is currently experiencing pressure on most of its infrastructure systems and severe development pressure in the municipalities just outside of the core city areas. It is characterized by a climate with four distinct seasons with annual precipitation of 1,000 mm relatively evenly distributed throughout the year; some falling as snow in the winter. The average monthly temperature is approximately 10°C. For the purpose of analysis, the

CLIMB region was divided into the seven zones shown in Fig. 1 based upon similar land use and geographic conditions.

2 Study area

As shown in Fig. 2, the coastal area spans the area between Duxbury in the south and Ipswich in the north, is 825 km long and lies in parts of CLIMB zones 1 through 5. The 32 towns abutting the coast contain 110,000 ha of land area, and approximately 1.2 million people (US Census 2000). Land use is also shown in Fig. 2. The coastal zone is a popular location for residential housing and a site of much commercial, industrial, and recreational activity. In Boston and the directly surrounding cities there are densely populated areas. Along the northern and southern edges of the study area, there are generally suburbs and farmland except for the a few urban areas such as Lynn and Quincy. Based upon actual field mapping, well over one half of the coastline presently has shorelines hardened with

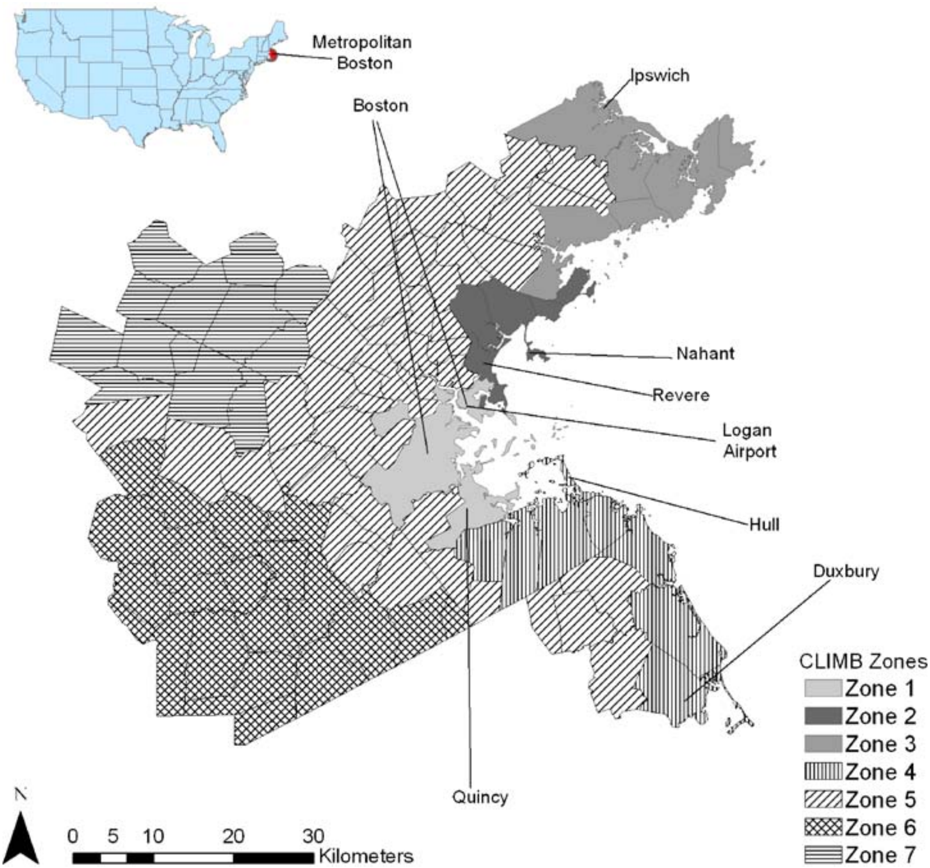

Fig. 1 Seven CLIMB zones: zone 1 = South Coastal Urban, zone 2 = North Coastal Urban, zone 3 = North Coastal Suburban, zone 4 = South Coastal Suburban, zone 5 = Developed Suburbs, zone 6 = Developing Suburbs South, zone 7 = Developing Suburbs North

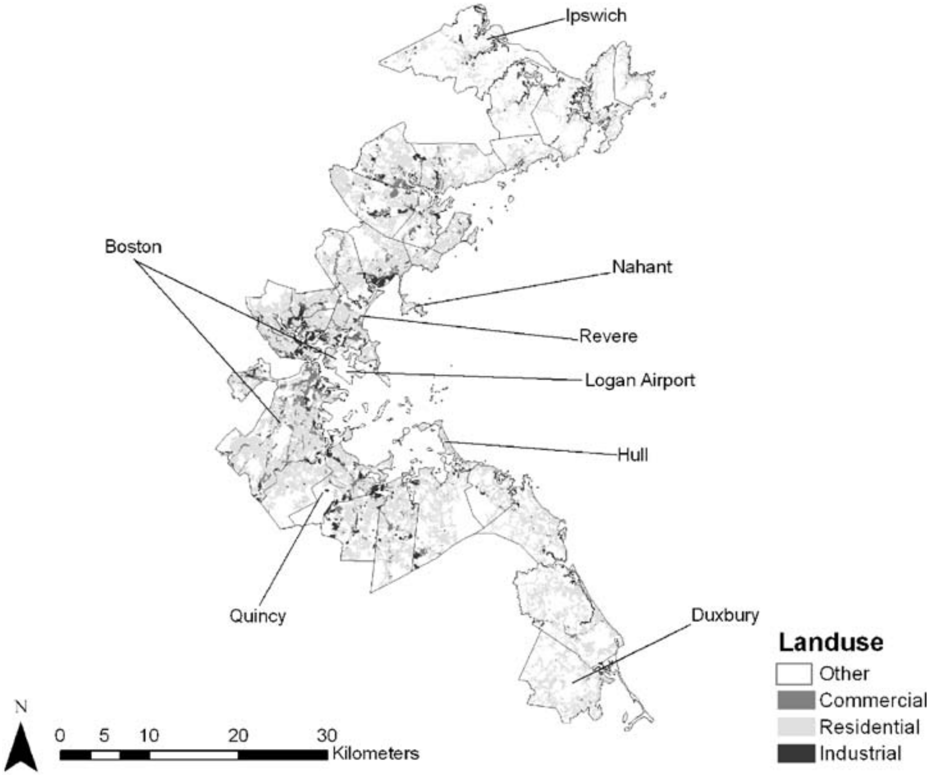

Fig. 2 Present land use in the coastal portion of Metro Boston

seawalls, revetments, and bulkheads (Knee 2002). The diverse coastline is host to a variety of ecosystems including sandy beaches, rocky shores, estuaries, and salt marshes.

Coastal flooding in the metro Boston region generally results from extra-tropical storms locally known as "nor'easters". The long arm of Cape Cod, southeast of the study area, protects much of metro Boston from the full force of tropical storms such as hurricanes, but leaves the area exposed to nor'easters. The Blizzard of 1978 was the most recent 100-year coastal flood of the Massachusetts shoreline and caused damages of $550 million (2,000 dollars, US Army Corps of Engineers 1990) and required $95 million in emergency costs; most of the damage occurred within our study area.

In Metro Boston the floodplain of the 100-year coastal storm is approximately 11,000 ha (10% of the area of the CLIMB coastal towns). The additional incremental area of the 500-year floodplain is 1,000 ha. As shown in Table 1, the entire 500-year floodplain currently contains 1,560 ha of residential land, 265 ha of commercial land, and 355 ha of industrial land. It also has 23,000 residential structures (Knee 2002).

Table 2 shows expected population and employment changes in the 7 CLIMB zones. Population and employment projections were developed from municipal population projections to 2025 from the Metropolitan Area Planning Council (2000) and county level projections to 2050 from NPA Data Services, Inc. (1999, 2001]. MAPC expects buildout conditions to be reached by 2050 when the population of the entire region will be approximately 3.5 million people; 1.4 million will be in the coastal towns. MAPC expects the employment in the commercial sector (retail and service) to increase while that in the

Table 1 2000 land use in 500 year flood plain in Metro Boston (see Fig. 1 for location of zones)

CLIMB zone	Development in the floodplain (ha)			Total floodplain area (ha)
	Residential	Commercial	Industrial	
South Coastal Urban	230	90	200	1,370
North Coastal Urban	350	70	50	1,330
North Coastal Suburban	215	40	80	4,490
South Coastal Suburban	710	50	10	3,960
Developed Suburbs	55	15	15	790
Total	1,560	265	355	11,940

Source: MassGIS (2003)

industrial and manufacturing sector to decline. Assuming changes in land use proportional to changes in local population and employment, by 2050, residential area in the present 500 year floodplain is expected to be 1780 hectares containing 26,000 structures, commercial area will increase to 350 ha, and industrial area will decline to 290 ha.

In the Boston area, relative sea level rise, which is a combination of land subsidence and eustatic sea level rise, has caused an increase in sea level elevation of approximately 0.3 m over the last century (Nucci Vine Associates, Inc. 1992). Two scenarios of sea level rise were examined. One used an eustatic SLR of 0.45 m in Boston over the next century. If the historical rate of subsidence of 1.5 mm/year is added to this, the total relative SLR between 2000 and 2100 is 0.6 m. We also did the analyses for a relative SLR of 1.0 m by 2100, which is an estimate based upon 0.85 m of eustatic SLR added to local subsidence of 0.15 m over that period. 0.45 m is approximately midpoint of the SLRs of several SRES scenarios (IPCC 2007). Rahmstorf (2007)shows that some of higher emission SRES scenarios could actually result in eustatic SLRs of 0.85 m or more even without considering major melting of continental ice.

IPCC (2007) reports that in the future it is likely there will be increases in intensities of tropical storms and projects continued poleward movement of extra-tropical storm tracks. For Boston, Flick et al. (1999, 2003) show a trend of 13.7 mm/100 years in the difference between monthly mean high water and monthly mean low water indicating a slight increase in mean tidal range. Flick et al. (1999) also show a greater upper trend in highest reported monthly elevations (361 mm/100 years) than in mean sea level (268 mm/100 years, pg B12). None of these trends were included in our analysis.

Even ignoring the above trends, both these scenario increases in relative SLR by 2100 will lead to significant decreases in the average recurrence interval of design floods in metro Boston by adding to the base elevation of any storm surge. An US Army Corps of Engineers study (Weiner 1993) found the 10-year surge elevation in Boston Harbor is 2.8 m above National Geodetic Vertical Datum (NGVD), the 100-year surge elevation is 3.16 m and the 500-year surge elevation is 3.41 m. The relationship between the 10-year, 100-year, and 500-year storm surges is significant as each differs by approximately 0.3 m. Therefore, assuming the entire frequency distribution of water levels rises by the same as mean sea level, a linear increase in SLR each year and a total SLR increase of 0.6 m by 2100, by 2050 the increase would be 0.3 m and the 10-year storm elevation then would be approximately equivalent to the current 100-year storm and the 100-year storm then approximately equivalent to the present 500-year storm.

Table 2 CLIMB scenario population and employment changes (from Kirshen et al. 2004)

	Y2000	Y2015	Y2030	Y2050
Population (thousands)				
Zone 1	682.2	712.9	741	805.1
Zone 2	211.4	215.7	219.7	226.2
Zone 3	137.9	145.1	150	158.4
Zone 4	149.4	154.3	158.6	174
Zone 5	1,495.6	1,536.9	1,558.5	1,621.5
Zone 6	242.7	271.1	299.1	314.8
Zone 7	145.1	158.4	167.7	176.4
Total	3,064.2	3,194.3	3,294.7	3,476.3
Employment—Basic (thousands)				
Zone 1	49.4	47.3	46.4	44.1
Zone 2	11.4	10.7	9.9	8.4
Zone 3	12.7	12.1	11.4	10
Zone 4	7	7.7	7.9	8.1
Zone 5	153.2	155.7	147.1	132.9
Zone 6	16.5	17.1	15.5	14.3
Zone 7	11.8	11.8	15.1	13.6
Total	261.9	262.3	253.3	231.3
Employment—Retail trade (thousands)				
Zone 1	66.3	67.2	68.3	68.2
Zone 2	8.8	8.8	8.7	8.1
Zone 3	9.2	9.4	9.5	9
Zone 4	8.2	9.1	9.4	9.6
Zone 5	128.9	137.9	137.2	132.7
Zone 6	15.6	17.2	16.5	16.1
Zone 7	8.9	9.4	12.7	12.5
Total	246	259	262.2	256.2
Employment—Service (thousands)				
Zone 1	514.5	595.2	662.5	743
Zone 2	37	42.7	46.7	49.3
Zone 3	32.5	38.6	42.9	45.9
Zone 4	27.3	34.9	39.7	45.3
Zone 5	602.3	758.4	837	912.1
Zone 6	65.3	85.1	90	99.1
Zone 7	45.9	56.8	85.9	94.9
Total	1,324.88	1,611.62	1,804.69	1,989.61

3 Studies of other nearby areas

There are several other detailed studies of SLR of places near or in Metro Boston. Our research is somewhat unique with its emphasis upon impacts of various adaptation actions. Rosenzweig and Solecki (2001) produced a study of the impacts of climate change on the New York Metropolitan area, which predicts serious impacts to the region's transportation systems and an increase in the rates of beach erosion. Cooper et al. (2005) determined possible changes in coastal flood frequencies due to SLR in New Jersey and associated increases in floodplains. Kirshen et al. (2008b) under low and high emission greenhouse gas emission scenarios estimated changes in recurrence intervals of 100 year floods and extents of new 100 year floodplains in 2100 in Boston, Woods Hole, New London, New York City, and Atlantic City. The methodology was different from that in this paper but found similar results in recurrence interval changes. No damage assessments were done. The New England Regional Assessment Group (NERA) performed an analysis of climate change for all of New England and New York and concluded that both low-lying infrastructure and wetlands would be at-risk (NERA 2001). The impacts of sea level rise for inner Boston Harbor have also been studied, and many port facilities such as container areas will be at-risk (Nucci Vine Associates, Inc. 1992). Few damage estimates are given in all these studies. The US Army Corps of Engineers (1990) estimated that the additional annual flood losses arising from one foot of SLR in the next 100 years to the heavily developed and industrialized Saugus River estuary area directly north of Boston with a coastline 8 km of would be $1.4 million. While not directly examining the impacts of climate change, Clark et al. (1998) mapped the vulnerability of residents of Revere MA by determining areas at risk to various amounts of coastal flooding and residents' socioeconomic characteristics.

4 Methodology

As described above, we examined impacts under two relative SLR scenarios for 2100: 0.6 m and 1.0 m. We examined the annual impacts for the period 2000 to 2100 in light of four possible adaptations to climate change that could be taken in the region and which will be discussed subsequently: Ride It Out (RIO); nonstructural, environmentally benign or green accommodation (GREEN); Build Your Way Out (BYWO), and Retreat (RETREAT). Details on these are given subsequently. We examined the impacts assuming that SLR occurs gradually at a constant amount each year even though there are strong possibilities of abrupt climate change causing major changes over decades instead of a century. We do not include any possible impacts of changes in the frequency or intensity of storms because they are not well known at this time or possible shoreline changes due to increased erosion under SLR. We also did not examine impacts occurring beyond 2100 even though impacts would still be occurring then; the magnitudes would depend upon mitigation actions which the world and in particular the USA and industrially expanding countries take to curb emissions of greenhouse gases. We did not discount any of the future costs of property damage or flood protection; we assumed that property values appreciated at the discount rate and, since flood protection costs are very closely related to property costs (such as floodproofing), that discounting was also unnecessary for these costs. We do, however, present graphical time series of damages over the period 2000 to 2100 so a discount factor can be applied if desired by readers. Damage costs were estimated as accurately as possible but if judgment was required, the lesser value was always chosen. Tables of the values are available to those interested.

Since no significant developed land would be permanently inundated because of SLR and we ignored possible shoreline changes, we did not have to be concerned with losing developed land because of permanent flooding. Therefore the first step in the analysis was to determine for each CLIMB zone the relationship between flood elevations and the area flooded. As an example of the method, the flood elevation versus flooded area curve for CLIMB zone 3, the North Coastal Suburban zone, is shown in Fig. 3. It was derived by linearly interpolating between the elevations of the present 100 year (that is, the elevation that has a probability of being equaled or exceeded in any year of 1/100 or 1%) and 500 year floodplains whose locations have been mapped by the Federal Emergency

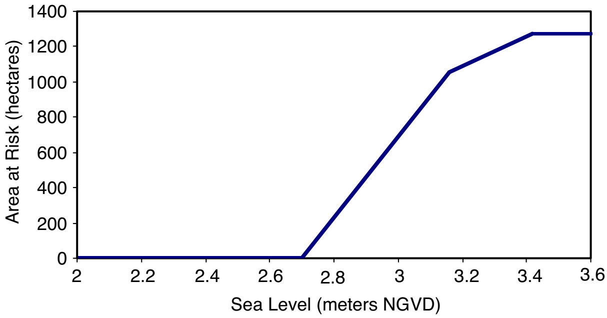

Fig. 3 Sample damage function for zone 3, the North Coastal Suburban

Management Agency (FEMA). The floodplain water level elevations were taken from the US Army Corps of Engineers (Weiner 1993), adjusting the data to 2000 levels. These are approximately the same as the elevations used by FEMA. Based upon some actual flooding events, we estimated that property damages begin when the surge elevation reaches 2.7 m. This corresponds to the present 7 year surge. A higher initiation of flooding threshold captured only extreme events and lower thresholds caused too much damage from small storms. The threshold was confirmed with the Halloween Storm of 1991 (FEMA 1999), which is the last major storm to impact the area. Since there were no feasible methods to determine the extent of the floodplain beyond the present 500 year delineation, we optimistically assumed that damages resulting from storms of greater magnitude were equal to damages caused by the 500 year storm. The present residential, commercial, and industrial areas at risk in each floodplain were calculated by combining the landuse and floodplain layers from the Commonwealth of Massachusetts Geographic Information System, MassGIS (2003). Economic damages to residential development were based upon the number of units and average value per unit by census tract from 2000 US Census data. Using historical flood damage data from FEMA (1999) for the period 1977 to 1999, we determined that approximately 40% of all the residential units in the present 100 year or less floodplain file claims and thus are assumed to get flooded during an event in their location and 25% of all units in the area between the 100 and 500 year floodplains get flooded during an event in that area. The reason for the different rates of flooding is unknown but may be due to local topography around homes and incomplete data on flooding. The flood data also indicated that flood damages to building and contents ranged from 3 to 8% of residential property values from US Census (2000) depending upon CLIMB zone. The damages averaged between $7,000 and $18,000 depending on location. The best source of data we could find for damages to commercial and industrial property was from the Lynn Harbor study of the US Army Corps of Engineers (1990) from which we derived an estimate of $750,000 per hectare. We added 17% to the total damage costs as emergency costs (US Army Corps of Engineers 1990).

It was necessary to account for land use changes in the floodplains over the next century. This was accomplished by assuming that all areas zoned for eventual development would be developed, and that none of the areas zoned for recreation or conservation would become residential, commercial, or industrial. It was assumed that no future development of wetlands would be permitted.

We assumed that development occurred in the floodplains at the same rate as in the coastal CLIMB zones. The rates of residential area change were proportional to the projected population changes and the commercial and industrial area changes were proportional to the changes in their employment. The population and employment data are reported in Table 2.

As explained in more detail below, bootstrapping of historic sea level data and Monte Carlo simulation were used to project sea levels and impacts for the next century. Historical sea level data from 1920 to 2000 from the National Oceanographic Survey (NOS) for Boston Harbor were utilized. Since sea level rise has been occurring over this time period, the data required adjustment to 2000 levels before it could be included in the analysis. The adjustment was made by assuming a 0.3 m increase in sea level over the last 100 years (Nucci Vine Associates, Inc. 1992) and then linearly interpolating the total relative SLR that had occurred in each year since 1920 and adding this interpolated value to the elevations for that year.

To develop possible time series of the three highest future sea levels that might occur in any year in the period 2000 to 2100, the following was done. An historical year from 1920 to 2000 was randomly assigned to each year in the study period from 2000 to 2100 and the three highest SLR elevations that had occurred in that historic year were extracted. This process was repeated 100 times to develop 100 possible time series of future annual maximum sea levels (i.e. bootstrapping, Vogel and Shallcross 1996). Then the coastal impacts were determined for each of the 100 time series of elevations (Monte Carlo simulation) and the resulting damages were averaged to obtain the expected value of damages. Because the process accounts for 100 possible patterns in the timing of future storm surges, uncertainty in the timing of future storm surges is inherently included. In the climate change scenarios, the cumulative increase in sea level was added to the three maximum sea levels corresponding to the year in the bootstrapped time series.

Monte Carlo simulation of the impacts under various adaptation options was performed using STELLA simulation software from High Performance Systems Inc (1997). For each year in period 2000 to 2100, the simulation model used the annual maximum sea levels, the flood area function in Fig. 3 described above, and the areas of development in the floodplain to calculate the annual damages. The output included residential, commercial, and industrial areas flooded and economic damages. Variables such as the types of adaptation strategy (described below), the development scenario, the rate of sea level rise, and the number of damage events per year considered were varied for each set of runs. A listing of the simulations is in Table 4.

5 Adaptation scenarios

The baseline or no climate change analysis determines expected future damages for growth and no growth conditions considering only local subsidence rates (increasing relative sea level by 0.15 m by 2100). It was included to explore adaptation co-benefits for the case of no climate change. Analyses were performed for both the cases of: (1) only damage from the largest event each year, (in effect assuming that it takes one year to rebuild); and (2) the possibility of damages from all three events in a year (assuming rapid reconstruction).

The ‘Ride-It-Out’ adaptation (RIO) assumes that existing buildings will be repaired to current conditions after each flood over the 100 year period with no additional floodproofing. All growth in the present 100-year floodplain is floodproofed 100% effectively so there are no damages to this property if flooded by any event. It is assumed that increased cost of floodproofing new structures is insignificant compared to the total cost of new construction. There are no requirements for floodproofing in the present 500 year floodplain. This scenario most closely mimics current FEMA policy. Environmental costs for this option are low since it does not prevent the natural migration of the shoreline as the sea rises with the exception of existing barriers. Since over the next 100 years there will be little permanent inundation of existing and developable land, there will not have to be abandonment of the coastal area. The streets, however, will be frequently flooded; these damages were not considered in this scenario.

Under 'Build Your Way Out' (BYWO), unregulated growth is allowed in all floodplains because all current and future development is protected with retrofit or new coastal protection structures, which are all built following the second flood that occurs in the period 2000 to 2100 with a magnitude greater than or equal to the present 100 year flood. Damage is incurred until that event occurs, and as with RIO, damaged structures are repaired to their previous state, allowing repetitive damages. Coastal flooding protection in this option consists of seawalls (Woodroffe 2003). This is similar to the "Protection" SLR adaptation response. A GIS coverage developed from a coastline survey of Knee (2002) of existing coastal protection structures including seawalls to manage flooding and shoreline protection structures such as revetments was used to determine the amount of retrofitting needed to protect existing development from flooding. Segments along the coastline and in major estuaries where there were no seawalls were determined from the GIS coverage as a means to estimate where additional seawalls would be needed to protect current or potential development. Unfortunately, seawalls also interrupt the natural movement and replenishment of sand (Massachusetts Office of Coastal Zone Management 1989) and contributes to the loss of beachfront areas. Another negative environmental impact is that the structures can prevent the natural migration inland of wetlands as SLR occurs.

It is assumed that the coastal protection structures are built to withstand the 500 year storm as the incremental cost of protecting the coast from the 500-year surge level rather than just the 100-year surge level is small compared with the total cost of the retrofit or new structure. The cost of retrofitting existing structures is approximately $1,000 per linear meter of protection structure (US Army Corps of Engineers 2000), while building new structures costs about $7,200 per linear meter (US Army Corps of Engineers 2000).

These costs do not include maintenance, beach nourishment projects to prevent foreshore erosion and undercutting (which can be high and necessary every 5 to 10 years), drainage of any areas behind seawalls flooded during storms, any environmental consequences associated with seawalls such as impeding the natural flows of coastal freshwaters, and aesthetic consequences.

In a stricter version of current FEMA regulations, the 'Green' scenario requires that all growth in the current 100 and 500 year floodplains be totally floodproofed at the time of construction and we again assume that floodproofing new residential, commercial, and industrial structures only nominally adds to the cost of construction. It also requires that current residential development in the present and 100 and 500 year floodplains be floodproofed upon sale of the structure assuming a 15-year turnover rate. The retrofitting of those structures already present in the floodplain is assumed to be 80% effective; that is, when a retrofitted building is flooded, damages to buildings and contents are reduced to 20% of the damages without floodproofing. In the 100-year floodplain homes are retrofitted by elevating them at approximately $17,000 per home. In the area outside the 100-year floodplain, wet floodproofing is used at a cost of $3,500 per home. Both costs were from tables in FEMA (1998) for a home with a 90 m^2 footprint and frame construction set on a basement/crawlspace. Elevation prevents flooding of the living spaces of the home; wet floodproofing allows floodwaters to enter the home, but prevents damage to the structure and its contents. The cost of commercial and industrial floodproofing was assumed to be 10% of the commercial and industrial damages that would otherwise be incurred; this is the approximate ratio between the cost of residential floodproofing and residential damages incurred. Floodproofing of industrial and commercial properties is implemented after they are flooded. This is an "Accommodation" SLR response. As in the case of the RIO scenario, streets will be frequently flooded in the future; these damages were not considered in this scenario.

As with the 'Ride-It-Out' scenarios, the 'Green' scenario has low environmental impacts. As is shown in the results, however, it is much more economically effective because the floodproofing procedures reduce repetitive damages.

The 'Retreat' scenario assumes that no more residential, commercial, or industrial development is allowed in floodplains and that no rebuilding after flooded is permitted; there is no damage threshold below which an owner can repair instead of abandon. This scenario is distinctly different from the other scenarios because in this scenario property owners are forced to vacate the floodplain or not build in it. It is assumed that when a property is flooded, the owner loses the value of the building, contents, and the land. Yohe et al. (1999), however, argue that the value of abandoned coastal land is really equal to the value of a far inland lot. This is because coastal land values are transferred inland as coastal land is abandoned; lots that were previously inland now become more coastal. They also argue that the values of coastal building depreciate once the market knows they might be flooded. Therefore in the retreat scenario if we assume that the value of inland land is 50% of coastal land and that coastal buildings depreciate to 50% of their values, then the aggregate loss to society of not being able to rebuild on the floodplain is 50% of the market value of the building and the land, demolition costs, and removal expenses. For undeveloped land that is now prohibited to be developed it is assumed the owner losses its land value, but since it makes land inland more valuable, only 50% of its value is lost to society.

Demolition costs are $20,000 per household [from costs in a nearby coastal town, Byefield (Bennett Contracting, Personal Communication, November 2004)] and thus, assuming that commercial and industrial developed land is equivalent to eight households on a hectare of land, $160,000/ha for commercial and industrial properties. Discussions with local realtors (Macdonald and Wood Real Estate, November 2004, personal communication) indicate that the value of land right on the water are 70% greater than residential building values and that inland, but still a walk to water, land values are 55% more than building values. Therefore, based upon this information, it is assumed that the values of residential, commercial and industrial land in all the coastal area are 50% greater than building values. As in the cases of the RIO and Green scenarios, streets on which buildings remain will be frequently flooded in the future; these damages are not considered in this scenario.

6 Results

Table 3 shows changes in the recurrence intervals of the 100 and 500 year events for the 0.6 m scenario of relative SLR. Because the data used for the bootstrapping procedure encompassed only 80 years, but contained a 100-year flood, the 100 year flood elevation under a scenario of no SLR occurs approximately every 80 years in the Monte Carlo simulation. If this was the only assumption, this would have the effect of increasing the damages because this extreme event would occur more frequently than in reality. The effect of this assumption, however, is probably offset by assumptions that lower the value of damages such as the flood damages remaining the same after the present 500 year storm elevation has been exceeded, neglecting impacts of increased erosion, and likely increases in the intensities of hurricanes. Figure 4 shows some possible time series of the maximum

Table 3 Change in recurrence intervals for 0.6 m relative sea level rise scenario

	No change			Subsidence			0.6 m of relative SLR by 2100		
Year	Zero damage threshold	100-year flood	500-year flood	Zero damage threshold	100-year flood	500-year flood	Zero damage threshold	100-year flood	500-year flood
2000–2025	4.5	100	N/A	4.4	100	N/A	3.4	71.4	N/A
2026–2050	4.7	67.6	N/A	3.6	67.6	N/A	1.7	25.3	104.2
2051–2075	5.1	80.6	N/A	3.5	48.1	N/A	1.1	7.1	48.1
2076–2100	4.8	92.6	N/A	2.6	38.5	N/A	1	3.8	13.8

N/A not applicable

annual flood elevation over 2000 to 2100 for a SLR of 0.6 m by 2100. As can be seen, after approximately 2050, the present 100 year flood is being exceeded at least every 10 years.

The damages vary with growth, sea level rise, number of events, and adaptation scenarios. Table 4 summarizes for the coastal CLIMB zones the total areas flooded for each model run or scenario. The "area flooded" each year is that cumulative area flooded by the assumed number of damaging events for that year. In some scenarios we assume only one possible damaging event per year (the largest flood that occurs that year) because it takes one year for rebuilding. In other scenarios, we assume three possible damaging events per year (the three largest separate floods that occur in that year); there is very rapid rebuilding between floods so that damaged property owners are vulnerable to multiple floods in a year. Table 5 has the costs of damages, adaptation costs, and total costs. By comparing the baseline runs (subsidence only) with and without growth (runs 1 through 4), it can be seen that the results of these runs are not very sensitive to growth. This is because the region is already close to buildout as well as our assumption that new construction is floodproofed. In addition, if land outside the present 500 year floodplain in the model gets flooded, the damages are the same as that caused by the elevation of present 500 year flood—see Fig. 3. The cumulative amounts of residential, commercial, and industrial lands flooded in the Baseline Runs are greater that the areas of these sectors in the present floodplain (Table 1).

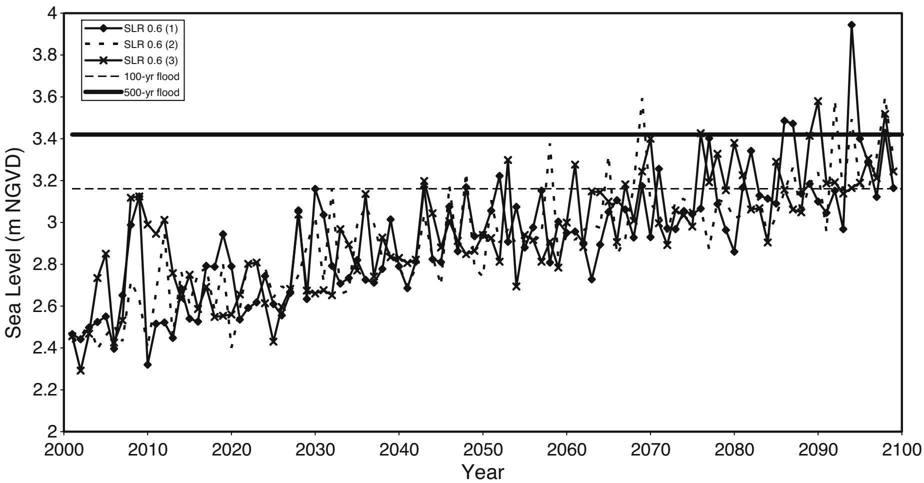

Fig. 4 Possible annual maximum sea levels 2000 to 2100

Table 4 Summary of expected values of total areas flooded from 2000 to 2100 (ha)

	Model run	Residential area	Commercial area	Industrial area
1	Baseline—no growth, one event	15,714	2,334	3,030
2	Baseline—no growth, three events	20,971	3,108	4,030
3	Baseline—growth, one event	17,429	3,076	2,663
4	Baseline—growth, three events	23,350	4,121	3,526
5	Ride-It-Out—0.6 m SLR, one event	51,752	7,918	10,115
6	Build-Your-Way-Out—0.6 m SLR, one event	15,834	2,786	2,525
7	Green—0.6 m SLR, one event	51,597	7,785	10,192
8	Retreat—0.6 m SLR, one event	51,820	7,508	9,733
9	Ride-It-Out—0.6 m SLR, three events	115,692	17,381	22,321
10	Build-Your-Way-Out—0.6 m SLR, three events	27,803	4,902	4,331
11	Green—0.6 m SLR, three events	115,512	17,226	22,410
12	Retreat—0.6 m SLR, three events	115,607	16,909	21,883
13	Ride-It-Out—1 m SLR, one event	90,236	14,817	18,535
14	Build-Your-Way-Out—1 m SLR, one event	14,017	2,455	2,363
15	Green—1 m SLR, one event	89,428	5,610	18,935
16	Retreat—1 m SLR, one event	84,339	12,696	16,568
17	Ride-It-Out—1 m SLR, three events	236,471	37,920	47,746
18	Build-Your-Way-Out—1 m SLR, three events	26,287	4,604	4,334
19	Green—1 m SLR, three events	234,822	13,414	48,561
20	Retreat—1 m SLR, three events	225,304	33,643	43,799

This is because many properties receive repetitive damages and an increase in the area of the floodplains. A decrease in industrial area flooded under the growth scenarios occurs because, as stated previously, industrial employment is decreasing over time the region.

0.6 m of relative SLR and one annual damage event Table 4 shows that the total flooded areas under the 0.6 m or moderate SLR-RIO scenario (run 5), which is the same as the Baseline with eustatic SLR added, approximately triples the baseline areas. Comparing the Baseline to RIO, cumulative damages increase from $6.4 billion to $20 billion. The largest residential area flooded and the highest residential damages for both the Baseline and RIO runs are in zone 4, Coastal Suburban South, which is mainly the City of Boston. Figure 5 shows that the annual costs of RIO (scenario 5) steadily increase over time.

Under BYWO, unregulated growth is allowed in all floodplains because all current and future development is protected with retrofit or new coastal protection structures, which are built following the second flood with a magnitude greater than or equal to the present 100-year flood. Damage is incurred until that event occurs, and as with RIO, damaged structures are repaired to their previous state, allowing repetitive damages. Coastal protection structures are built to withstand the 500 year storm because the incremental cost of protecting the coast from the 500-year surge level rather than just the 100-year surge level is small compared with the total cost of the retrofit or new structure. Thus the area at risk calculated for these runs accounts only for flooding occurring before the threshold of two 100-year storms has been reached. In every simulation this threshold is reached before 2075 and all flooding and damages after that date are avoided. Thus Table 4 shows less area flooded under BYWO than the other scenarios. Table 5 shows that the damages from the BYWO scenario are also less at $5.9 billion. After adding the BYWO adaptation costs of

Table 5 Costs of SLR scenarios (million dollar)

	Model run	Residential	Commercial/ industrial	Emergency	Adaptation	Total
1	Baseline—no growth, one event	1,087	4,023	869	0	5,979
2	Baseline—no growth, three events	1,452	5,354	1,157	0	7,963
3	Baseline—growth, one event	1,205	4,305	937	0	6,447
4	Baseline—growth, three events	1,616	5,735	1,250	0	8,601
5	Ride-It-Out—0.6 m SLR, one event	3,563	13,525	2,905	0	19,993
6	Build-Your-Way-Out—0.6 m SLR, one event	1,091	3,984	863	3,462	9,400
7	Green—0.6 m SLR, one event	756	2,697	587	1,766	5,806
8	Retreat—0.6 m SLR, one event	5,093	9,142	2,420	500	17,155
9	Ride-It-Out—0.6 m SLR, three events	7,993	29,776	6,421	0	44,190
10	Build-Your-Way-Out—0.6 m SLR, three events	1,924	6,925	1,504	3,462	13,815
11	Green—0.6 m SLR, three events	1,649	5,945	1,291	3,391	12,276
12	Retreat—0.6 m SLR, three events	5,164	9,244	2,449	646	17,503
13	Ride-It-Out—1 m SLR, one event	6,131	25,014	5,295	0	36,440
14	Build-Your-Way-Out—1 m SLR, one event	969	3,613	779	3,462	8,823
15	Green—1 m SLR, one event	1,268	4,959	1,059	2,897	10,183
16	Retreat—1 m SLR, one event	5,564	9,632	2,583	546	18,325
17	Ride-It-Out—1 m SLR, three events	16,140	64,250	13,666	0	94,056
18	Build-Your-Way-Out—1 m SLR, three events	1,820	6,703	1,449	3,462	13,434
19	Green—1 m SLR, three events	3,272	12,760	2,726	6,798	25,556
20	Retreat—1 m SLR, three events	5,651	9,632	2,598	558	18,439

$3.5 billion, total BYWO cost is $9.4 billion, which is considerably less than RIO. As described earlier, however, the environmental costs are much greater, particularly in the lesser developed coastal areas. Figure 5 shows the average annual damage costs under BYWO (scenario 6). The average time when the protection structures is built is 2053 at a cost of approximately $3.5 billion. Average damages persist beyond that date because in some BYWO scenarios runs structures are built after 2053.

Based on engineering cost assessments by Weggel et al. (1989) and Leatherman (1989), a report to Congress by the US Environmental Protection Agency presented a cumulative nationwide construction cost of ‘holding back the sea” in 1986 dollars of $32–$43 billion under a 0.50 m SLR scenario (Titus and Greene 1989). Factoring in land and other costs, those authors later revised their estimate to $128–$232 billion (Titus et al. (1991). The equivalent CLIMB scenarios are the BYWO ones. The adaptation costs are the same for each BYWO scenario, approximately $3.5 billion (2,000 dollars). A comparison of costs indicate that the CLIMB estimates for protection are reasonable.

Under the Green adaptation scenario, all growth in the current 100 and 500 year floodplains must be floodproofed and current development is gradually floodproofed over time. While the cumulative areas flooded are approximately the same as RIO because there is no flood protection, the damages are considerably less than RIO because of the additional floodproofing; damages decrease from $20 billion to $4.0 billion. This requires an expenditure of $1.8 billion for floodproofing of existing residential, commercial, and

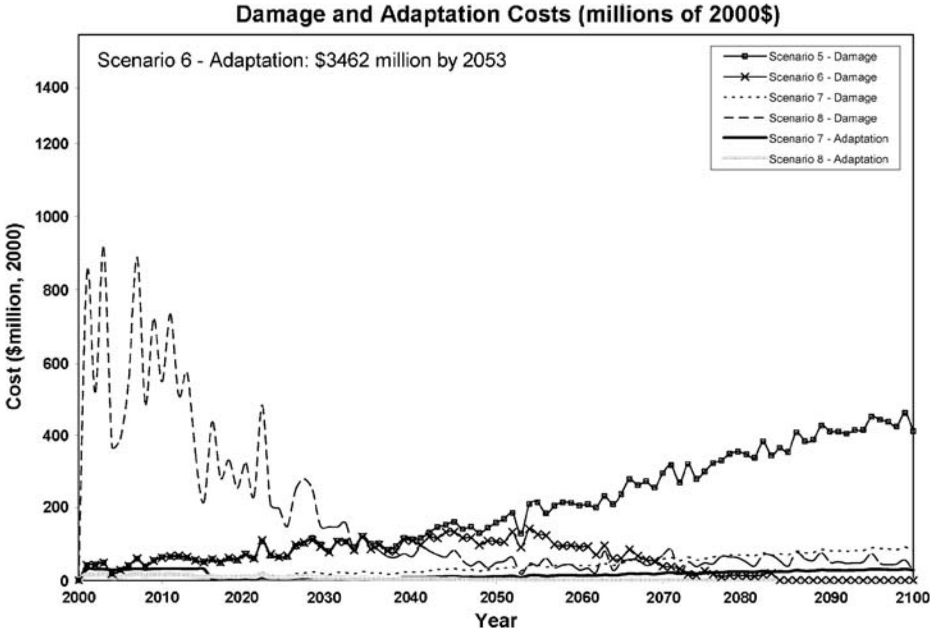

Fig. 5 Damage and adaptation costs, scenarios 5–8

industrial structures or a total damage and adaptation cost of $5.8 billion. While the area flooded under Green is greater than under BYWO, Table 5 shows that the damage and adaptation costs are less than BYWO so that the total cost of Green adaptation is less than both RIO and BYWO. This is also the case in the areal distribution of the cost impacts in the four of the five CLIMB zones. The exception is zone 1 (South Coastal Urban, mainly the City of Boston) where the total costs differences are small between BYWO and GREEN; $2.3 billion versus $2.6 billion. This is because while the flood damages under BYWO are greater (due to high concentration of expensive buildings getting flooded several times before action is taken), the adaptation costs are considerably lower since it is less expensive to structurally protect a small area of the coast compared to flood proofing many individual structures in the Green approach. Figure 5 shows that for the Green scenario (scenario 7), adaptation costs significantly decrease after 2015, when all existing residential structures in the present 100 and 500 year floodplains have been floodproofed. The adaptation costs that persist beyond 2015 are due to floodproofing of industrial and commercial properties as they are flooded. The costs of damages in the Green Scenario have a slight gradual increase over time after 2020 because, as stated earlier, retroactive flood proofing only protects against 80% of flood damages.

The 'Retreat' scenario assumes that no more residential or commercial and industrial development is allowed in floodplain and that no rebuilding after flooded is permitted. While this scenario is more environmentally sensitive than the previous 'Green' scenario, we use the name 'Retreat' here to make it clear that in the terminology of SLR adaptation, this is Retreat. As shown in Fig. 5, the costs of this retreat scenario initially are very high because of the abandonment of coastal building and land as flooding first occurs; property owners are losing their investments. The residential damage costs are higher under Retreat than other scenarios because society losses 50% of the building and land value, not just the partial value of the building and contents due to flooding. Therefore, for example, even with repetitive damages under RIO, the aggregate damages remain slightly less under RIO compared to Retreat. Adaptation costs for this scenario are the costs of demolition and removal and are low compared to the abandonment costs. As shown in Table 4, the total area flooded over 2000 to 2100 is approximately equal to the RIO and Green scenarios. The total costs are very high (Table 5, $17.1 billion) because of the high value of the abandoned land and buildings in the coastal region. This scenario does, however, have the least environmental impacts of other scenarios, and as land is abandoned it may revert back to such natural systems as wetlands and beaches.

Three annual damage events and/or 1.0 m relative SLR When climate change damage was calculated using three events (that is, rapid complete rebuilding between events so that the three largest events of each year can cause damage) or 1 m of or severe SLR, damages resulting from the RIO scenario approximately doubled compared to RIO with moderate SLR and one annual damaging event. If both occurred, then total damages increased more than 4 times compared to the initial RIO scenario. Under these most extreme conditions the damage totals $94 billion over the 100 year period (Table 5). In all these cases, the total costs of RIO are considerably greater than BYWO, Green or Retreat. Under BYWO, area flooded approximately doubled with three annual flood events. There, however, were slightly less flooded area and damages with 1 m of SLR than with moderate SLR because of the protection is built sooner under the 1.0 m SLR scenario. Under the worst case of severe SLR and three flood events, the total damages and adaptation cost of BYWO increase to $13.4 billion compared to the situation of moderate SLR and one annual event of $9.4 billion. Under these conditions, BYWO is the least expensive option, excluding environmental and maintenance costs, because protection is provided early in the century. Green damages and total adaptation costs also increase compared to the initial Green scenario under separate and combined increases in annual flood events and SLR. Under the worst case of severe SLR and three flood events, the total damages and adaptation cost of Green increase to $25.5 billion compared to the situation of moderate SLR and one annual event of $5.8 billion. The Retreat Scenario becomes relatively more attractive under conditions of more flooding events and/or higher SLR. In all these cases, the total costs of retreat are generally the same as the scenario of moderate SLR and damage from only one event per year. This is because actions are taken after the first flood event that occurs.

Figures 6, 7, 8 show the time series of costs of these scenarios. As can be seen by comparing, for example, Figures 5 and 7, the damages with 1.0 m of SLR occur sooner than in the scenarios with 0.6 m of SLR because properties are flooded earlier in the century.

Distribution of costs In the scenario of three annual damaging events and moderate sea level rise, the total costs of BYWO and Green are similar in all zones except zone 4 (South Coastal Suburban) where the cost of BYWO is approximately $1.4 billion higher. Here the cost of structurally protecting a long coastline that is not densely developed is not cost-effective compared to floodproofing. The results of 1 m of SLR in all zones with and without three annual damaging events are in Table 6. In the case of 1.0 m of SLR and one annual damaging event, in most zones the total costs of BYWO are less than or approximately equal to the total costs of Green. The major difference between BYWO and Green is the decrease in damage costs of zone 1 (mainly the City of Boston) under BYWO. Adaptation costs are also less in this region because a large amount of expensive property can be protected with a relatively short length of coastal protection. Retreat remains

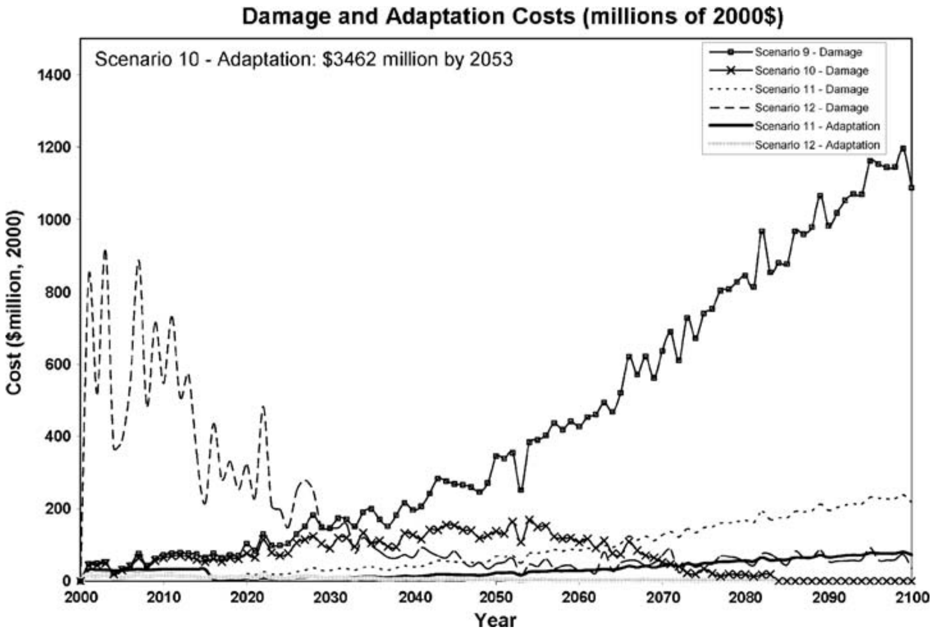

Fig. 6 Damage and adaptation costs, scenarios 9–12

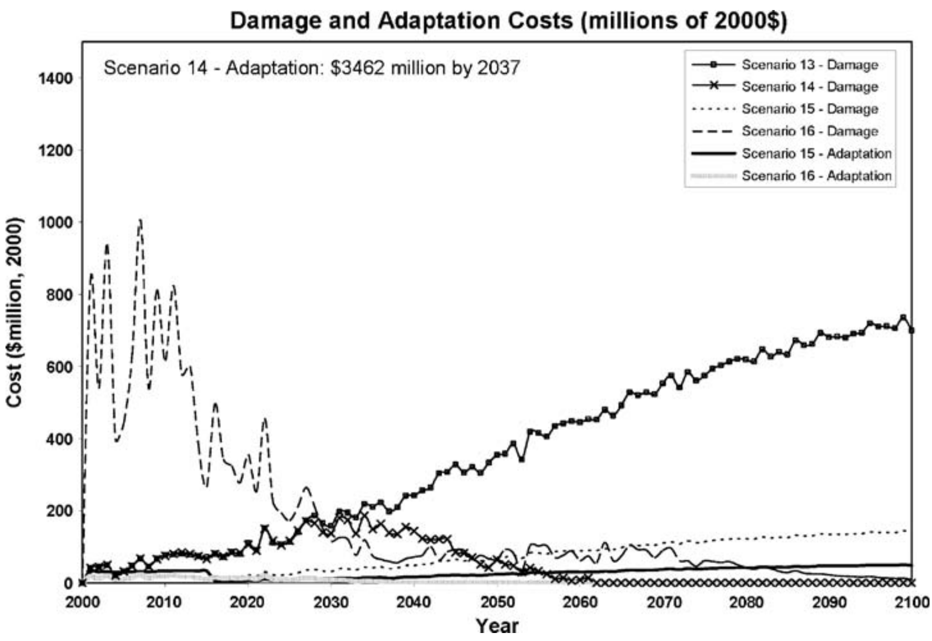

Fig. 7 Damage and adaptation costs, scenarios 13–16

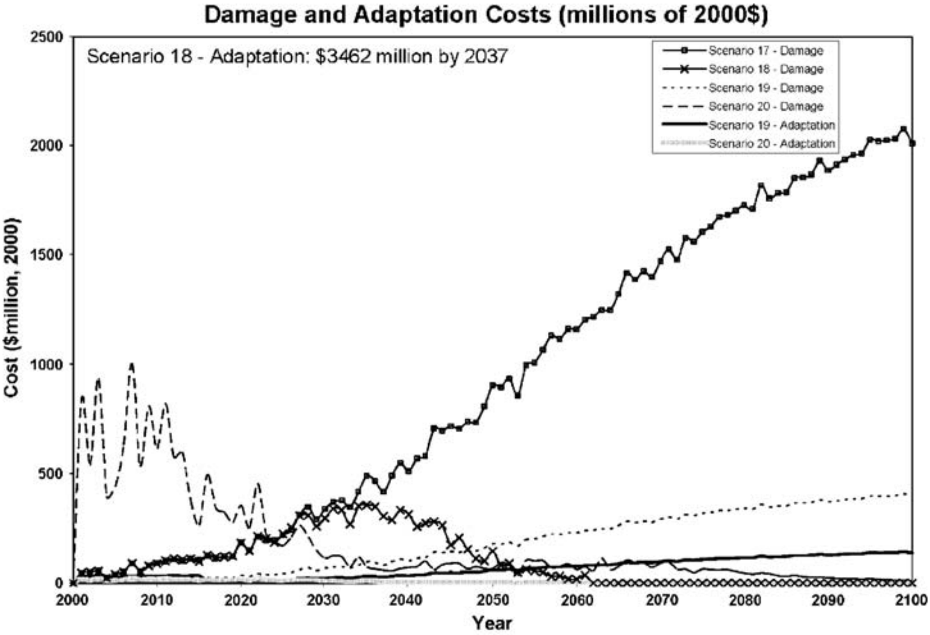

Fig. 8 Damage and adaptation costs, scenarios 17–20

expensive in all zones but particularly in zone 1 because of the high value of property. BYWO costs in zone 4 (South Coastal Suburban) remain higher than Green because, as in the case of moderate SLR and three damaging events, the cost of structurally protecting a long coastline that is not densely developed is not cost-effective compared to floodproofing. In the most extreme case of 1.0 m of SLR and three annual damaging events, Table 6 shows that in all zones the total costs of BYWO are less than or approximately equal to the total costs of Green Adaptation.

These findings are, of course, based upon the assumptions of the scenarios. Two major assumptions that may particularly influence the results are the neglect of the maintenance costs of seawalls and their environmental impacts and the estimate of values of land and buildings lost under the Retreat scenario.

7 Conclusions

Depending upon the rate of SLR, how quickly property owners rebuild after storms, and the adaptation scenario employed, the cumulative 2000 to 2100 damage and adaptation costs of coastal flooding in metro Boston range from approximately $6 billion to $94 billion. The cumulative costs for the present flood management strategy over that period but with subsidence only, no eustatic SLR, is approximately $6 billion to $9 billion. The costs do not include operation and maintenance costs, environmental costs or the distribution of costs among different socioeconomic groups. The costs will differ based upon discount rates and possible changes in values of property as society becomes more aware of possible SLR impacts. We did not discount any costs and assumed no changes in market values.

Table 6 Costs of SLR scenarios (million dollars) by CLIMB zone

	Residential	Commercial/industrial	Emergency	Adaptation	Total
Run 14		Build-Your-Way-Out—1 m SLR, one event			
Zone 1	236	1,496	294	391	2,417
Zone 2	229	808	176	502	1,715
Zone 3	75	650	123	1,041	1,889
Zone 4	396	494	151	1,266	2,307
Zone 5	33	165	34	263	495
		Total			8,823
Run 15		Green—1 m SLR, one event			
Zone 1	307	2,243	434	1,276	4,260
Zone 2	312	1,034	229	633	2,208
Zone 3	101	953	179	499	1,732
Zone 4	500	490	168	360	1,518
Zone 5	48	239	49	130	466
		Total			10,184
Run 16		Retreat—1 m SLR, one event			
Zone 1	2,265	6,320	1,459	208	10,252
Zone 2	1,502	1,564	521	147	3,734
Zone 3	304	958	215	45	1,522
Zone 4	1,344	454	306	126	2,230
Zone 5	149	336	82	20	587
		Total			18,325
Run 18		Build-Your-Way-Out—1 m SLR, three events			
Zone 1	442	2,754	543	391	4,130
Zone 2	428	1,512	330	502	2,772
Zone 3	141	1,197	228	1,041	2,607
Zone 4	747	939	287	1,266	3,239
Zone 5	61	301	62	263	687
		Total			13,435
Run 19		Green—1 m SLR, three events			
Zone 1	788	5,676	1,099	2,992	10,555
Zone 2	802	2,723	599	1,478	5,602
Zone 3	257	2,456	461	1,250	4,424
Zone 4	1,303	1,300	442	765	3,810
Zone 5	122	605	124	313	1,164
		Total			25,555
Run 20		Retreat—1 m SLR, three events			
Zone 1	2,312	6,320	1,467	211	10,311
Zone 2	1,526	1,564	525	148	3,764
Zone 3	311	958	215	45	1,529
Zone 4	1,348	454	307	133	2,243
Zone 5	154	336	83	21	594
		Total			18,438

Our findings on adaptation to increased storm surge impacts support those of others; it is advantageous to use expensive structural protection in areas that are highly developed and take a less structural approach in less developed areas and/or environmentally sensitive areas (Titus et al. 1991, Darwin and Tol 2001, Yohe 2000, Neumann et al. 2000). Besides being more cost effective, the less structural approaches are no-regrets or co-benefit policies, are environmentally benign, and allow more flexibility to respond to future uncertain changes. While uncertainty in the expected rate of SLR and damages makes planning difficult, the results also show that no matter what the climate change scenario or the location, not taking action is the worst response as in our Ride It Out scenario.

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