Adapting Urban Infrastructure to Climate Change: A Drainage Case Study

Paul Kirshen, M.ASCE[1]; Lauren Caputo, A.M.ASCE[2]; Richard M. Vogel, M.ASCE[3]; Paul Mathisen, M.ASCE[4]; Ana Rosner[5]; and Tom Renaud, A.M.ASCE[6]

Abstract: Attributes of an effective infrastructure adaptation planning process as well as methods for choosing among adaptation strategies are described. The major attributes include: (1) a vulnerability assessment, (2) proactive adaptation strategies that are implemented over time and space, (3) climate change scenario analysis including climate surprises to handle the uncertainty of the future climate, (4) actions that are robust and/or flexible and adjustable, (5) a planned, progressive approach that ties implementation to critical thresholds of actual climate changes and preserves options for future actions, (6) evaluation with multiple social, economic and environmental criteria, and (7) integration of local stakeholders into the planning process. Multiple methods can be used to generate and evaluate adaptation strategies. A subset of the key attributes is then used in a case study of urban drainage management, which was designed and implemented to illustrate these attributes. It is shown that multicriteria scenario analysis can be effectively used to generate and evaluate alternative adaptation strategies. The identification of when critical thresholds are reached under conditions of climate variability and change is a major research need. **DOI: 10.1061/(ASCE)WR.1943-5452.0000443.**

Introduction

It is generally agreed that the volumes of precipitation in extreme events will increase under conditions of a changing climate (IPCC 2012; Interagency Climate Change Adaptation Task Force 2011). Kharin et al. (2013) used frequency analysis of daily data from general circulation models (GCM) to determine changes in the amount of precipitation for the 20-year, 24-h storm. The multimodel median showed 5–10% increases by midcentury, and 10% to more than 20% increases by end of century over the continental United States under moderate climate change. With these increases in precipitation magnitude and intensity, associated increases in runoff, storm water discharges, and flooding are expected. These concerns are particularly acute in urban areas due to the extensive development and high population densities that exist in these areas. Thus, for example, it can expected that urban drainage networks designed for the conditions of the past or present climate will not function as effectively in the future as they do now. Municipalities and other stakeholders must have effective plans or processes in place to ensure that infrastructure services will be not be adversely affected by these changes, the process of adaptation.

Given the ever-increasing attention given to societal responses to climate change, there is a rapidly burgeoning literature on the development and evaluation of methods for effective adaptation planning under a variety of forms of uncertainty. This paper begins by summarizing that literature in an effort to synthesize the critical elements of an effective infrastructure adaptation planning process as well as those methods that have been advanced for developing and choosing among strategies. Next, a subset of key attributes of those approaches is selected and used in a case study. This case study is designed and implemented in such a way as to reflect many of the attributes of an effective adaptation planning process for infrastructure using drainage as an example. The paper concludes with a summary of further research needs in infrastructure adaptation planning.

[1]Research Professor, Environmental Research Group, Dept. of Civil Engineering, Institute for the Study of Earth, Oceans and Space, Univ. of New Hampshire, Durham, NH 03824 (corresponding author). E-mail: paul.kirshen@unh.edu

[2]Water Resources Engineer, ESS Group, Waltham, MA 02451. E-mail: lauren.r.caputo@gmail.com

[3]Professor, Dept. of Civil and Environmental Engineering, Tufts Univ., Medford, MA 02155. E-mail: richard.vogel@tufts.edu

[4]Associate Professor, Dept. of Civil and Environmental Engineering, Worcester Polytechnic Institute, Worcester, MA 01609. E-mail: mathisen@wpi.edu

[5]Research Associate, U.S. Geological Survey Conte Anadromous Fish Research Center, 1 Migratory Way, Turners Falls, MA 01301. E-mail: arosner@usgs.gov

[6]Environmental Engineer, Vertex Environmental Services, 1 Congress St., Boston, MA 02114. E-mail: trenaud@vertexeng.com

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Adaptation Planning

The adaptation planning process normally includes two major components: (1) completion of a vulnerability assessment, and (2) development of an adaption strategy. The vulnerability assessment provides an estimate of the degree to which a system is susceptible to and unable to cope with the effects of climate change. The vulnerability assessment typically includes an analysis of climate change exposure and sensitivity, and an evaluation of adaptive capacity, which represents the extent to which the effects of climate change can be mitigated with adaptation (Snover et al. 2007). The adaptation strategy represents a set of actions to be employed to adjust the natural or human systems to mitigate the damage or harm that would result from the anticipated changes in climate (Kiparsky et al. 2012). The remainder of this section concentrates on considerations and factors that are important in the development of an effective adaptation strategy.

It is recognized that a major challenge of proactive adaptation planning is the uncertainty of the future climate (Milly et al. 2008).

The uncertainty arises from the unknown possible future emissions of greenhouse gases (GHG) combined with additional uncertainty in the response of the climate system to the emissions. To address the range of conditions that could potentially arise given this high degree of uncertainty, a scenario approach to adaptation planning is normally undertaken (Titus et al. 2009; Dessai and Hulme 2004; Water Utility Climate Alliance 2009; Brown et al. 2011). Scenarios are internally consistent narratives of plausible future states that may evolve from present conditions, given various driving forces (Groves and Lempert 2007). Scenarios are used when reliable projections of future conditions are not available, as is recognized to be the case for climate change. The scenarios attempt to constrain the range of plausible future conditions and can be based not only on climate variables, but also on socioeconomic conditions. The scenarios can be integrated into an adaptation plan using either a top-down or bottom-up approach. The top-down approach uses scenarios of future climates with system modeling to determine the range of possible impacts at a particular site; with an understanding of these impacts, the effectiveness of individual adaptation actions are subsequently tested (USEPA 2010). In contrast, the bottom-up approach determines the critical climate sensitivities of a system and then focuses upon the possibilities of them occurring (USEPA 2010; Cromwell and McGuckin 2010; Brown et al. 2011).

Adaptation Strategies and Actions

An adaptation strategy includes a set of local and regional proactive actions that are implemented by public and private organizations over time and space to manage systems that are vulnerable to future climate and other forms of change. Three general classes of proactive adaptation strategies for urban areas or other built environments (Kirshen et al. 2008a) include:

1. Protection: construction of a barrier to lessen the impacts of the climate changes, such as a seawall to protect against more coastal flooding;
2. Accommodation: allowing the impacts to occur but attempting to lessen them by taking specific actions. Examples of accommodation actions are flood proofing, developing evacuation plans, building cooling shelters, and purchasing insurance; and
3. Retreat: moving away from the impact. Examples of retreat actions include leaving floodplains and moving to cooler climates.

Because ecosystem services are important for the functioning of some infrastructure services, analogous proactive adaptation strategies for ecosystems include (Millar et al. 2007):

- Resistance: forestalling impacts and protecting highly valued resources;
- Resilience: improving the capacity of ecosystems to return to desired conditions after disturbance; and
- Response: facilitating transition of ecosystems from current to new conditions.

The various infrastructure adaptation strategies can be classified into two categories: *here and now* actions, and *prepare and monitor* actions. *Here and now* actions are normally designed for new projects or for presently threatened areas. Such projects should be designed for climate change adaptation. The incremental costs for new projects are relatively low compared to capital costs under the present climate. *Prepare and monitor* actions are for areas where present threats are low. A planned, progressive approach is developed in an adaptation plan that is not implemented immediately; rather, options are preserved for future adaptation implementation. The actions are undertaken when designated trigger points or thresholds, which are also determined as part of the adaptation planning process, are reached (Reeder and Ranger 2011; Brekke et al. 2011; Ray et al. 2012; Rosner et al. 2014; Douglas et al. 2013; Haasnoot et al. 2012). The *prepare and monitor* approach is similar to the *real options* approach, for which planning is carried out now at some price to preserve the possibility of taking actions in the future (L. Dobes, "Notes on applying 'real options' to climate change adaptation measures, with examples from Vietnam," CCEP working paper 7.10, Centre for Climate Economics & Policy, Crawford School of Economics and Government, The Australian National University, Canberra).

Designation of trigger points or thresholds normally requires the development of the monitoring system to support the determination of the threshold values. The monitoring system could include local and global data such as from in situ sensors, remote sensing instruments, monitoring networks, and local assessor reports. Examples of relevant datasets include meteorological variables, tide measurements, socioeconomic conditions, demographics, and stakeholder values (Reeder and Ranger 2011).

An effective adaptation strategy developed for a particular site should consist of actions that are robust (meaning that they function acceptably well under most future uncertainties and risks), and/or flexible and adjustable such that they can be implemented successfully as biophysical and socioeconomic conditions change. Yohe and Leichenko (2010) refer to the latter approach as *Flexible Adaptation Pathways*.

In addition, an effective adaptation strategy includes:

- No-regret (i.e., valuable even without climate change) and cobenefit (i.e., valuable to multiple sectors) actions,
- Actions that effectively integrate with sustainability planning to respond to other pressures on the region such as population and land use changes and GHG mitigation, and
- A portfolio of approaches for multiple levels of safety.

An effective strategy is evaluated with multiple social, economic, and environmental criteria and respects equity and adaptive capacity needs. It is also responsive to climate surprises, and employs adaptive management as needed. Additionally, because adaptation is often implemented at the local level, local stakeholders must be integrated into the planning process (Kousky et al. 2009; Stakhiv 2010; Brekke et al. 2011; Lempert and Groves 2010; Ray et al. 2012; National Research Council 2009; Matthews et al. 2011; Hallegatte et al. 2011; Douglas et al. 2013).

Development of Adaptation Plans

Development of a particular adaptation strategy can range from a trial-and-error approach based on comparing the performance of several adaptation strategies under a small set of scenarios and criteria (e.g., Kirshen et al. 2012) to sophisticated methods such as decision scaling (Brown et al. 2011) and robust decision making (RDM, Hall et al. 2012). For example, Brown et al. (2011) developed the decision-scaling approach for application to bottom-up adaptation planning. Here, the sets of climate change conditions for which an adaptation plan decision is most sensitive are determined. Then, efforts are focused on determining the plausibility of these climate change conditions occurring. Once the plausibility is known, this additional information on future possible climates can be used to evaluate plans in general.

RDM provides a very powerful method to evaluate a possible adaptation strategy. The process systematically examines the performance of a plan over thousands of possible biophysical and socioeconomic scenarios, and then determines the sets of scenarios to which the performance is most sensitive. The results can then be iteratively used by decision makers to develop improved plans.

Adaptation strategies can also be developed from the output of complex optimization models such as the model developed by Ray et al. (2012) using robust optimization or using real options as discussed by Gersonius et al. (2013) and Wang and de Neufville (2006). Both the approaches of Ray et al. (2012) and Gersonius et al. (2013) require assigning probabilities to future streamflow or precipitation conditions over time. However, as illustrated by Ray et al. (2012), by analyzing the results from many possible probability distributions it is possible to find adaptation strategies that function reasonably well over a range of conditions. In theory, if designed and used properly, optimization techniques can help sort through a myriad of possible alternative strategies to generate a much smaller and more reasonable set of adaptation strategies. The advantage of using an optimization model to generate alternatives is that they can theoretically examine the entire planning horizon and all the linkages among the components of a strategy.

Urban Drainage Case Study: Somerville, Massachusetts

Methodology Summary

This case study is designed and implemented to reflect many of the attributes of an effective adaptation planning process for infrastructure using an urban drainage system in the northeastern United States as an example. The vulnerability assessment includes development of possible climate change scenarios, definition of a set of indicators to assess impacts, evaluation of sensitivities of the system to the scenarios, and a review of the adaptive capacity of the system. Adaptation planning includes development and testing of several sets of alternative, integrated adaptation actions over time and space that may manage the impacts. Two different decision-making approaches are used to quantify the economic results: a design storm least-cost approach and a risk-based approach where performance is evaluated over all possible precipitation conditions. Present expected value costs to meet design criteria for the design storms are compared for each climate change scenario over time to identify the least costly adaptation strategy. Similarly, present expected value net benefits over time are compared to identify the most effective adaptation strategy in this approach.

Recent literature has assessed the drainage vulnerabilities of urban areas to potential changes in extreme rainfall. The Water Environmental Research Foundation (WERF 2009) presents general flow charts of vulnerability networks and possible resulting drainage stresses in urban areas under climate change. Rosenberg et al. (2010) cites previous research completed in U.S. and Canadian cities prior to 2009. For three major urban areas in the state of Washington, Rosenberg et al. (2010) found that drainage impacts varied by GCM. Zhou et al. (2012) summarize some of the recent literature on urban drainage and climate change and concluded that a process is needed for adaptation planning for urban drainage. They present a method based upon determining the impacts of climate change on two adaptation options and choosing the option that maximizes the expected value benefit/cost ratio over time. They do not, however, include multiple climate change scenarios. Similarly, Olsson et al. (2013) evaluate the performance of several drainage management strategies under climate change but only consider costs of the adaptation options for one composite climate change scenario.

Researchers are also stressing the possibilities of using flexible, decentralized approaches to adapt to the increased drainage flooding and associated water quality impacts under climate change (Auld et al. 2006; WERF 2009; Roseen et al. 2011). This is in contrast to large-scale solutions such as sewer separation, which might be effective and robust, but also can be expensive and inflexible. One of the most flexible and decentralized approaches is low-impact development (LID), in which, even without climate change, there is currently much interest. Some, such as Heaney and Sansalone (2009), view LID as one of the best approaches for the future management of urban drainage. Thus LID is a no-regrets policy. LID is "an approach to land development (or re-development) that works with nature to manage storm water as close to its source as possible" (http://www.epa.gov/region1/topics/water/lid.html, accessed June 16, 2013). The LID approach employs principles such as preserving and recreating natural landscape features, minimizing effective imperviousness to create functional and appealing site drainage that treat storm water as a resource rather than a waste product. LID techniques include decentralized approaches such as porous pavement, preservation of buffers, bioretention, distributed storage, and rain gardens. As WERF (2009, p. 62) states "As more and more green infrastructure is added . . . .year after year, it may be capable of keeping up with the gradually increasing rainfall intensity phenomenon over the course of time." Another approach to storm water management is to combine it with the holistic management of storm water, flood waters, water supply, and wastewater management, an approach advocated by many (Novotny and Brown 2007; Zoltay et al. 2010; Daigger 2009).

Case Study Area

With a 2010 population of 75,754 over an area of approximately 11 sq km, Somerville, Massachusetts (Fig. 1), is "the most densely populated municipality in New England" (City of Somerville 2011). The city is highly urbanized, almost completely built out, and has limited open space.

The case study site is the Winter Hill neighborhood and the commercial Assembly Square area, which are serviced by the combined sewer system of the Somerville-Medford Branch Sewer (S-MBS). This site was chosen because the Somerville city engineer identified this as an area that was already experiencing negative impacts because of climate, i.e., local drainage flooding and combined sewer overflows into the Mystic River. For example, the system has the capacity to handle the wastewater flow but is "only sufficient to handle storm flows resulting from about a one-year storm" (CDM 1974). A storm that occurred on July 10, 2010 in

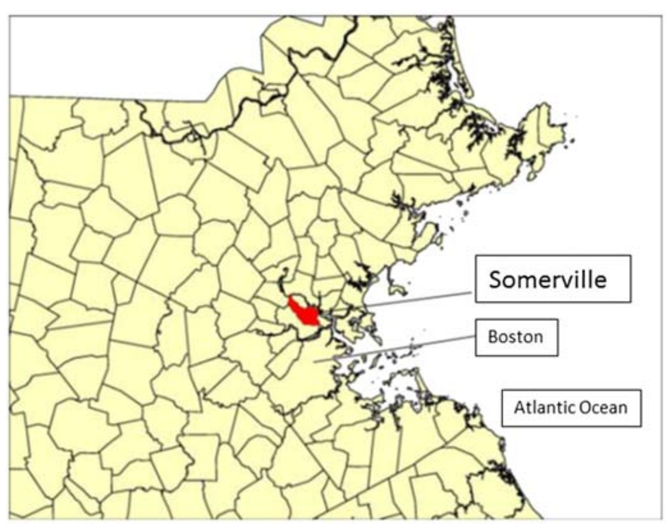

Fig. 1. Location of Somerville, Massachusetts (the polygons represent municipal boundaries) [data from Office of Geographic Information (MassGIS), Commonwealth of Massachusetts, Information Technology Division]

Somerville dropped approximately 9 cm of rain in an hour, causing combined sewage to surcharge into the streets. One woman needed to be rescued from a highway underpass near Assembly Square because the water rose too quickly for her to drive out of the tunnel (TheBostonChannel.com 2010).

In addition to the wastewater and storm water generated in the Winter Hill area, sanitary flow and storm water also enters the S-MBS from several other neighborhoods bordering the area. The Winter Hill and Assembly Square watersheds draining to the S-MBS cover a total area of 2.7 sq km and are shown in Fig. 2. A number of the watersheds have separate infrastructure for storm water and sanitary sewage; however, all separated storm water in the watershed drain into the S-MBS. A separate storm water outfall was never built due to financial constraints.

Under low flow conditions, S-MBS storm water and combined sewage flow to the Chelsea Creek headworks and subsequently the Deer Island wastewater treatment plant through the DeLauri pump station (Fig. 3). Under high flow conditions, excess flow is diverted through the Somerville Marginal Combined Sewer Overflow (CSO) facility, triggering an overflow into the Mystic River. The Somerville marginal facility is gravity-operated, unmanned and has a capacity of 11 m^3/s (245 million gallons per day). Water flowing through the facility is screened and chlorinated and then is discharged into the Mystic River via one of two outfalls depending on the tidal elevation. During low tide, flow discharges through Outfall 205 (located downstream of the Amelia Earhart Dam) and, during high tide, flow discharges through Outfall 205A (located upstream of the dam).

The Winter Hill area is comprised of multiresidential neighborhoods (54%), followed by much smaller areas of industrial (14.5%), commercial (11.4%), transportation (7.7%), and urban public/institutional (6.8%) land use. There are smaller areas of recreation, open land, forest, marina, and water. The watershed is 73% impervious, a very high percentage even for an urban city.

There are few existing storm water controls within the watershed that either promote infiltration or retain runoff before entering the combined sewer system. Most rooftop drains are directly connected to catch basins. The high impervious area in Somerville makes it almost impossible for storm water to recharge into soils to replenish groundwater. Many homeowners pave their front yards to create more parking for residents (Carlson et al. 2014). The highly urbanized watershed forces Somerville to rely heavily on its storm water infrastructure to prevent flooding.

At the time of the preparation of this paper, Assembly Square is currently under construction with new office space, retailers, and residential units. When complete, the Assembly Square storm water management network will drain into the system downstream of the Somerville CSO facility. Thus it will not affect volume of flow through the Somerville CSO facility. The finished storm water management network in Assembly Square includes some LID features.

Vulnerability Assessment

The first step was a vulnerability assessment to determine the impacts without any adaptation, referred to in the figures below as the No Action plan. The 3-month, 10-year, and 100-year design storms were chosen to serve as a basis for evaluation. The 3-month storm was chosen specifically to evaluate system performance against the US EPA CSO policy that states there should be no more than an average of four overflow events per year under the presumption approach (USEPA 1995). The 10-year and 100-year storms

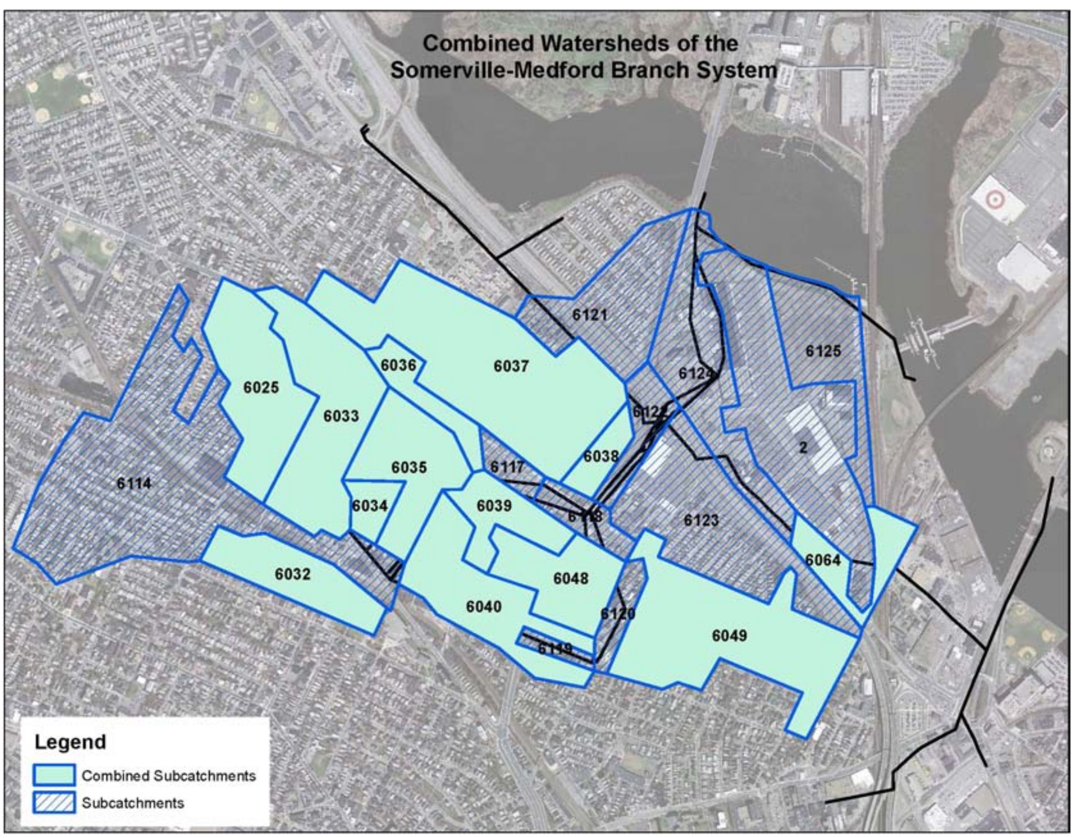

Fig. 2. Separate and combined watersheds of the S-MBS [base layer from Office of Geographic Information (MassGIS), Commonwealth of Massachusetts, Information Technology Division]

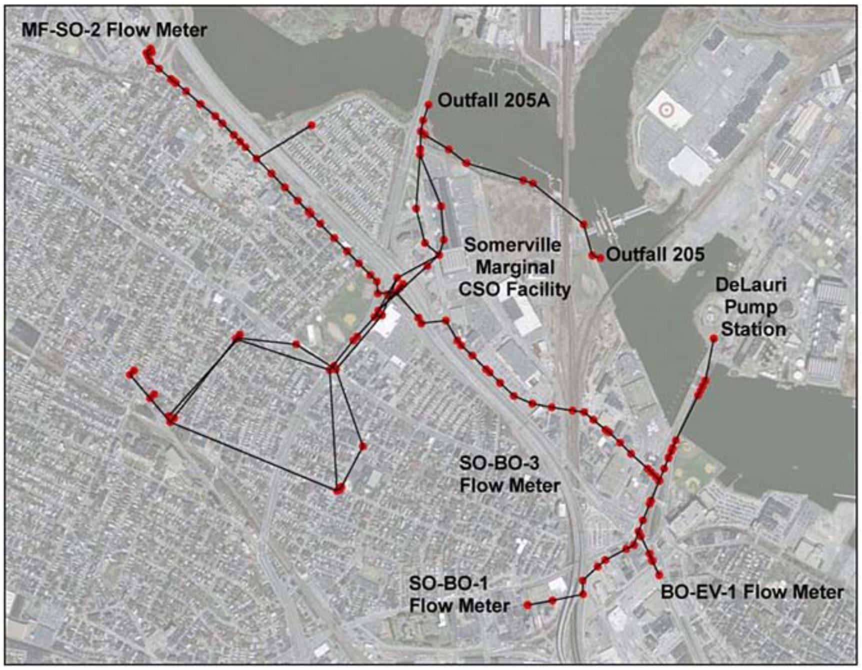

Fig. 3. Layout of Somerville-Medford Branch Sewer (S-MBS) [base layer from Office of Geographic Information (MassGIS), Commonwealth of Massachusetts, Information Technology Division]

were chosen for evaluation according to Standard 2 of the Massachusetts Stormwater Rules for storm water management design (MassDEP 2008).

Plausible scenarios of the future ranges of the extreme design precipitation for the area were developed by Powell (2008) based upon the Special Report on Emission Scenarios (SRES, Nakicenovic and Swart 2000). For each SRES scenario of B1, A1b, and A2 and each 20-year time period around 2010, 2050, and 2100, an extreme value statistical distributions was fit to the daily values of each of 20 general circulation models for the GCM grid cell closest to Somerville. The future extreme values for the various frequencies of interest from each GCM and for each scenario were then scaled by the ratios of the present design values derived from measured historical data to the present values from the GCM. The results are displayed as box and whisker plots to show the variability in percent changes for precipitation. The analysis was completed for 2, 10, and 100-year storms. Fig. 4 is an example of the output.

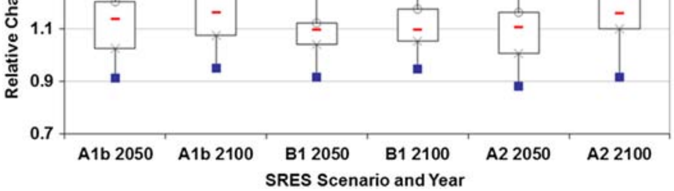

Fig. 4. Example of extreme event analysis in Somerville, Massachusetts

Scenarios for changes in sanitary and storm water flows entering the system upstream and downstream of the area were not developed; it was assumed that they would remain the same because system managers there would take actions in the future to ensure the flows would not increase. Because the case-study area was already built out, the authors assumed no changes in sanitary flows. Thus, their low-impact and high-impact scenarios only included precipitation changes.

For the analysis, three scenarios were selected to represent high, moderate, and low climate change impacts. The selection of low and high impact scenarios was intended to provide an envelope that covers a wide range of plausible scenarios. The moderate scenario provides a basis for understanding how the costs and impacts may vary with the extent of climate changes.

The authors chose as the low-impact scenario the value of the change that was exceeded by 75% of the values (bottom of the box in Fig. 4) in the SRES scenario with the lowest 75 exceedance value. The high value was that exceeded by 25% of the values (the top of the box in Fig. 4) for the SRES scenario that had the largest increase. The moderate scenario was defined as the median value of the median values of each SRES scenario. In some instances, the scenario of the high or low scenario value in 2100 was different than the scenario of the high or low scenario value in 2050. In these cases, the SRES scenario chosen for 2100 was chosen as the scenario for 2050 to ensure consistency.

The overall planning horizon was selected to be the year 2070, with an interim evaluation point set at the year 2040. Because the precipitation results were available for 2050 and 2100, interpolation was used to determine climate scenarios values for 2040 and 2070. The planning window of the years 2040 through 2070 was selected because it provides (1) reasonable correspondence with the typical design life of many urban storm water facilities, (2) a time frame for which significant changes in climate are expected to have measureable and (potentially significant) impacts,

Table 1. Storm Total for Each Climate Change Scenario in Somerville, Massachusetts

		Storm total for each climate change scenario (mm)					
		2040			2070		
24-h design storm	2010	Low	Moderate	High	Low	Moderate	High
3-month	42.93	44.70 (1.05%)	45.72 (1.08%)	47.75 (1.14%)	46.23 (1.08%)	48.01 (1.12%)	50.55 (1.18%)
10-year	123.95	127.76 (1.04%)	133.60 (1.09%)	138.94 (1.14%)	129.54 (1.05%)	139.45 (1.13%)	148.34 (1.20%)
100-year	224.54	231.14 (1.04%)	247.40 (1.14%)	272.80 (1.27%)	230.63 (1.03%)	254.76 (1.14%)	296.16 (1.32%)

and (3) a realistic planning window that could be tenable for many communities and cities. The three-month storm volume was derived from the two-year volume. Results are shown in Table 1.

In addition to precipitation, the surface water elevations of the Mystic River needed to be adjusted for climate change because they control the elevation heads at the CSO outfalls. Low, moderate, and high scenarios were defined for water surface elevations and applied in conjunction with the same climate change scenarios defined for precipitation in the models. At the upstream outfall above the Amelia Earhart Dam, it was assumed that dam operations would change to accommodate future upstream flooding and the water surface level would remain constant behind the dam at the present elevation of 32 m above the Metropolitan District Commission (MDC) datum. At the downstream outfall below the Amelia Earhart Dam, the elevations of a typical 24-h tidal cycle data were increased by scenarios of expected global sea level rise (SLR) for 2040 and 2070 from Vermeer and Rahmstorf (2009).

The peak of the tide was set to occur one hour after the rainfall peak for each precipitation condition to create a worst-case scenario for drainage in the S-MBS. The small amount of subsidence in the region of approximately 19.8 cm/100 years (Kirshen 2008b) was ignored.

To evaluate the impacts of climate change, a set of metrics was required. The three performance metrics for this study were the volume of hazardous flooding in streets, volume of combined sewage discharged from the Somerville Marginal CSO facility, and the peak flows in the main trunk line at the intersection of the S-MBS with the Cambridge branch. These metrics were selected because they (1) are parameters that would be directly affected by increased runoff associated with climate change, (2) are quantifiable in terms of flow, volume, and cost, (3) would likely have impacts on the environment and public health, and (4) were concerns of the City of Somerville.

Hazardous flooding is defined as flooding volume in the streets minus *nuisance* flooding. Nuisance flooding is the volume of water that can flow through the streets of Somerville without overtopping the curb; in other words, this type of flooding is a nuisance but causes no harm or damage. A value for nuisance flooding was calculated for each junction in the S-MBS as the product of pipe length, average road width, and average curb height. Values for nuisance flooding were found to be very small compared to total flooding during model simulations, so nuisance flooding was ignored when determining hazardous flooding.

The design standard for flow through the CSO facility was to have no increase in volume beyond the present volume for each future design storm. The design standard for the hazardous street flooding was to tolerate only a minimal total volume (1,900 m^3) under all design storms and for all climates. It was also required that the peak flows in the main trunk line at the intersection of the S-MBS with the Cambridge branch be equal to or less than existing peak flows. Since the analysis found that the peak flows were reduced under all adaptation strategies in all future scenarios of climate when the other metrics and conditions were met, peak flows are no longer included in discussions for the remainder of this paper. They were reduced because lower flows were entering the sewer system.

The drainage and the sewer system flows were modeled with the US EPA Stormwater Management Model (SWMM, http://www.epa.gov/nrmrl/wswrd/wq/models/swmm/). The modeled sewer system started at meters MF-SO2, SO-BO1 and BO-EV-1 in Fig. 3. It included these watersheds as well as the watersheds in the S-MBS system. Downstream boundary conditions were set at the DeLauri pump station, and at the CSO outfalls above and below the Amelia Earhart Dam. As stated earlier, the *above* outfall was set to a fixed water surface elevation and the *below* outfall varied tidally. Upstream sanitary flows entering the system remained unchanged. The drainage catchments were modeled above the three upstream boundary conditions but, as stated earlier, it was assumed that adaptation activities were undertaken in these catchments such that there would be no increases in runoff in the future as a result of climate change (i.e., no changes in precipitation were ever applied to these subcatchments).

The model was calibrated and verified with the measured discharge and elevation data at meter SO-BO-3 from several precipitations events and the corresponding meter data at the upstream boundaries. It was also calibrated and verified with some limited data on CSO releases. Those calibration and verification runs may be seen in Caputo (2011). The model was run with one previous day of dry weather before the storm simulation to ensure that the antecedent conditions at the beginning of wet weather events would be appropriately simulated. Because the Assembly Square drainage network was not connected to the network below the CSO facility during the period of time of the calibration and verification data, its drainage network was not included during calibration and validation of the model.

The vulnerability of the current drainage network to present and future climate scenarios was the first analysis completed with the SWMM model. Fig. 5 illustrates that in all time periods and for all climate change scenarios (even the case of the 100-year, low climate change scenario in 2070), the CSO release exceeded present volumes, a violation of the design metric. Fig. 6 shows that there are also hazardous volumes under all present and future conditions except for the three-month storm—again a violation of design conditions. Given these assumptions, the system is in violation now, and some actions are needed to manage both present and future climate conditions.

Somerville Adaptation Planning

With the system vulnerability established, the next step was adaptation planning. Strategies for controlling combined sewer overflows in urban areas were identified through review of literature, correspondence with engineers at municipal agencies, and experience of the authors in regards to long-term CSO planning. The authors searched for strategies that might meet the design goals with the lowest possible present value cost. Some common strategies for

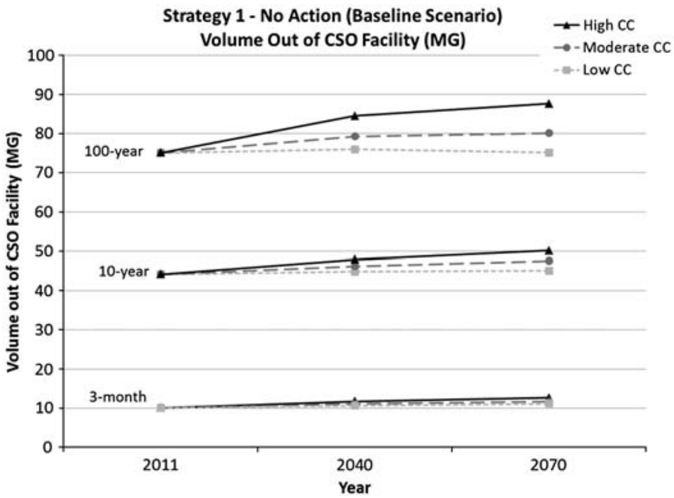

Fig. 5. Volume discharged from the CSO facility for the no action (baseline) strategy (1 mg = 3,790 m^3)

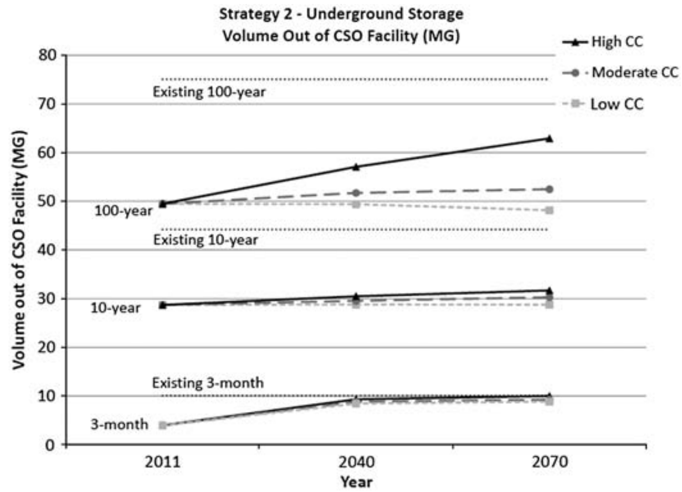

Fig. 7. Volume discharged from the CSO facility for the underground storage strategy (1 mg = 3,790 m^3)

urban CSO control include sewer separation, underground storage, and more recently, green infrastructure or low-impact development controls. For the purposes of this analysis, the selected adaptation strategies included underground storage, LID applied throughout the watershed, sewer separation, and a combination of sewer separation and LID. These strategies could be classified as protection adaptation actions because they are attempting to keep the threat away from stakeholders.

Underground storage incorporates retention basin storage throughout the S-MBS as a flexible, distributed design. The vulnerability assessment indicated that under all climate scenario conditions for the periods 2011, 2040, and 2070, the majority of hazardous flooding occurred at approximately the same 20 nodes. Therefore, 20 retention basins were incorporated in the S-MBS in SWMM and the storage needed to manage the hazardous flooding in 2070 under the high precipitation scenario was determined. This mimics the goal of flexibility in design and preserving options for later action. Then, depending upon the climate scenario for each time period (2011, 2040, 2070), the necessary amount of storage was added to meet the design conditions. As shown in Figs. 7 and 8, this strategy managed the conditions over all time periods and scenarios.

The LID adaptation strategy employed LID throughout the watershed draining to the S-MBS. Through discussion at research meetings with municipal officials, LID techniques that were considered viable include infiltration trenches/dry wells, porous pavement, rain barrels, blue roofs, green roofs, and bioretention.

In residential areas, impervious areas were broken down into two categories: rooftops and driveways/pathways. LID techniques that homeowners may install to store storm water from rooftops include drywells, rain barrels, green roofs, and blue roofs. Porous pavement was selected as the technique that homeowners would install to store storm water from driveways/pathways. Maximum feasible amounts of LID by type are below:

Rooftop
- 60% of roofs drain to on-site drywells,
- 10% of roofs drain to rain barrels,
- 10% of roofs are converted to green roofs,
- 10% of roofs are converted to blue roofs, and
- 10% of roofs make no changes in existing drainage.

Driveways/pathways
- 25% of area is converted to porous pavement.

Design of each LID approach was determined using the Massachusetts DEP Stormwater Handbook (MassDEP 2008). Not all the LID techniques modeled were directly available in SWMM; in these cases the most representative element in SWMM was used for the modeling.

LID options for commercial, business, and industrial areas to store storm water from rooftops include drywells, rain barrels, and blue roofs. LID techniques that may be installed to store storm water from parking lots/sidewalks/pathways include only porous pavement. LID that may be installed to store storm water from grass and shrub areas include bioretention. Maximum feasible amounts of LID are below.

Rooftop
- 50% of roofs drain to on-site drywells,
- 20% of roofs are converted to green roofs, and
- 20% of roofs are converted to blue roofs.

Parking lots/sidewalks/pathways
- 75% of impervious area is converted to porous pavement grass/shrubs, and
- 15% of pervious area is converted to bioretention.

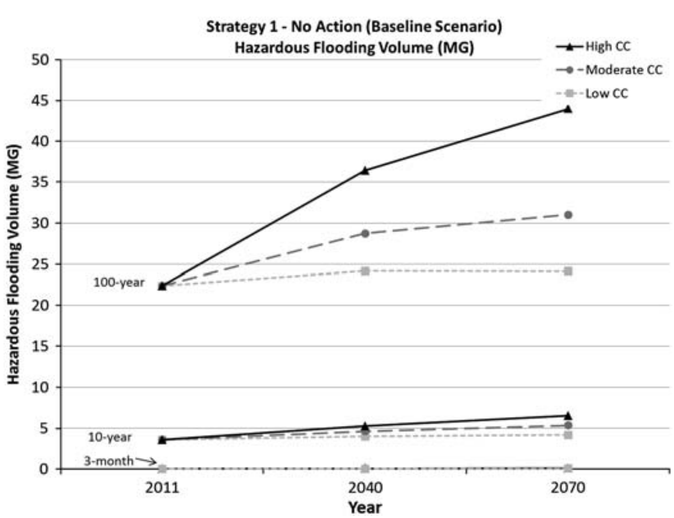

Fig. 6. Hazardous flooding volume for the no action (baseline) strategy (1 mg = 3,790 m^3)

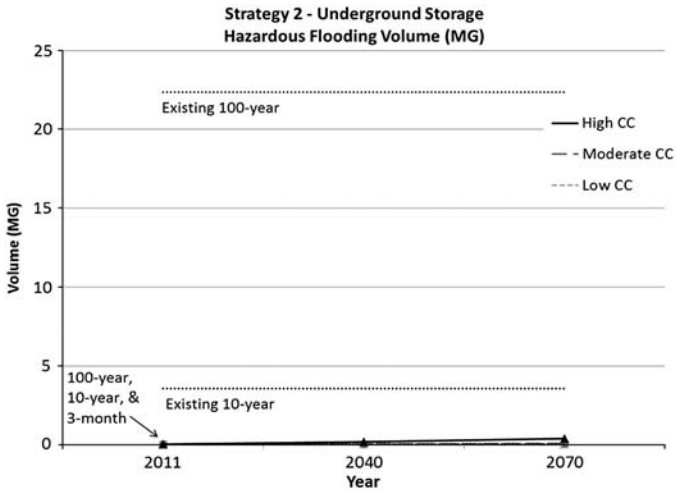

Fig. 8. Hazardous flooding volume for the underground storage strategy (1 mg = 3,790 m^3)

It was assumed that LID would be installed with the following schedule:

- 2011: Install 30% of the maximum amount of LID planned to be installed;
- 2040: Install additional 50% of the maximum amount of LID; and
- 2070: Install remaining 20% of LID.

The performance of the LID strategy was then simulated under the climate change scenarios. This strategy met design conditions for the CSO volume being discharged out of the treatment facility under all the scenarios. As shown in Fig. 9, however, the LID strategy did not meet the performance metrics for hazardous flooding under the moderate and high scenarios for all the times and therefore did not meet design conditions. The LID techniques used in this study cannot contain more than a 5.1-cm storm, and therefore, cannot alone manage even the present 10-year or 100-year storms.

Sewer separation was the next strategy investigated. To meet the performance targets for hazardous flooding and reduction in CSO volumes, it was necessary to perform sewer separation in all subcatchments that drained to the main trunk of the S-MBS and the Winter Hill sewer system. Sewer separation resulted in meeting design conditions for all the scenarios over all time periods.

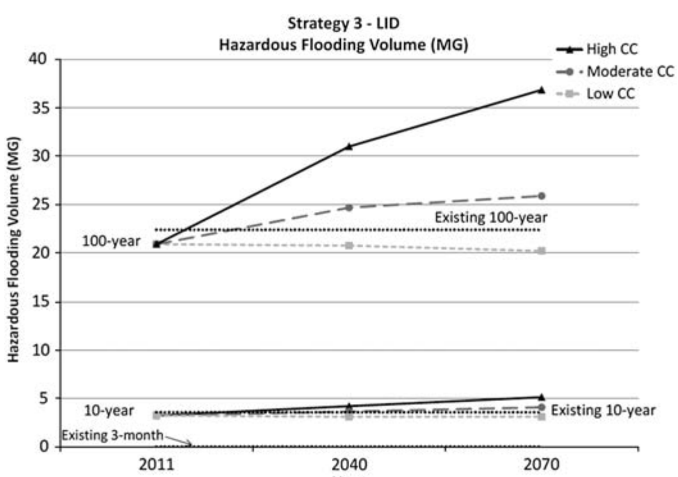

Fig. 9. Hazardous flooding volume for the LID strategy (1 mg = 3,790 m^3)

Because the Winter Hill system was not meeting design conditions under the present climate, it was assumed that this alternative would be built over the next decade.

The final adaptation strategy employed a combination of sewer separation and LID. LID techniques were eliminated if they were deemed costly and did not provide much storage/retention. Thus the LID techniques considered included the following: blue roofs, dry wells, and porous pavement. With a trial and error iteration of two to three steps, the authors found a strategy that worked reasonably well. Under this strategy, staged actions would be carried out as follows:

- 2011: Perform sewer separation in all but five subcatchments, install 100% of possible LID in 4 subcatchments;
- 2040: Separate another subcatchment; and
- 2070: No action necessary.

This staged strategy was found to be effective for all scenarios over all time periods.

Cost Analysis

To evaluate the adaptation scenarios, the expected present value costs of each alternative were determined. Here, capital costs include construction, design and engineering (D&E) costs. Variable costs include costs associated with operations and maintenance (O&M), the treatment of water flowing to Deer Island WWTP, and treatment of water flowing through the Somerville Marginal CSO facility. Future costs were discounted by a real discount rate of 2.3%.

Expected values of variable costs for each management alternative were calculated as follows. For each climate change scenario and each planning year (2011, 2030, 2070), the variable costs for meeting each design event (e.g., the 100-year storm) were plotted against the probability of each event and then the area under the curve determined. Next, the expected values of the variable costs for each planning year for each climate change scenario were plotted over the 60-year time frame. The total expected value variable cost over all the years for that scenario and management alternative was then calculated by determining the area underneath this curve.

The total expected present value costs of the strategies meeting the design conditions were determined by added the discounted present value capital costs to the expected present value variables costs and are summarized in Table 2. Because Strategy 3 (LID) did not satisfy the design goals, it was not included. The costs are very large compared to actual investments in similar cities in drainage management because of the very high degree of service being provided under present and future climates. The authors realize that the actual planning process may result in trade-offs being made between costs and level of drainage management.

The difference of the costs in Table 2 for an adaptation strategy is low primarily because of the high capital costs to meet conditions in the present. For example, the costs of underground storage to meet design conditions under one climate change scenario were approximately \$310 million in 2010, then \$65 million in 2040, and \$25 million in 2070. Results show that Strategy 4, sewer separation, is the most cost-effective strategy for all climate change

Table 2. Comparison of Strategy Costs for 100-Year Storm Design Conditions under Various Climate Change Scenarios

	CC scenario		
Strategy	Low	Moderate	High
2	\$485,000,000	\$486,200,000	\$487,600,000
4	\$191,200,000	\$191,200,000	\$191,200,000
5	\$217,240,000	\$217,360,000	\$217,450,000

Note: 2 = storage; 4 = separation; 5 = LID and separation.

Table 3. Net Benefits and Costs for the Underground Storage Strategy

CC scenario	Benefits	Costs	Net Benefits
Low	$721,500,000	$536,600,000	$184,900,000
Moderate	$731,300,000	$540,200,000	$191,200,000
High	$744,000,000	$543,900,000	$200,100,000

scenarios because it is the least expensive for each scenario and meets the performance standards for each scenario. The results may have been different if other criteria such as flexibility, cobenefits, and no-regrets were considered.

Net Benefits Approach

Another evaluation approach is to select the alternative that maximizes the expected value of the net benefits of adaptation. Benefits are defined as the costs of the damages that would be avoided as compared to the No Action plan. Costs include the same costs as in the design storm approach as well as the costs of the residual damages. A similar analysis as for the design storm approach was employed for each adaptation alternative strategy; the benefits and costs associated with the frequency of each event and each scenario were determined and then integrated for each scenario.

Damages avoided include any reductions in volumes flowing through the CSO facility and to Deer Island WWTP, and any reductions in hazardous flooding. The costs and hence values of flows through the CSO facility and the WWTP have been described above. Hazardous flooding damages cover all expenses incurred due to building structural damage, damage to contents in basements, and costs to pump out combined sewage and clean and disinfect basements. Costs for structural and content damage are based on the Army Corps of Engineers relationship tables (U.S. Army Corps of Engineers 2003). Pump-out, cleaning, and disinfection costs are based on costs from commercial services (Caputo 2011). Assumptions were made to estimate the number of houses affected by flooding and how much flooding occurred by estimating the number of buildings flooded by the 100-year and 10-year storms. No hazardous flooding occurred under the 3-month storm. Then, given an assumed footprint of each building, the average depth of flooding in each building was determined assuming all the hazardous flooding flowed into basements.

As an example, the expected value and discounted benefits and costs for the Underground Storage strategy are in Table 3. The costs for Underground Storage are greater than those of the design storm approach because they include the residual damages as well as the capital and operation and maintenance costs. The results in Table 3 exhibit benefit-cost ratios of approximately 1.3 for all the climate change scenarios. Table 4 compares the net benefits of all the alternatives and the costs of the system vulnerability.

Table 4 illustrates that Strategy 4, sewer separation, is the most beneficial strategy when analyzed using the net benefits approach because this strategy has the highest net benefits for all climate change scenarios. This result is consistent with the result obtained from the design storm approach. Again, the results may have been different if other criteria such as flexibility, cobenefits, and no-regrets were considered.

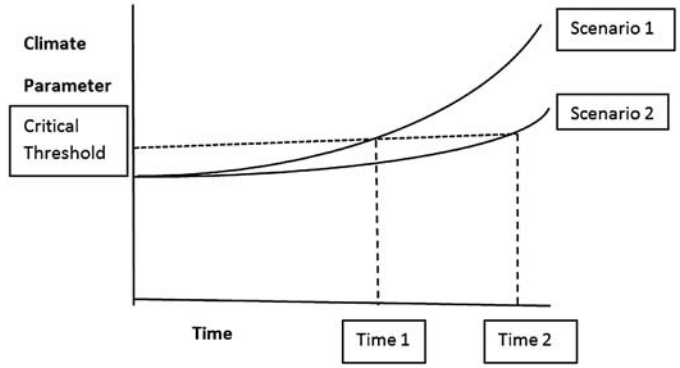

Fig. 10. Range of time for obtaining critical threshold given two climate change scenarios

Conclusions and Recommendations for Further Research

This paper has presented and illustrated a vulnerability assessment and an evaluation of adaptation strategies for the impacts of climate change upon urban drainage flooding and CSOs. The vulnerability assessment showed that the design metrics for hazardous flood volumes and CSO discharges are exceeded under present climate conditions and an envelope of future climate change scenarios. Thus, adaptation actions are required. Four adaptation strategies were defined, and the performance of each of these strategies over each climate change scenario was evaluated using least cost and risk-based net-benefits approaches. For this particular case study, sewer separation over the next decade was found to be the most favorable adaptation strategy. Using both evaluation approaches, it performed the best over all the climate change scenarios compared to the other strategies.

The case study illustrates aspects of vulnerability and adaptation planning for managing drainage and CSO infrastructure. Because the approach used in this paper is limited to the direct economic damages of the flooding, it does not explicitly include other criteria such as flexibility, cobenefits, or resilience. It also does not consider other associated impacts, such as disease, lost economic activity due to temporary lack of access to commercial and industrial facilities, and decrease in response of emergency services due to street flooding. Impacts such as these and other socioeconomic and biophysical factors can also be considered in a similar manner if suitable metrics are quantified. If quantification is not possible, then qualitative descriptions can be used. Climate surprises were also not considered. This could have been done by evaluating the strategies for the higher extremes in Fig. 4.

Evaluation of the adaptation strategies in the case study assumes that the adaptation actions are implemented in preselected times in the future. This is not the case with *prepare and monitor* adaptation

Table 4. Comparison of Net Benefits for All Strategies

Strategy	Low CC	Moderate CC	High CC
	CC scenario		
1. No action	−$746,200,000	−$756,200,000	−$769,100,000
2. Underground storage	$184,900,000	$191,200,000	$200,100,000
3. LID	−$944,300,000	−$954,300,000	−$959,700,000
4. Sewer separation	$549,000,000	$559,200,000	$572,300,000
5. Sewer separation and LID	$519,500,000	$529,300,000	$542,000,000

strategies in which adaptation options are preserved and actions are taken when designated climate change trigger points or thresholds are reached. Examples of such strategies for coastal flooding protection in Boston Harbor under rising sea levels are given by Douglas et al. (2013). Because the present evaluation uses climate change scenarios, only the possible range of time over which an adaptation action should be taken can be obtained from such an analysis. This is conceptually shown in Fig. 10. The authors are currently testing an adaptation planning approach where the evaluation of a *prepare and monitor* strategy is applied to the time period when a critical threshold is reached under a climate change scenario.

Of course, implementation of adaptation strategies which are dependent upon reaching thresholds related to climate change assumes that it is possible to define and identify when the climate change has occurred, e.g., when has the 10-year storm increased by 5 cm. Implementing an adaptation strategy too soon can result in an inefficient investment; implementing it too late can result in extra damages. Vogel et al. (2013) describe a more complete statistical analysis that outlines the importance of considering the likelihood of both underpreparation and overpreparation, and Rosner et al. (2014) introduce a combined statistical and decision analysis approach that begins to address adaptation decisions in this setting. Research is also continuing on this approach.

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