Climatic Change (2020) 162:445–464
https://doi.org/10.1007/s10584-020-02781-8

Integrated assessment of storm surge barrier systems under present and future climates and comparison to alternatives: a case study of Boston, USA

Paul Kirshen[1] · Mark Borrelli[1] · Jarrett Byrnes[1] · Robert Chen[1] · Lucy Lockwood[1] · Chris Watson[1] · Kimberly Starbuck[1] · Jack Wiggin[1] · Allison Novelly[1] · Kristin Uiterwyk[1] · Kelli Thurson[2] · Brett McMann[3] · Carly Foster[2] · Heather Sprague[2] · Hugh J. Roberts[3] · Kirk Bosma[4] · Di Jin[5] · Rebecca Herst[6]

Received: 19 February 2019 / Accepted: 25 June 2020 / Published online: 13 July 2020

Abstract
Large-scale barriers are a management option for present and increasing coastal storm flooding. The barriers have gates that are open most times except during storms. As an example of the assessment process for a barrier, an integrated assessment of two barrier options for the coastal city of Boston, located in the northeastern USA, is presented. The assessment also included a comparison to shore-based adaptation options such as elevated walkways, playing fields, and open space. While harbor-wide barriers in Boston could manage storm coastal flooding with perhaps minimal environmental impacts and moderate impacts on harbor users such as shipping, their cost-effectiveness is low. Their operational lives are limited by a rapidly increasing annual number of gate closures over time as sea level rises—placing considerable mechanical stresses on them. With low potential to adapt or adjust a barrier once it is in place, there are limited opportunities to respond to the uncertainties of climate change over time. The alternative of a wide spectrum of shore-based, district-level solutions using nature-based solutions located on the waterfront, however, has the potential for high cost-effectiveness and several key advantages. These solutions have the potential to incorporate multiple levels of protection, manage storm and tidal coastal flooding, provide flexibility and adaptability, offer co-benefits, endure for long operational lifetimes, and cause minimal impacts to the environment and harbor users.

Keywords Storm surge barriers · Sea level rise · Boston · Nature-based solutions

✉ Paul Kirshen
paul.kirshen@umb.edu

Extended author information available on the last page of the article

1 Introduction

Substantial sea level rise (SLR) of 2 m or more may occur by 2100 even if global temperatures are limited to a 2 °C increase from pre-industrial conditions as agreed to in the Paris Climate Agreement. Furthermore, the increases will continue for 1000s of years (Hinkel 2018). IPCC (Wong et al. 2014) reports that in the 136 port cities with populations greater than 1 million inhabitants, 39 million people are presently exposed to the 1% flood. With 0.5 m of global mean sea level rise and socio-economic development, this number may increase in 2070 to 148 million people. The estimated total value of assets in large port cities exposed to coastal flooding is US$3000 billion in 2005, which is 5% of global GDP. By 2070 with relative SLR and increases in extreme water levels, asset exposure might be approximately 9% of global GDP.

For the coastal built environment, flood hazard stems from the occurrence of storm surges and high-energy waves (acute events) and high tides (chronic events) that are compounded by loss of land mass to subsidence, coastal erosion, increases in storm intensity, and SLR (Burks-Copes et al. 2014; Neumann et al. 2014; US Global Change Research Program 2018; US Army Corps of Engineers 2015).

In the context of protection from coastal threats as opposed to accommodation and retreat (Kirshen et al. 2012), storm surge barriers are viewed as one adaptation option to coastal storm flooding and, in fact, have been employed throughout the world with continued consideration of new sites. The possible appeal of this option for the coastal city of Boston, located in the northeastern US, is shown in Fig. 1. As can be seen, constructing a barrier across the outer harbor from the Winthrop to Hull (the outer harbor barrier, OHB) would protect the city and other municipalities from present coastal storm surge flooding and the considerably more extensive flooding that would occur with 1.5 m of relative SLR, certainly plausible in Boston by the end of the century (Douglas et al. 2016). Another reasonable option is a less extensive barrier in place of the outer harbor barrier that would be constructed only from Logan Airport to the Seaport area (the inner harbor barrier, IHB) which would only protect the inner harbor of Boston. Here, we present an integrated analysis of the feasibilities of such barrier alternatives based upon a report carried out by Kirshen et al. (2018). The URL for the report is included in the reference as supplemental material. This paper expands upon the report by placing much of its analysis and findings in the context of other current related research.

Depending on how effectively the international community is able to curb global emissions, compared with 2013, the Boston area could experience 15 to 37 cm of relative SLR by 2050, and 55 to 222 cm by 2100 (Douglas et al. 2016). Changes in the future intensity and frequency of extratropical storms are uncertain; there is more certainty, however, that the intensity of tropical storms (i.e., hurricanes) may increase. Even if the region does not see an increase in storm intensity, the storms that do occur will cause more flooding when combined with sea level rise. The biggest unknown in these projections—the reason why the ranges are so broad later in the twenty-first century—is the amount of greenhouse gas reduction that will be achieved. If the global community is able to dramatically decrease emissions of the greenhouse gases that cause climate change, the amount of SLR that Boston will experience can be constrained to the lower end of the future projections—thereby decreasing the amount of adaptation measures that will be necessary over time.

In our assessment, we focus on the technological and economic aspects. Other recent reports prepared for Boston have focused on the financing, governing, and the social equity aspects of all types of adaptation (Levy et al. 2018; Mayor's Office of Resilience and Racial

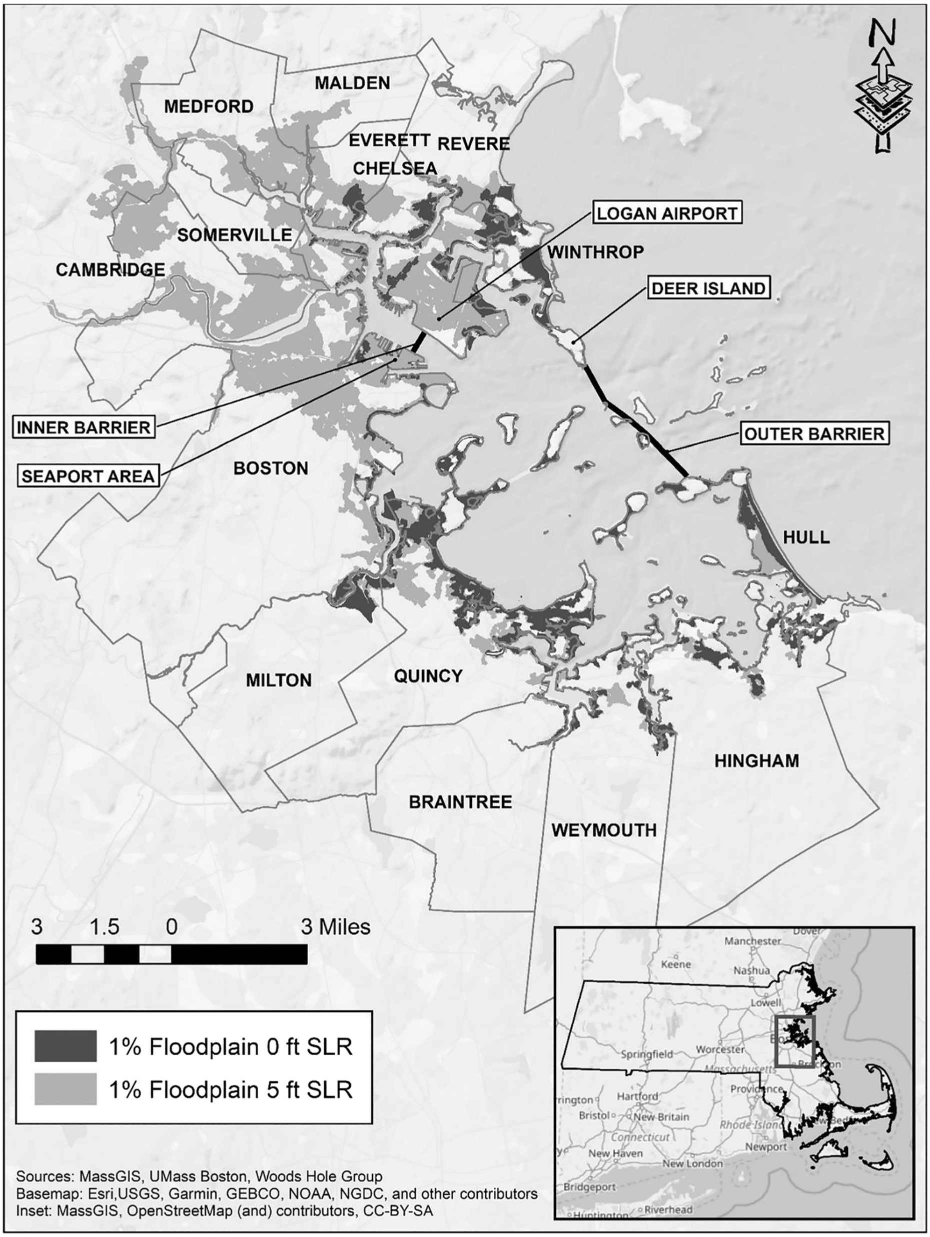

Fig. 1 Extent of the 1% coastal flood under present and future sea level conditions. From Kirshen et al. (2018). (1 ft = 0.3048 m, 5 ft = 1.524 m)

Equity 2017; Kruel et al. 2018). The technological analyses of the assessment considered here include the engineering, environmental, and operational issues. Associated economic issues consider shipping impacts and benefit-cost analysis. A comparison is also presented to a likely alternative to a harbor-wide barrier system, shore-based systems that provide resilience along the coastline. Given the limited budget for this analysis, only one pathway scenario of sea level rise and associated flooding was analyzed compared with 2013. This is approximately 30 cm of relative SLR by 2030, 91 cm by 2070, and 152 cm by 2100. For Boston, this is approximately equivalent to the IPCC RCP4.5 greenhouse gas emission scenario, which is a moderate emission scenario. As discussed in Section 7, limiting the analysis to a moderate scenario was reasonable because the research results with this scenario very strongly favor the alternative to storm barriers over the planning period. If the results were not as conclusive, a more complete scenario analysis would have been conducted.

This analysis assumes that the guiding principles for any coastal protection system in Boston are not only to provide flood protection from storm surges and high tides to Boston and neighboring cities and towns in Boston Harbor, but also to maintain present and future commercial shipping and other navigation, and to preserve as much as possible of the present ecological services of Boston Harbor in light of climate change. Commercial and recreational navigation is critical to Boston’s historical identity as a maritime city and its current economy. Likewise, hard-won environmental improvements in Boston Harbor over the past few decades have provided great benefits to the city and its natural resources.

The analysis of Kirshen et al. (2018) included a summary of the impacts of the barriers on vulnerable populations and is not presented here. It was found that the proportions of the socially vulnerable population compared with the general population now and then that protected from future flooding did not change with either barrier option.

2 Engineering analysis

Accelerated coastal development and the prospect of increased SLR have generated interest worldwide in the building of large-scale storm surge barriers to protect vulnerable coastal cities and populations. To date, however, only fifteen such storm surge barrier projects have been undertaken, most as part of the Delta Works project in the Netherlands (Mooyaart 2014). Other notable storm surge barriers have been built in the Thames River in the UK; St. Petersburg, Russia; the Ems and Eider Rivers in Germany; the MOSE project in Venice, Italy (not fully operational yet); and New Orleans, LA, New Bedford, MA, Stamford CT, and Providence, RI, in the USA. There are also several other notable large flood protection barrier and gate systems in early design or feasibility investigation stages. Examples include for the upper Texas coast (Gulf Coast Community Protection and Recovery District 2018), Bayou Chene in Louisiana (Office of the Louisana Governor 2019), and for New York and New Jersey (Aerts et al. 2013; United States Army Corps of Engineers 2019). The research tends to agree that major gates or barriers at strategic locations of the mouths of large estuaries can reduce the overall amount of ancillary interventions required around the perimeter of the estuary to protect against storm events (Jonkman et al. 2013).

Outer harbor barrier As shown in Fig. 2, the OHB would be a gated system that would only be closed during flood conditions caused by storm surge. This would have a minimal impact on maintaining Boston as a major shipping hub as well as minimize the environmental impacts of a more restrictive design if operated as intended. The in-water portion of the barrier from Winthrop to Hull would cover 6.1 km with an additional 15 km of shore-based protection in Hull, Winthrop, and Revere to prevent floods from flanking the barrier from the ocean. This alignment would enable relatively shallow water placement for large reaches of the barrier and would benefit from the presence of an island (Lovells Island). Reaches in deep water (depth greater than 1.5 m) were assumed to consist of concrete caisson sections which would either be constructed in place or floated to position, then sunk in place. The cap or top of the caisson could be designed in such a way that it could be expanded vertically or enhanced with green elements to protect from rising seas in the future. Several vertical lift gates across the top of the barrier will be required for water quality and minor local velocity considerations.

The northern gate would serve the major shipping channel in Boston Harbor (President Roads) and would be composed of a floating sector gate 457 m long; the length requested by the local district office of the US Army Corps of Engineers. A second floating sector gate to the south of 198 m would serve the secondary channel into Boston Harbor (Nantasket Roads). Floating sector gates are the most appropriate option for this type of barrier system because of the vast opening span in the horizontal and vertical directions (both below and above water) required for navigation and tidal exchange regulation (Dierke et al. 2012). Presently, only a few gates in the world are of this magnitude, namely the 366-m Maeslant Barrier in Rotterdam,

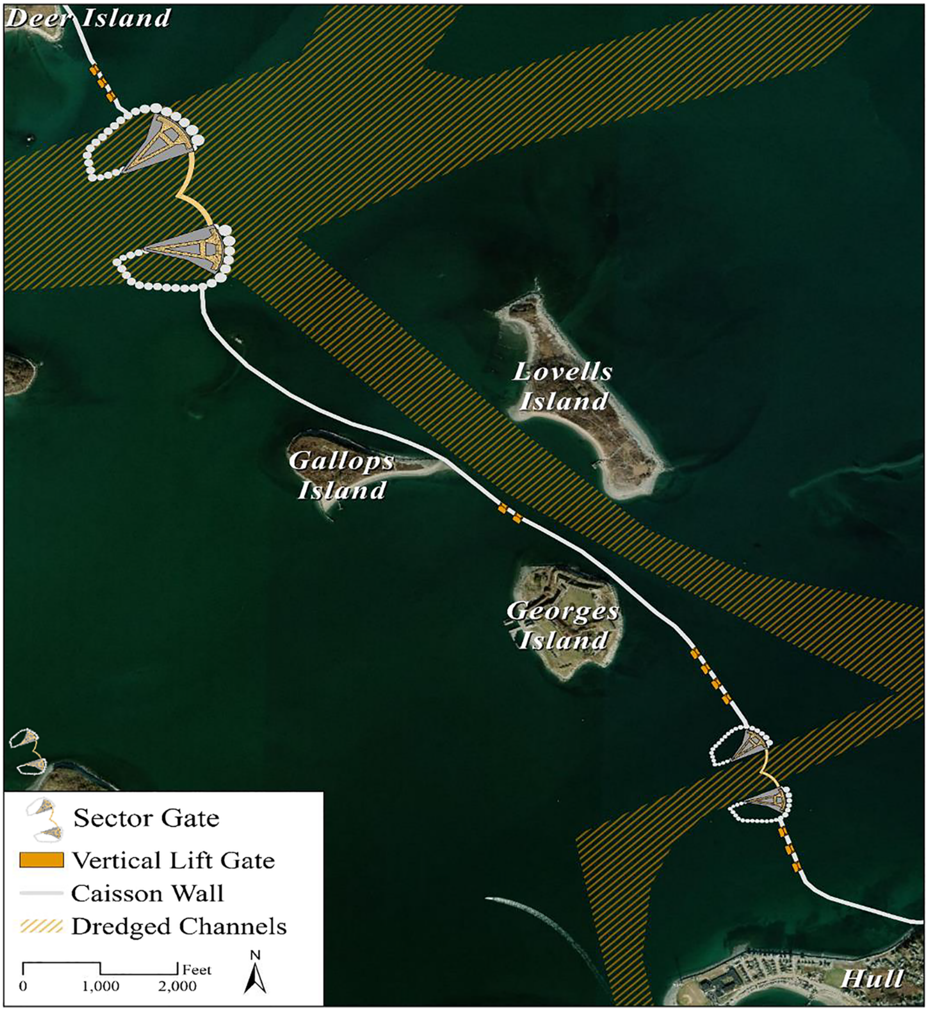

Fig. 2 Outer harbor barrier configuration. (1 ft = 0.3048 m). From Kirshen et al. (2018)

the Netherlands, and the 198-m sector gate component of the St. Petersburg Barrier in St. Petersburg, Russia. Similarly sized gates are proposed for Galveston and New York but are in early feasibility stages.

The conceptual design did not explicitly include wave forces. The type of wall proposed (sinkable caissons), however, was selected to have the ability to resist large waves, and there are examples of other projects with similar features in high-energy environments (e.g., Shen et al. 2009; Huntsman 2011). Inside of the OHB, the remaining fetch of greater than 8 km prior to land could, in part, negates wave protective properties of the barrier at the inner harbor shoreline as waves would have enough fetch to regenerate.

The elevation of the in-water portion elevation of the OHB would be 8.2 m above the North American Vertical Datum of 1988 (NAVD88, approximately the present mean sea level in Boston) and designed to manage the 1% storm surge with 2.13 m of SLR since 2013. This is the high end of the range of likely probabilistic rates of SLR for 2100 for RCP8.5 (Douglas et al. 2016). The probabilities of present and future flood events throughout Boston Harbor were from the hydrodynamic model and storm analyses described in Section 3.

Using existing data from plans for recently constructed or proposed projects, the total 2017 cost of the OHB ranges from \$8.0 to \$11.8 billion dollars with the cost of the two gates ranging from 64 to 70% of the total costs (see Table 4.2 in Kirshen et al. 2018). Costs for mitigation activities for damages to sensitive habitats and land rights are not included. Annual operation and maintenance costs are estimated to be 0.8% (see Table 4.3 in Kirshen et al. 2018).

Inner harbor barrier The IHB, as shown in Fig. 1, from Logan Airport to the Seaport area would be a 457-m gated barrier system that would only be closed during flood conditions caused by storm surge. It would require an additional approximately 29 km of shore-based protection systems to its north and south. This configuration assumes that the barrier and shore-based system could be compatible with Logan Airport operations. The elevation of the barrier crest would be 6.7 m NAVD88.

One added complexity of the IHB would be the pumps to adequately control upstream water levels from the Charles and Mystic Rivers during times when the barrier is closed. Because these gates are designed to be closed during the total duration of an event which could be as long as 72 h or more for an extratropical storm, large amounts of upstream water could accumulate behind the inner barrier. An analysis of this situation was carried out to estimate the possible size of pumps needed. Full details are on pages 43–44 of Kirshen et al. 2018.

Construction costs range from \$6.5 billion to \$8.7 billion (2017) with annual operation and maintenance costs of 1% (see Tables 4.5 and 4.6 in Kirshen et al. 2018). In both low and high cost ranges, the cost of the gates was 57% of the total costs. As in the case of the OHB, right of way and mitigation costs were not included.

Large infrastructure systems such as the proposed can take a decade or more to permit. Construction could take over one decade. Adding to this design and financing times, it is expected neither barrier could be built before 30 years from the present or 2050.

3 Hydrodynamic and closure analysis

The 2-dimensional, finite element, dynamic Boston Harbor Flood Risk Model (BH-FRM) was used to determine hydrodynamic conditions with and without harbor-wide barriers. BH-FRM is an enhanced version of the ADvanced CIRCulation model (ADCIRC, http://adcirc.org). The application of this model included not only the impacts of higher sea levels but also future changes in the frequencies and intensities of tropical and extratropical storms as described in detail in Bosma et al. (2015). Chapter 5 of Kirshen et al. (2018) describes the following analyses in detail.

Tidal attenuation and circulation changes Because the barrier openings are very large for the required vessel navigation, the modeling indicated that there is insignificant attenuation of the 3-m tidal range in either the OHB or the IHB. If attenuation occurred, it would be possible to protect the waterfront from tidal flooding (and perhaps moderate storm surge) without even closing the gates. Thus, a barrier would not protect Boston Harbor from nuisance tidal flooding associated with sea level rise without closure of the gates.

Since there is no significant tidal attenuation, the quantity of water entering and leaving the harbor during tide conditions would not change. The openings through which the water would flow, however, would be much smaller than without a barrier. As a result, significant changes in current velocities in the vicinities of the OHB gates openings are expected. At normal flood tide, the peak velocity through the northern gate could increase from approximately 0.6 to 1.5 m/s (1.2 knots to 3 knots). For the southern gate, the peak velocity could increase from approximately 0.6 to 2.4 m/s (1.2 knots to 4.8 knots). These high velocities would make navigation challenging for certain vessels. Therefore, it is unlikely that entry and exit into the harbor would be available throughout the entire tidal cycle, especially for recreational boating with limited power. At the same time, some new zones of stagnation in the harbor are expected.

There were minimal differences in circulation dynamics outside of the OHB when the barrier was open under normal tidal conditions compared with present circulation. Changes only occurred within close proximity to the gates, where water was entrained due to increased tidal velocities. With the gates closed during storms, local circulation dynamics outside of the barrier change more significantly. In particular, the flood tidal currents with the gates closed during storms may be perpendicular to the southern coast instead of generally parallel as is the case now. This change in storm processes would need to be evaluated further to determine potential impacts on adjacent shorelines (e.g., erosion).

The IHB would have minimal impact on the tides and currents in the harbor since the gate opening is not much less than the width of the current channel.

Closure analysis These types of gates are intended to protect against low-frequency events with infrequent gate closure. For example, the Maeslant flood barrier in Rotterdam was designed for an estimated closure frequency of once in 10 years (van den Brink and de Goederen 2017). SLR could increase closure frequency to once every 3.2 years by 2050 and once every 1.1 years by 2100 (Zhong et al. 2012). The Thames Barrier in London was originally designed to be closed 2 to 3 times per year and has recently experienced a closure rate of 6 to 7 times per year (World Heritage Committee 2006). Similarly, the MOSE barrier in Venice is intended to be closed on average 10 times per year. With approximately 0.46 m of sea level rise, it would be closed once per day and with just over 0.61 m of sea level rise, it will be closed more than it is open (Goodell 2017).

Increasing rates of closure of the gates will lead to increasing rates of failure and/or operational costs to repair or prevent failures and shipping disruption, among other impacts. Furthermore, increasing rates of operation and closure will lead to increases in environmental impacts on the tidal prism and flushing regimes of the protected basins and estuaries behind either barrier.

Using the long-term historical record of tides and storms in Boston of over 90 years with the projected sea level rise scenarios over time, a forecast was developed of how many years after barrier construction (estimated to be 2050) annual gate closure would exceed 50 times (Fig. 3). This is a very high frequency (approximately once per week) compared with how often comparable systems worldwide are designed to close. The closure analysis is based on stillwater levels that include wave set-up. Wave run-up and overtopping are not included; however, in most of the internal areas of Boston Harbor, this process is small (waves even during 100-year storm events and greater are of 0.61 to 0.91 m maximum).

As shown in Fig. 3, the closure analysis found that with no additional shore-based protection compared with the present (present protection is assumed to be 3.05 m NAVD88—the approximate elevation of the present 1% storm), a barrier system implemented in 2050 (assumed to be the earliest time a barrier could be constructed) would function as designed for 30 to 40 years under moderate and high SLR scenarios. At the end of this period, it would no longer be feasible to close the barrier gate sufficiently often to prevent damages from all flooding events.

With shoreline protection to 4.3 m NAVD88 throughout Boston Harbor (which is the present approximate target design elevation of Boston for coastal resiliency) (City of Boston 2017), a barrier system would not be needed until near the end of the century because shore-based solutions would protect against both tidal and coastal flooding until then. Under moderate and high SLR scenarios, a barrier would then function as designed for approximately

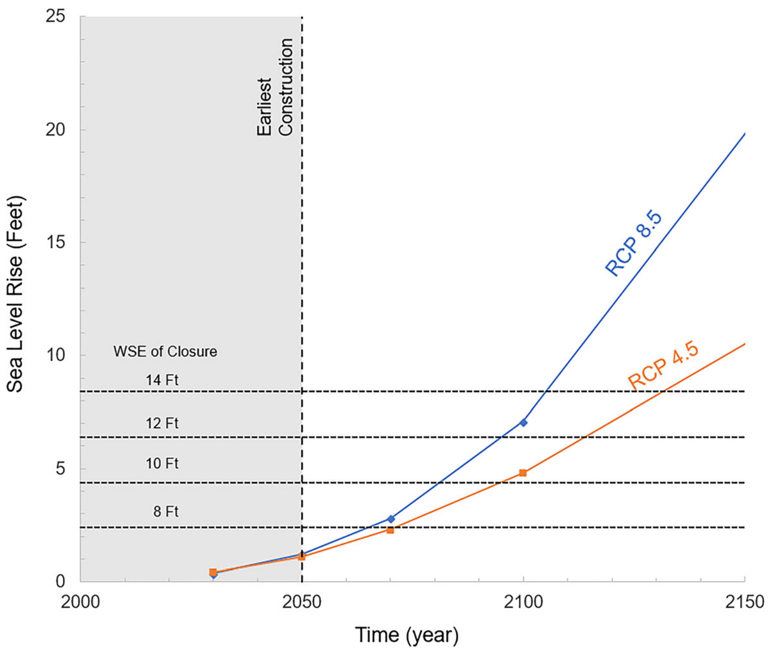

Fig. 3 Time period when closure frequency of 50/year is exceeded The outer Y-axis is the relative sea level rises over time in the X-axis for the RCP 4.5 and 8.5 emission scenarios. The inner Y-axis is the water surface elevation (WSE, NAVD88) of the flood the shoreline is designed to manage. Presently, most of the shoreline of the harbor is at approximately 10 ft NAVD88, the approximate elevation of the present 100-year flood. Thus, e.g., for RCP 8.5, the SLR increase in 2100 is approximately 7.5 ft, and with a shoreline designed to manage a flood of 14 ft NAVD88 (dashed line), by 2105, the gate will be closing over 50 times per year (1 ft = 0.3048 m)

25 to 40 years. If the closures were limited to 25 years or less instead of 50, the design lives would be less by approximately 5 years. As can be seen, the results of the closure analysis are independent of the elevation of the type of opening-barrier system proposed; the increase in the frequency of closure over time depends upon the rate of SLR and the elevation of the shoreline to be protected. At the end of these periods, a barrier could still be used to lessen the impacts of the increasing number of storm tides, but not eliminate them as before. Several options that could be investigated separately or in combination are increasing the elevation of shoreline protection, letting some areas flood, retreating, protecting individual assets, and implementing a storm surge forecasting system to allow operation of the gate system for larger storms with the additional level of risk due to the uncertainty of storm forecasting. The gate system could also be converted to a lock system with associated negative impacts on water quality and shipping and boating compared with a storm barrier.

4 Environmental impacts

Understanding of the engineering and hydrodynamic considerations of storm surge barriers has advanced well ahead of the understanding of the environmental impacts of such structures, particularly their impacts over time and on a regional, ecological scale. This is a new, emerging area of research worldwide (De Vriend et al. 2011; Tuin et al. 2017). While multiple studies have been conducted on the environmental impacts of the Netherlands Delta Works project (e.g., Bakker et al. 1994; Van der Tol and Scholten 1997; Reise 2005; Eelkema et al. 2011; Troost and Ysebaert 2011; Eelkema et al. 2012; Eelkema et al. 2013; Van Wesenbeeck et al. 2014; Ysebaert et al. 2016) and some on the New Orleans delta barriers (Costanza et al. 2006; Van Ledden et al. 2012), few such studies exist for large system-wide barriers, and none to date for the St. Petersburg barrier. Research on the effects of storm surge protection barriers on river deltas is useful in considering potential impacts of a barrier in Boston; however, the geology, habitats, and hydrology of Boston Harbor differ considerably from that of the coastal Netherlands or New Orleans area, which limits the transferability of the results.

Due to budget and time constraints, the environmental assessment of the proposed barrier systems was qualitative. It is based on general concepts and logical relationships, the knowledge of this specific system drawn from experts familiar with various aspects of it, and the hydrodynamic modeling of present and future SLR conditions in the previous section. The authors of this paper determined which factors to consider and qualitatively ranked them under each scenario with a scale of 1–5 (1, very bad; 2, poor; 3, fair; 4, good; 5, excellent) as shown in Figs. 4, 5, and 6. These scores were shared with the Advisory Committee of approximately 30 individuals from a wide variety of backgrounds and experience, and adjusted after discussion if necessary. A key factor in assessing the environmental impacts of a storm surge barrier in Boston Harbor is that major environmental changes would be taking place independent of barrier construction due to climate change. Warming water and air temperatures (IPCC 2013), changes in precipitation (Feng 2017; Prein et al. 2017), and rising sea levels (Chen et al. 2017; Sweet et al. 2017; Douglas et al. 2016) will have a significant impact on Boston Harbor ecosystems regardless of barrier construction.

Environmental impacts of the IHB and the OHB were considered under present conditions and in 2100 with 1.5 m of SLR. Because of the tidal attenuation finding mentioned above, it was assumed that the presence of either barrier would not affect the tidal range in the Harbor, and that the barriers would be closed for 46 to 84 h during an extratropical storm to reduce storm surge—less during a hurricane—and that the barriers would be closed no more than a few times per year.

Environmental considerations were grouped into impacts on water quality, habitat quality, and ecosystem services. Impacts were comparatively assessed under conditions of the present climate, and then 1.5 m (5 ft) of SLR with increased water temperature, with and without a barrier. The results are displayed in the radar diagrams in Figs. 4, 5, and 6.

The OHB analysis yielded the following findings:

- Water quality would degrade slightly with a barrier due to lower flushing rates.
- Habitat quality impacts would be mixed. For example, salt marshes might receive some benefit from a barrier as erosion during storms is reduced, while other habitats might degrade.
- Ecosystem service impacts would be mixed. Fishery ratings would generally decrease under future conditions with and without a barrier, but carbon storage and shoreline use could actually increase in the presence of a barrier, depending on its installation and specifications.

Overall, the preliminary, qualitative assessment found that the environmental impacts of an OHB would be measurable, but minor. The overall changes to the system are likely less than the changes expected due to sea level rise and to estimated increases in sea surface temperature regardless of a barrier.

The analysis found that the installation of an IHB would likely have very minor if immeasurable impacts on environmental conditions except when the barrier is closed for 46 to 84 h during a storm. When this happens, the high freshwater discharge from accompanying precipitation coming out of the Charles and Mystic Rivers over their respective dams would sit

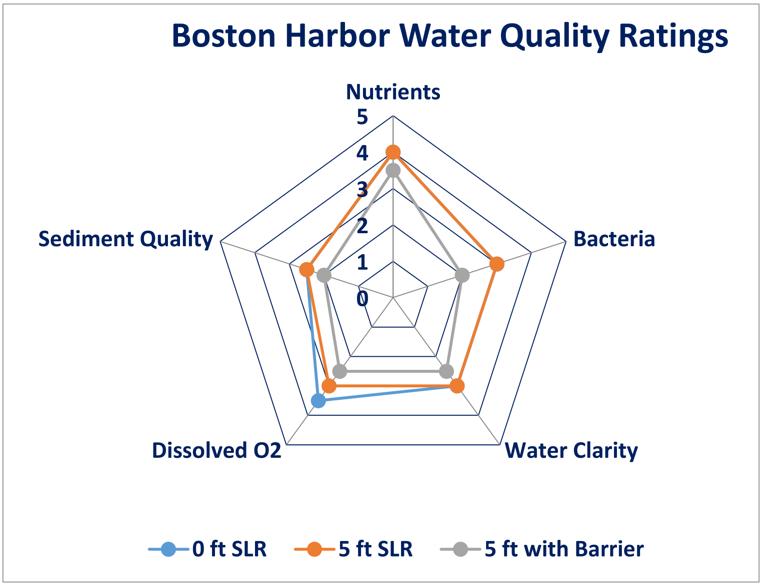

Fig. 4 Boston Harbor water quality ratings currently (0 m SLR), in the future with 1.5 m SLR, and in the future with 1.5 m SLR and an outer harbor barrier. From Kirshen et al. (2018). (1 ft = 0.3048 m)

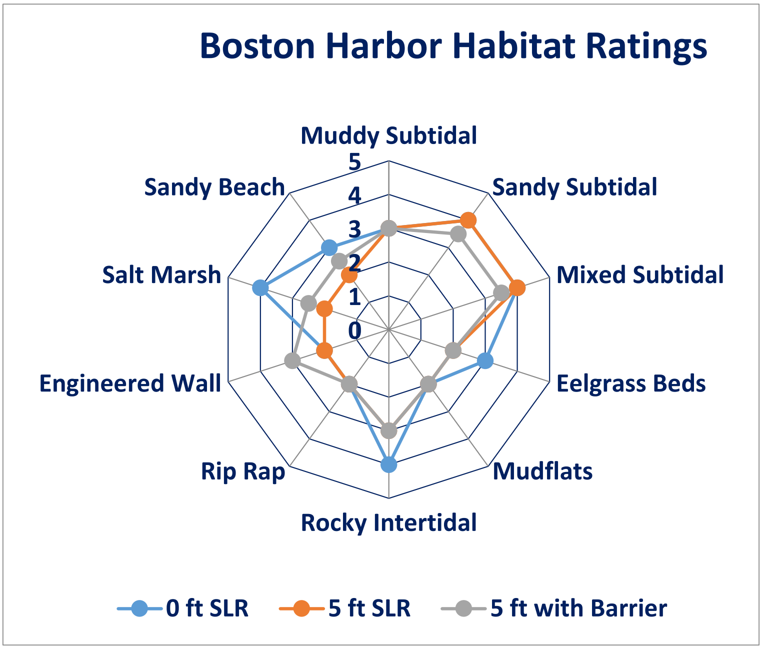

Fig. 5 Boston Harbor habitat quality ratings currently (0 ft SLR), in the future with 1.5 m SLR, and in the future with 1.5 m SLR and a barrier. From Kirshen et al. (2018). (1 ft = 0.3048 m)

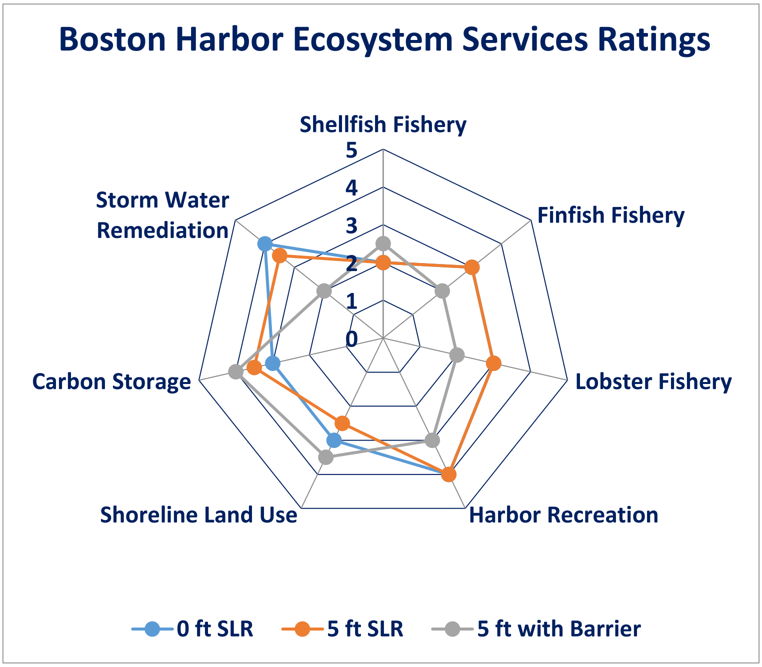

Fig. 6 Boston Harbor ecosystem service ratings currently (0 ft SLR), in the future with 1.5 m SLR, and in the future with 1.5 m SLR and an outer harbor barrier installed. From Kirshen et al. (2018). (1 ft = 0.3048 m)

on top of the seawater because freshwater is less dense than seawater. This freshwater would be contaminated with combined sewer overflow effluent and street runoff (assuming present levels of wastewater and nonpoint source pollution management) and would create a film on top of the rest of the inner harbor seawater until the barrier re-opened. Pumps installed to drain the water to prevent it from overflowing the barrier would likely have pump inlets set below this contaminated surface water and, as a result, would be unable to pump out the contamination.

There are admittedly still a number of unknowns in anticipating the impacts of installing any harbor barrier. These include the effect of trapping a contaminated freshwater lens of river discharge during storms inside a closed OHB or IHB, the effects of the open barriers on fish migration patterns, the environmental impacts of the actual construction procedures, and the exact locations of sediment relocation and current changes and subsequent impacts on the Boston Harbor Islands.

It, however, does not appear that the construction of the OHB or the IHB will cause any irreversible negative transformations of the entire harbor environment in terms of water quality, habitat quality, or ecosystem services if a barrier is only open and closed a few times per year. While there are some foreseeable impacts, most of these are modest or limited spatially or temporally. For a great part of the harbor system, 1.5 m of SLR and expected increases in sea surface temperature may cause more environmental impact than the construction of a harbor-wide barrier. The team also analyzed the change in the economic value of ecological services in Boston Harbor. This analysis showed some decrease in services due to the barrier of 2 to 3% (Jin et al. 2018).

5 Economic analysis

The economic feasibility of a harbor-wide barrier is based upon the expected value benefits and costs over its lifetime given the moderate SLR planning scenario. The expected values are estimated based upon the probabilities of the extent and depth of flooding from Monte Carlo simulation of BH-FRM, described in Section 3. Damages avoided by the barrier system are the economic benefits and were determined for Boston Harbor as a whole, not just for Boston. The damages included here are damages to buildings and contents and displacement costs for residents due to flooding. A full description of the damages considered is in Table 8.1 of Kirshen et al. (2018). Similar to the gate closure analysis, the benefit-cost analysis was done for several levels of shore-based protection implemented in different time periods with low and high estimates of project costs and discount rates. We used two scenarios of shore-based adaptation providing protection greater than the present shoreline flood protection elevation because it is unrealistic to assume that no actions will be taken over time while waiting for a barrier to be built.

The benefit-cost results are approximately the same for the inner and outer harbor-wide options. As in the case of the closure analysis, the benefits of a barrier system depend upon the elevation of shore-based adaptation. If the shore-based systems are effective in managing flooding and a barrier is designed to manage all the events greater than the elevation of the shore-based protection, the benefit-cost ratios (BCR) of any barrier system are low—ranging from 0.05 to 0.33 for 7% discount rate and from 0.20 to 1.69 for 3% discount rate. The costs do not include the costs of shore-based protection. The results indicate the low cost-effectiveness of barrier systems. More details are in Chapter 8 of Kirshen et al. (2018).

6 Shipping and recreational use analysis

As described in Section 1, one of the guiding principles of this analysis was the importance of finding a solution that would minimize the disruption of the various uses of Boston Harbor. Many commercial and recreational activities occur within Boston Harbor. This analysis determined that the proposed inner and outer barriers could have both positive and negative impacts on these activities. The proposed barriers would provide added protection to activities occurring within the harbor—including commercial shipping and fishing, and recreational boating and fishing—as they would protect shore-side infrastructure and vessels from storm turbulence and flooding.

The openings to the barriers would generally accommodate federal requirements for navigation channels, minimizing impacts to commercial vessels entering and exiting Boston Harbor (including the new post Panamax vessels). Vessels would not be able to enter or exit when the barriers are closed and would have to plan their travel in advance of closing.

The anticipated increase in water velocity in and around the barrier openings could cause navigational and safety issues for both recreational and commercial vessels near the barrier openings. Additionally, there may be vessel congestion near the openings in the OHB, especially at the northern barrier opening as its water velocity is expected to be more manageable than the southern barrier opening. The OHB could also impact the abundance, distribution, and behavior of fish populations, which would in turn impact both commercial and recreational fisheries.

7 Comparison to shore-based adaptation

While the research focused primarily on the feasibility of different harbor-wide barrier systems, a decision about whether or not to build a barrier would not be made in isolation but in comparison with other options. The analysis identified several key advantages that shore-based solutions have over a single harbor-wide barrier.

Multi-faceted options Shore-based adaptations can fall under the general categories of protection, accommodation, and retreat. As described in the City of Boston (2016), within each of these categories, a mix of different strategies exist. These include policy-level actions such as flood insurance, zoning, or managed retreat from the coast. Shore-based protection systems include traditional hardened (i.e., grey) and/or nature-based solutions (NBS, see below), augmented with temporary floodwalls that can be deployed in advance of impending floods. They can be employed at the regional scale or the individual asset scale and, if designed correctly, can provide multiple layers of effectiveness and flood risk mitigation. In addition, they can provide management of high tide nuisance flooding, which harbor-wide barriers do not. All types of coastal protection systems can be deployed as a single line of defense or as part of a tiered system extending from the sub-tidal zone through the shoreline to beyond the shoreline.

Benefits of nature-based solutions (NBS) coastal flood protection systems Some of the shortcomings of conventional coastal protection infrastructure made of concrete, stone, and other hardened systems (i.e., grey systems such as seawalls, revetments, and levees) include erosion of the systems, loss of ecosystem services, and high replacement costs as well as a relatively inflexible framework to adjust under uncertain changing climate and/or mission-needs. It may be possible to address these shortcomings by substituting or complementing conventional systems with NBS that incorporate or mimic some aspects of the environment (Bridges et al. 2015). These were initially of interest for use in ecosystem and habitat restoration but are now increasingly seen as beneficial in coastal flood risk reduction under present and future climates. In some conditions, NBS protections can adapt to climate change and rising sea levels, improve performance over time, and provide socio-economic benefits in addition to flood protection (co-benefits, Sutton-Grier et al. 2015). Examples of co-benefits include recreation, public access, open space, and urban heat island cooling. These co-benefits may be particularly important in communities suffering from environmental and social injustices if they are equitably applied (Floater et al. 2016; Kabisch et al. 2017; Shi et al. 2016; Eriksen et al. 2011; Schlegel 2018; USGCRP 2018; Magan et al. 2016).

Flexibility and adaptability It is now recognized that one method to respond to the uncertainty rates of SLR over time is to use flexible solutions that can be implemented over time using the principles of adaptive management as SLR and flooding increases, projections improve, and more is known about future socio-economic conditions. In addition, management funds can be expended as necessary (Kirshen et al. 2015; Toimil et al. 2020; Mendoza et al. 2018). The modular and multiple possibilities for shore-based solutions provide these advantages for urban coastal protection. In contrast, constructing a harbor-wide barrier would require estimating the coastal storm conditions decades ahead given the long lead-time for implementation and also large expenditures of funds before the project is operational. This may lead to over- or under-investing in flood management with possible negative consequences associated with either possibility (Rosner et al. 2014). While increasing the height of the non-moveable part of the barriers is possible over time, it is not possible to adaptively increase the height of the floating sector gates, which are the most expensive cost component.

Risk management The risk of singularly relying on a barrier for areas not covered by shoreline protection, even if technology could be developed to ameliorate the concerns around closure frequency, is that if completion is delayed or the barrier is less effective than designed, then the City and the region may be left exposed, and, in the words of Climate Ready Boston (2016), with potentially “catastrophic” results.

Higher benefit-cost ratios (BCR) As stated above, the BCRs at a 7% discount rate of harbor-wide barriers that effectively manage flooding above the level of shoreline protection range from 0.05 to 0.33.

For the same level of protection at the same discount rate (7%) and a shorter functional lifetime (20 years), City of Boston (2017) estimated a benefit-cost ratio of 3.22 to 5.3 for a shore-based flood protection system in the Greenway/Border Street area of East Boston, and a benefit-cost ratio of 4.3 to 7.9 for a shore-based protection project for the Boston neighborhood of Charlestown. These BCRs are less than most of the other neighborhoods of Boston that could be protected with shore-based strategies because the values of assets protected there are less. For example, the BCR for shore-based flood protection strategies for South Boston ranges from 8.7 to 44.9 depending upon the discount rate of 3% or 7% (City of Boston 2018). If one assumes that the cost for either of the barriers is distributed proportional to the benefits received by a municipality in Boston Harbor, the BCR for the Boston portion for the barrier will be the same as the entire barrier. Therefore, the barrier BCR for Boston is considerably less than for shore-based systems in Boston.

Similarly, the BCRs of the barriers for the other municipalities in the harbor would be the same as the entire barrier, i.e., 0.05 to 0.33. An estimate of the BCR for shore-based protection for the other municipalities in Boston Harbor besides Boston can be estimated. The value of damages avoided in the other municipalities for 1% floods for various SLR scenarios is approximately the same as for Boston with their total shorelines being approximately 3 times that of Boston (Kirshen et al. 2018). Thus, it can be assumed the BCR for the rest of Boston Harbor is approximately 33% of that of Boston as the same avoided cost benefits but costs 3 times as much (this is a conservatively higher estimate of the BCR because the construction costs for the other municipalities may be less than those in Boston). Thus, the BCR for these other municipalities may vary from one-third of 3.22 to one-third of 7.9 or 1.1 to 2.6 using the 7% discount rate. This is still more than the comparable BCR for either the IHB or OHB of 0.05 to 0.33. Therefore, shore-based adaptation approaches can be estimated to be more cost-effective for all the municipalities in Boston Harbor than either of the barrier options.

8 Additional research topics for barriers

The objective of the research was to carry out a high-level assessment of the feasibility of a barrier system for Boston and Boston Harbor. This research was sufficiently robust and inclusive that the City of Boston in October 2018 committed to managing coastal flooding with shore-based solutions, not any type of harbor-wide barrier. In addition, the results of the research were reviewed by a large set of stakeholders and external experts. Thus, sufficient research was carried out to achieve the objectives of the analysis. There are, however, some additional research topics that may be of value to others carrying out similar analyses.

- Analyses under several sea level rise scenarios. The benefit analysis was done in most cases assuming 1.5 m of SLR by 2100, essentially emission scenario RCP4.5. Given recent historical emissions, the world is currently in the higher emission scenario of RCP8.5 (USGCRP 2017).
- Engineering analyses such as (1) refinement of loaded unit price and scaled cost features, (2) impacts of a possible evolution from a flood and storm tide gate system to a lock system, (3) more examination of the risk tolerance of the stakeholders and a detailed uncertainty analysis for all the components of flood management strategies.
- Research into the greenhouse gas emissions of different flood management solutions.
- Benefit-cost additions such as (1) refined closure analysis and evaluation of residual benefits over time when a barrier cannot be closed for all surge events, (2) inclusion of other direct and indirect damages avoided by barriers to improve the estimates of their benefit to cost ratios, (3) more explicit analysis of values of co-benefits of barriers and shore-based adaptation systems and also the potential for maladaptation due to either system. As shore-based systems are implemented, a valuable database of their performance and co-benefits needs to be developed. Social impacts and equity need to be especially monitored.
- Some of the additional research that needs on the environmental effects are (1) impacts of climate change on the ecosystems in harbors, (2) impacts if any of a barrier on migrating species, (3) impacts of a day or longer freshwater cap (a freshwater layer on top of a dense saline layer that cuts off air-sea exchange and vertical mixing), which could occur during freshwater flooding with a closed barrier, on water column and benthic quality and habitat; (4)

possibilities of salt marshes being nourished to keep up with sea level rise; (5) impacts of local human adaptations to SLR and climate change on the environment both locally and within the system as a whole; (6) differences between the expected first-order impacts of a harbor-wide barrier and the potential impacts at the local level, e.g., at the 200 × 200-m scale; (7) impacts of a barrier closing approximately 50 times per year on the results of the environmental analysis; and (8) the combined impacts of climate change and a barrier system interacting in a presently unforeseeable manner than increases the impacts described here.

- The nature and presence of future shore-based solutions will vary across a study area as will the impacts of sea level rise and coastal flooding. Thus, their effectiveness and adaptive capacity must be evaluated so that they can be directly compared with harbor-wide barrier systems.
- More studies need to be conducted to determine more specifically how a barrier could impact boating and shipping occurring in a harbor, e.g., velocity changes at gate locations, and whether and how trends in commercial shipping, water transportation, recreational boating, and other uses over time might be more or less accommodating to barrier systems of various kinds.
- More analysis into the management trade-offs of a large, one-time project versus smaller short-term projects, and the funding and governance mechanisms for both harbor-wide barriers and shore-based systems

9 Conclusions

The analysis has shown that while a harbor-wide barrier system could manage storm coastal flooding with perhaps minimal environmental impacts if the barriers were to be closed no more than a few times per year and moderate impacts on harbor users, its cost-effectiveness is low and its operational life would be limited. With low potential to adapt or adjust the barrier once it is in place, there would be limited opportunities to respond to the uncertainties of climate change over time. The alternative of a wide spectrum of shore-based, district-level solutions located around the inner harbor waterfront, however, has the potential for high cost-effectiveness, and have several key advantages. With proper planning and design, these solutions have the potential to incorporate multiple levels of protection, manage both storm and tidal coastal flooding, provide flexibility and adaptability, offer co-benefits that address social justice and other issues, endure for long operational lifetimes, and cause minimal impacts to the environment and harbor users. Thus, it is reasonable that the City and other harbor municipalities focus their solution strategies in the near and mid-term on the multi-layered, shore-based approach.

Within a few decades, more will be known about the rate of sea level rise, the effectiveness of shore-based solutions, and technological advances, if any, that may improve the feasibility and cost of harbor-wide barrier systems. In the meantime, focusing on shore-based solutions will provide flood protection more quickly at less cost. These shoreline solutions will be needed in any case over the next few decades to manage coastal flooding during the design and construction period of any harbor-wide barrier if it is decided to build one in the future. Any future barrier would probably best be used to complement shore-based systems by managing the very large floods with the shore-based systems managing smaller events and helping to manage the very large events. This would limit the annual number of closures of a future barrier system. The decision regarding a barrier is very much dependent upon the future risk tolerance of the city and the performance of shore-based systems as well as other uncertainties.

Similar to Thames Estuary adaptation plan (Environment Agency 2016), the City should also monitor over time climate, environmental, economic, and social changes, and the risk tolerance of the city to determine if the feasibility of a harbor-wide barrier should be re-examined at some point in the future.

It is also reasonable for the region to continue to undertake strong greenhouse gas mitigation actions in concert with cities and nations globally to lessen the rate of climate change. Strong mitigation starting now could limit SLR by 2100 to possibly 0.70 m or less. This would greatly reduce the need for considerations of harbor-wide barrier systems in this century and early next century.

Acknowledgments This research was sponsored by the Boston Green Ribbon Commission with funding from the Barr Foundation. The results do not represent the views of particular City of Boston agencies, the sponsors of the research, or the University of Massachusetts Boston. The authors appreciate the advice of the research Steering Committee and the comments from the international review panel. Eric Holmes, Zach Stromer, Joe Famely, Alex Shaw, and Brittany Hoffnagle assisted with the hydrodynamic analysis. Emily Moothart, Courtney Humphries, and Robert Turner are acknowledged for their project support roles. The authors appreciate the helpful comments of the reviewers and editors. The full report from the research is available at https://www.umb.edu/ssl/research.

References

Aerts J, Bowman M, Botzen W, de Moel H (2013) Storm surge barriers for NYC and NJ. Annual of the New York Academy of Sciences 1294:2013

Bakker C, Herman P, Vink M (1994) A new trend in the development of the phytoplankton in the Oosterschelde SW Netherlands during and after the construction of a storm-surge barrier. Hydrobiologia 282(1):79–100

Bosma, K., Douglas, E., Kirshen, P., McArthur, K., Miller, S., and Watson, C. (2015). MassDOT-FWHA pilot project report: climate change and extreme weather vulnerability assessments and adaptation options for the Central Artery, Report to MassDOT and FWHA, June

Bridges T, Wagner P, Burks-Copes K, Bates M, Collier Z, Fischenich C, Gailani J, Leuck L, Piercy C, Rosati J, Russo E, Shafer D, Suedel B, Vuxton E, and Wamsley T (2015). Use of natural and nature-based features (NNBF) for coastal resilience, final report, US Army Corps of Engineers, Engineer Research and Development Center, January, 2015

Burks-Copes, K., Russo, E., Borne, S., et al. (2014). Risk quantification for sustaining coastal military installation assets and mission capabilities, SERDP Project RC-1701 final report, June 2014

Chen X, Zhang X, Church J, Watson C, King M, Monselesan D, Harig C (2017) The increasing rate of global mean sea level rise during 1993-2014. Nat Clim Chang 7(7):492–495

City of Boston (2016). Climate ready Boston, final report, Boston MA, December 2016

City of Boston (2017). Coastal resilience solutions for East Boston and Charlestown, Boston MA, October 2017

City of Boston. (2018). Coastal resilience solutions for South Boston, Boston MA, October 2018

Costanza R, Mitsch WJ, Day JW (2006) A new vision for New Orleans and the Mississippi delta: applying ecological economics and ecological engineering. Frontiers in Ecology and the Environment 4(9):465–472

De Vriend HJ, Wang Z, Ysebaert T, Herman P, Ding P (2011) Eco-morphological problems in the Yangtze Estuary and the Western Scheldt. Wetlands 31(6):1033–1042

Dierke PTM, Jongeling THG, Jansen PLM (2012). A global overview of navigable storm surge barriers: suitable gate types for New York for a Dutch perspective. In Storm surge barriers to protect New York City (pp. 150–169). (https://doi.org/10.1061/9780784412527.011)

Douglas E, Kirshen P, Hannigan R, Herst R, Palardy A, DeConto R, Fitzgerald D, Hay C, Hughes Z, Kemp A, Knopp R, Anderson B, Kuang Z, Ravela S, Woodruff J, Barlow M, Collins M, DeGaetano A, Schlosser C, Ganguly A, Kodra E and Ruth M (2016). Climate change and sea level rise projections for Boston, The Boston Research Advisory Group, for Climate Ready Boston, City of Boston, June 1, 2016

Eelkema, M., Wang, Z. B. and Stive, M. J. (2011). Sediment transport dynamics in response to a storm-surge barrier. The Proceedings of the Coastal Sediments 2011: In 3 Volumes, 1933–1945

Eelkema M, Wang ZB, Stive MJ (2012) Impact of back-barrier dams on the development of the ebb-tidal delta of the eastern scheldt. Journal of Coastal Research 28(6):1591–1605

Eelkema M, Wang ZB, Hibma A, Stive MJ (2013) Morphological effects of the Eastern Scheldt storm surge barrier on the ebb-tidal delta. Coast Eng J 55(03):1350010

Environment Agency. (2016). Thames Estuary 2100 (TE2100), 5 year monitoring review, United Kingdom, October 2016

Eriksen S, Aldunce P, Bahinipati C, Martins R, Molefe J, Nhemachena C, O'Brien K, Olorunfemi F, Park J, Sygna L, Ulsrud K (2011) When not every response to climate change is a good one: identifying principles for sustainable adaptation. Climate and Development 3(1):7–20. https://doi.org/10.3763/cdev.2010.0060

Feng Z (2017) Near doubling of storm rainfall. Nat Clim Chang 7:855–856

Floater, G., Heecky, C., Ulterino, M., Mackie, L., Rode, P. (2016). Co-benefits of urban climate action: a framework for cities. Economics of Green Cities Programme, London School of Economics and Political Science. https://www.c40.org/researches/c40-lse-cobenefits

Goodell, J. (2017). "Rising waters: can a massive barrier save Venice from drowning?" Yale Environment 360. Yale school of forestry and environmental studies. Retrieved from https://e360.yale.edu/features/rising-waters-can-amassive-sea-barrier-save-venice-from-drowning

Gulf Coast Community Protection and Recovery District, Storm Surge Suppression Study. (2018). Phase 4 report, November 30, 2018, http://box5735.temp.domains/~pgsqcemy/wp-content/uploads/2019/01/FORMATTED_GCCPRD-Phase-4-report-120718.pdf),

Hinkel J, Aerts J, Brown S, Jimenez J, Lincke D, Nicholls R, Scussolini P, Sanchez-Arcilla A, Vafeidis A, Addo K (2018) The ability of societies to adapt to twenty-first century sea-level rise, perspective. Nat Clim Chang 8:570–578

Holland G, Clark M (2017) Increased rainfall volume from future convective storms in the US. Change 30:80

Huntsman SR (2011). Design and construction of the Lake Borgne surge barrier in response to Hurricane Katrina. In Coastal engineering practice (2011) (pp. 117–130). https://doi.org/10.1061/41190(422)11

Jin D, Watson C, Kite-Powell H, and Kirshen P (2018). Evaluating Boston Harbor cleanup: an ecosystem valuation approach. Frontiers in Marine Science, 5 DOI: https://doi.org/10.3389/fmars.2018.00478

Jonkman SN, Hillen MM, Nicholls RJ, Kanning W, van Ledden M (2013) Costs of adapting coastal defences to sea-level rise—new estimates and their implications. Journal of Coastal Research 29(5):1212–1226

Kabisch N, Korn H, Stadler J, Bonn A (2017). Nature-based solutions to climate change adaptation in urban areas, Springer Open, DOI https://doi.org/10.1007/978-3-319-56091-5

Kirshen P, Merrill S, Slovinsky P, Richardson N (2012) Simplified method for scenario-based risk assessment adaptation planning in the coastal zone. Clim Chang 113:3–4. https://doi.org/10.1007/s10584-011-0379-z

Kirshen P, Caputo L, Vogel R, Mathisen P, Rosner A, Renaud T (2015) Adapting urban infrastructure to climate change: a drainage case study. J Water Resour Plan Manag 141(4):2015

Kirshen P, Borrelli M, Byrnes J, Chen R, Lockwood L, Watson C, Starbuck K, Wiggin J, Novelly A, Uiterwyk K, Thurson K, McMann B, Foster C, Sprague H, Roberts H, Jin D, Bosma K, Holmes E, Stromer Z, Famely J, Shaw A, Hoffnagle B and Herst R (2018). Feasibility of harbor-wide barrier systems: preliminary analysis for Boston Harbor, Sustainable Solutions Lab, University of Massachusetts Boston, May 30, 2018. (https://www.dropbox.com/s/zwznes9jin41i5k/Feasibility%20of%20Harbor-wide%20Barriers%20Report.pdf?dl=0)

Kruel, S., Herst, R., and Cash, D. (2018). Governance for a changing climate, Sustainable Solutions Laboratory, University of Massachusetts Boston, Boston MA

Levy D, Bevington Cash D, Cobleigh W, du Pont C, Kartez J, Kirshen P, Loren S, Macomber J, Markowitz J, Merrill S, Van Deveer S, Weber N, Wormser J, Herst R (2018). Financing climate resilience, mobilizing resources and incentives to protect Boston from climate risks, Sustainable Solutions Lab, University of Massachusetts, Boston, April 2018

Magan AK, Schipper E, Burkett M, Bharwani S, Burton I, Eriksen S, Gemenne F, Schaar J, Ziervogel G (2016) Addressing the risk of maladaptation to climate change. WIREs Clim Change 2016(7):646–665. https://doi.org/10.1002/wcc.409

Mayor's Office of Resilience and Racial Equity. (2017). Resilient Boston, an equitable and connected city, City of Boston, 2017

Mendoza G, Jeuken A, Matthews J, Stakhiv E, Kucharski J, Gilroy K (2018). Climate Risk Informed Decision Analysis (CRIDA), UNESCO, Paris, and International Center for Integrated Water Resources Management, Alexandria VA, 2018

Neumann J, Emanuel K, Ravela S, Ludwig L, Kirshen P, Bosma K, Martinich J (2014). Joint effects of storm surge and sea level rise on US coasts: new economic estimates of impacts, adaptation, and benefits of mitigation policy, climatic Change, December, 2014

Office of the Louisana Governor. (2019). https://gov.louisiana.gov/news/-cpra-pledges-80-million-for-permanent-floodgate-across-bayou-chene, March 27, 2019

Prein AF, Liu C, Ikeda K, Trier S, Rasmussen R (2017) Increased rainfall volume from future convective storms in the US. Change 30:80

Reise K (2005) Coast of change: habitat loss and transformations in the Wadden Sea. Helgol Mar Res 59:9–21

Rosner A, Vogel R, and Kirshen P (2014). A risk-based approach to flood management decisions in a nonstationary world, Water Resources Research, published online March 7 2014

Schlegel C (2018). Climate justice for the City of Boston: visioning policies and processes, REPORT TO the Boston City Council, . Retrieved from http://michelleforboston.com/wp-content/uploads/2018/02/CJ-Report.pdf , January 2018

Shen D, Carr C, Yavary M, Cunningham L, and Baker B (2009). Effective causeway design in severe wave conditions, Energia Costa azul Lng Terminal, Mexico. in Coastal structures 2007 (vol. 1–0, pp. 1818–1829). World scientific publishing company. https://doi.org/10.1142/9789814282024_0160

Shi L, Chu E, Anguelovski I, Aylett A, Debats J, Goh K, Schenk T, Seto K, Dodman D, Roberts D, Roberts T, and Van Deveer S (2016). Roadmap towards justice in urban climate adaptation research, Nature Climate Change, 27 January 2016

Sutton-Grier A, Wowk K, Bamford H (2015). Future of our coasts: the potential for natural and hybrid infrastructure to enhance the resilience of our coastal communities, economies and ecosystems, Environmental Science and Policy, April 2015

Sweet W, Kopp R, Weaver C, Obeysekera J, Horton R, Thieler E, and Zervas C (2017). Global and regional sea level rise scenarios for the United States, US NOAA, Silver Spring

Toimil A, Losada I, Nicholls R, Dalrymple R, Marcel J (2020) Addressing the challenges of climate change risks and adaptation in coastal areas: a review. Coast Eng 156:2020

Troost K, Ysebaert T (2011). ANT Oosterschelde:long-term trends of waders and their dependence on intertidal foraging grounds. Report Number C063/11, IMARES Wageningen UR, May 26

Tuin, H.G., Voortman, H., Bodin-Sköld, H., Andréasson, M., Schaap, G., Moback, U. (2017). Design of storm surge barriers in Gothenburg, Sweden. In Louise Wallendorf and Daniel T. Cox (Ed.), Coastal structures and solutions to coastal disasters 2015: resilient coastal communities (pp. 135–146). Reston, VA: American Society of Civil Engineers

United States Army Corps of Engineers, New York District (2019). Final report: integrated Hurricane Sandy general reevaluation report and environmental impact statement – East Rockaway Inlet to Rockaway Inlet and Jamaica Bay

USGCRP. (2017). Climate science special report: fourth national climate assessment, volume I [Wuebbles, D.J., D.W. Fahey, K.a. Hibbard, D.J. Dokken, B.C. Stewart, and T.K. Maycock (eds.)]. U.S. Global Change Research Program, Washington, DC, USA, 470 pp., doi: https://doi.org/10.7930/J0J964J6

USGCRP. (2018). Impacts, risks, and adaptation in the United States: fourth national climate assessment, volume II [Reidmiller, D.R., C.W. Avery, D.R. Easterling, K.E. Kunkel, K.L.M. Lewis, T.K. Maycock, and B.C. Stewart (eds.)]. U.S. Global Change Research Program, Washington, DC, USA, 1515 pp. doi: https://doi.org/10.7930/NCA4.2018

Van den Brink, H. W. and de Goederen, S. (2017). Recurrence intervals for the closure of the Dutch Maeslant Surge Barrier. Ocean Science, 13, 691–701

Van der Tol M, Scholten H (1997) A model analysis on the effect of decreasing nutrient loads on the biomass of benthic suspension feeders in the Oosterschelde ecosystem (SW Netherlands). Aquat Ecol 31(4):395–408

Van Ledden M, Lansen A, De Ridder H, and Edge B (2012). Reconnaissance level study Mississippi storm surge barrier. In ICCE 2012: proceedings of the 33rd international conference on coastal engineering, Santander, Spain, 1-6 July 2012

Van Wesenbeeck BK, Mulder J, Marchand M, Reed D, de Vries M, de Vriend H, Herman P (2014) Damming Deltas: a practice of the past? Towards nature-based flood defenses. Estuar Coast Shelf Sci 140:1–6

Wong PP, Losada I, Gattuso J, Hinkel J, Khattabi A, McInnes K, Saito Y, Sallenger A (2014). Coastal systems and low-lying areas in: climate change 2014: impacts, adaptation, and vulnerability. Part A: Global and sectoral aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y .O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P .R. Mastrandrea, and L.L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY , USA, pp. 361–409

World Heritage Committee (2006). Report on predicting and managing the impacts of climate change on World Heritage and Strategy to assist States Parties to implement appropriate management strategies. Document WHC-06/ 30.COM/7.1 presented to the World Heritage Committee at its 30th session, Vilnius, Lithuania, July 8–16, 2006

Ysebaert T, van der Hoek D, Wortelboer R, Wijsman J, Tangelder M, Nolte A (2016) Management options for restoring estuarine dynamics and implications for ecosystems: a quantitative approach for the Southwest Delta in the Netherlands. Ocean & Coastal Management 121:33–48

Zhong H, van Overloop P, van Gelder P, and Rijcken T (2012). Influence of a storm surge barrier's operation on the flood frequency in the Rhine Delta area. Water. 4, 10.3390/w4020474

Publisher's note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Affiliations

Paul Kirshen[1] • Mark Borrelli[1] • Jarrett Byrnes[1] • Robert Chen[1] • Lucy Lockwood[1] • Chris Watson[1] • Kimberly Starbuck[1] • Jack Wiggin[1] • Allison Novelly[1] • Kristin Uiterwyk[1] • Kelli Thurson[2] • Brett McMann[3] • Carly Foster[2] • Heather Sprague[2] • Hugh J. Roberts[3] • Kirk Bosma[4] • Di Jin[5] • Rebecca Herst[6]

[1] School for the Environment, University of Massachusetts Boston, Boston, MA 02125, USA

[2] Arcadis, White Plains, NY 10601, USA

[3] The Water Institute of the Gulf, Baton Rouge, LA 70802, USA

[4] Woods Hole Group, Bourne, MA 02532, USA

[5] Woods Hole Oceanographic Institution, Woods Hole, MA 02543, USA

[6] Sustainable Solutions Laboratory, University of Massachusetts Boston, Boston, MA 02125, USA