Robust Stormwater Management Strategies under Climate Change:

A Case Study in Somerville, Massachusetts

A thesis

Submitted by

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Abstract

Stormwater management systems involve many challenges including flooding and associated property damage, combined sewer overflows, and poor water quality in surface waters. All these may be exacerbated under a changing climate in the future. This study uses a detailed methodology to identify robust adaptation strategies for managing urban stormwater under climate change uncertainty. Robust strategies are strategies that function acceptably well under all future uncertainties and risks. The objective of this study is to investigate effective responses for urban water managers to the challenges of drainage management in conditions of a changing climate through a new methodology.

Robust adaptation strategies are evaluated for a combined sewer system in Somerville, Massachusetts using the U.S. EPA Storm Water Management Model (SWMM). Various design storms are simulated in 2010, 2040, and 2070 under low, moderate, and high climate change scenarios. Five strategies for stormwater/CSO management are tested under these conditions to find a strategy which performs well under all conditions considered, which we term a robust strategy.

Two decision-making approaches are used to quantify results: a design cost approach and a net benefits approach. Both approaches utilize risk analysis for each climate change scenario to determine the expected values of costs, and in the case of net benefits, the benefits of management. Costs to meet design *criteria are compared for each climate change scenario to identify the most cost-effective robust strategy. Similarly, net benefits are compared and the most beneficial robust strategy is identified. This methodology identifies sewer separation as the best robust strategy under both approaches.*

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1.1 Definition of the Problem

Stormwater management is a significant responsibility to today's water resource manager in the urban environment. Traditional urban stormwater management systems are designed to move excess runoff as quickly as possible to downstream receiving waters through the use of open or closed conduits. These management systems are vital to the functioning of a city because excess runoff can cause flash floods, downstream flooding in major stream channels, expensive property damage, and washout of structures such as railroad beds. Stormwater management systems can exacerbate these problems if not functioning properly and they can degrade the water quality in nearby surface waters. Urban runoff picks up pollutants as it flows over impervious surfaces into storm sewers and is discharged directly into rivers and streams. The National Water Quality Inventory: 2000 Report to Congress identified "urban runoff as one of the leading sources of water quality impairment in surface waters" (USEPA, 2005). Pollution from urban runoff is difficult to manage because there are so many diffuse sources. Proper stormwater management has become an important, and somewhat complex, aspect of water resources.

In addition to urban runoff, older cities such as Boston, Massachusetts and the surrounding suburbs have an additional source of pollution due to combined sewer systems. Combined sewer systems are composed of piping infrastructure that drains storm water as well as sewage from surrounding neighborhoods. Figure 1 presents a comparison of a combined sewer system on the top row and a separate stormwater system on the bottom row.

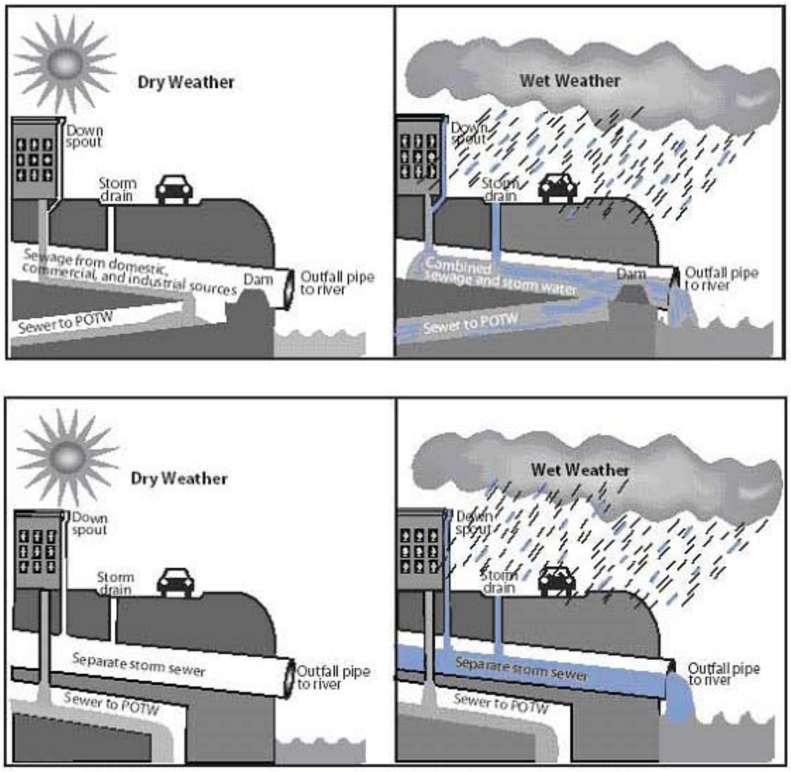


Figure 1. Comparison of Combined Sewer System and Separate Sewer System

(Rhode Island Stormwater Solutions, 2009)

The figure shows that under dry weather conditions, combined sewage and storm water is typically treated at a publicly owned treatment works (POTW), also known as a wastewater treatment plant (WWTP). During heavy rainstorms, WWTPs may exceed capacity and cause an overflow of combined sewage into a nearby water body which is called a combined sewer overflow (CSO). With a separate stormwater system, during heavy rainstorms only storm water flows into a water body. If no treatment facility exists before the outfall, CSOs contain raw sewage, pathogens, solids, debris, and toxic pollutants that flow directly into surface waters. Not only do CSOs degrade water quality but they can cause beach closures, shellfish bed closures, and other environmental and public health concerns.

The challenges of managing storm water and CSOs will increase as cities become more populated and urban development continues.

> "In 2008, world population was estimated to be equally split between urban and rural areas, marking the transition from a rural dominated to an urban dominated world. By 2030 the number of urban dwellers is expected to be about 1.8 billion more than in 2005 and to constitute about 60% of the world's population, while the number of rural inhabitants is expected to decline slightly from 3.3 billion to 3.2 billion." (UNESCO, 31)

Urbanization replaces natural surfaces with impervious surfaces such as pavement, sidewalks, and roofs which prevent infiltration of runoff into soils. Urbanization and the associated increase in impervious surfaces changes the natural hydrologic regime of the land causing flooding, CSOs, and non-point source pollution (Guiterrez, 2006).

The uncertainty of the future climate brings another level of complexity to the problem. The Intergovernmental Panel on Climate Change (IPCC) reports that "precipitation is likely to increase in most subpolar and polar regions…the increase is considered especially robust, and very likely to occur, in annual precipitation in most of northern Europe, Canada, the northeast USA and the Arctic…and available research indicates a tendency for an increase in heavy daily rainfall events in many regions" (Solomon et al., 2007). If an increase in heavy daily rainfall events is expected to occur, then stormwater management systems designed according to historical rainfall data will surcharge more frequently. In the case of combined sewer systems this is especially troublesome because CSOs will occur more frequently.

In summary, there are many challenges to stormwater management such as pollution from urban runoff, CSOs, urbanization, and the uncertainty of climate change. As quoted in Frederick et. al. (1997), the 1996 IPCC international assessment stated:

> "The challenge today is to identify short-term strategies in the face of long-term uncertainty. The question is not, what is the best course for the next 100 years, but rather, what is the best course for the next few years, knowing that a prudent hedging strategy will allow time to learn and change course."

Some researchers such as Barros and Evans (1997) call for more creative and comprehensive engineering solutions to deal with the issue of climate change.

Objectives and Approach

This study uses a detailed methodology to test robust strategies as the solution to deal with uncertainties when planning for stormwater and CSO management under climate change. Robust strategies are strategies that function acceptably well under all future uncertainties and risks. The primary objective of this study is to investigate effective responses for urban water managers to the challenges of drainage management under conditions of a changing climate through a new methodology.

The remainder of Chapter 1 describes typical solutions to stormwater management including best management practices (BMPs), low impact development (LID), solutions to CSO management such as retention basins and sewer separation, and a literature review. Chapter 2 presents existing stormwater regulations at the federal, state, and local levels of government and the Environmental Protection Agency (EPA) CSO Control Policy. Two U.S. cities are highlighted that are on the forefront of green infrastructure. Chapter 3 presents the combined sewer system in Somerville and the computer models used in the case study. Chapter 4 presents the methodology performed using the computer models. Chapter 5 presents the simulation results, costs, and net benefits, and Chapter 6 presents conclusions.

1.2 Solutions for Stormwater Management

Historically, storm water is managed by infrastructure and BMPs designed for a particular design storm event. The magnitude of the design storm is determined based on available historic precipitation data in the region. Over the years, BMPs were developed and shared by practitioners that work well to prevent flooding and improve water quality. This section describes specific BMPs, including storage and LID, in further detail.

Best Management Practices (BMPs)

Stormwater quantity can be reduced and quality can be improved through the use of BMPs within the watershed. BMPs exist in both structural and non-structural form. Examples of structural BMPs include detention/retention basins, infiltration trenches, dry wells, sediment traps, vegetated swales, bioretention, deep sump catch basins, sediment forebays, and constructed wetlands. Non-structural BMPs include education outreach (such as public education on benefits of pet waste cleanup), street sweeping, and zoning to protect open space. Structural BMPs are structures that “trap and detain runoff before they enter receiving waters, while nonstructural BMPs control pollutants at the source” (Guitierrez, 2006). The installation of structural BMPs within a watershed have potential to reduce flooding by detaining peak flows, removing pollutants through physical and biological processes, and infiltrating storm water to recharge aquifers. Nonstructural BMPs control pollutants at the source by preventing pollutants from entering the watershed and preserving natural green space.

Storage BMPs

Traditionally, storm water is managed by storage BMPs such as detention/retention ponds, stormwater wetlands, and underground storage. Storage BMPs capture flow and allow water to drain slowly to reduce peak flows and local flooding. They can be designed to allow water to infiltrate soils if the soils are permeable enough. Above-ground storage BMPs such as detention ponds and stormwater wetlands require large land areas which may be an unappealing option in areas with expensive real estate and limited land availability (USEPA, 2001). Storage BMPs also improve water quality by allowing pollutants time to settle out before flowing downstream or infiltrating soils.

There are different types of underground structures such as pre-cast concrete or plastic pits, chambers (manufactured pipes), perforated pipes, and galleys (MassDEP, 2008). In locations such as Somerville where there is potential for high sediment/pollutant loadings from streets and highways, pretreatment would be necessary. Pretreatment options for underground storage include deep sump catch basins, proprietary separators, and oil-grit separators that trap sediments and associated pollutants. These structures can be cleaned by a vacuum truck to ensure storage BMPs maintain their functionality.

Low Impact Development (LID)

A sub-type of BMPs is LID which is a relatively new concept that began in Prince George's County, Maryland in the early 1990's. LID is defined by the EPA as follows:

> "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. LID 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." (USEPA, March 2011)

Examples of LID include bioretention, rain gardens, green roofs, rain barrels, permeable pavements, infiltration swales, grassed swales, disconnected impervious areas, and cluster development. LID allows storm water to flow through the watershed in a way that mimics the natural hydrology before development. Many small applications of LID throughout a watershed can reduce flooding and improve water quality of nearby surface waters.

LID techniques that this study focused on include infiltration trenches / dry wells, porous pavement, rain barrels, blue roofs, green roofs, and bioretention. Typical cross sections for most of these LID designs were obtained from the Massachusetts Stormwater Handbook (MassDEP, 2008) and are shown in Figures 2, 3, 4, 6, and 7 below. Blue roofs (Figure 5) are a relatively new concept currently being piloted in New York City.

Infiltration Trench / Dry Well

Infiltration trenches are shallow excavations filled with stone. The void space created by the stone provides storage for runoff. Infiltration trenches can be designed to capture sheet flow or piped inflow, depending on the shape of the trench. The stored runoff gradually seeps out of the structure into surrounding soils or into an underdrain that flows to the storm sewer system. Dry wells are a type of infiltration trench, specifically used to infiltrate uncontaminated stormwater runoff from rooftops.

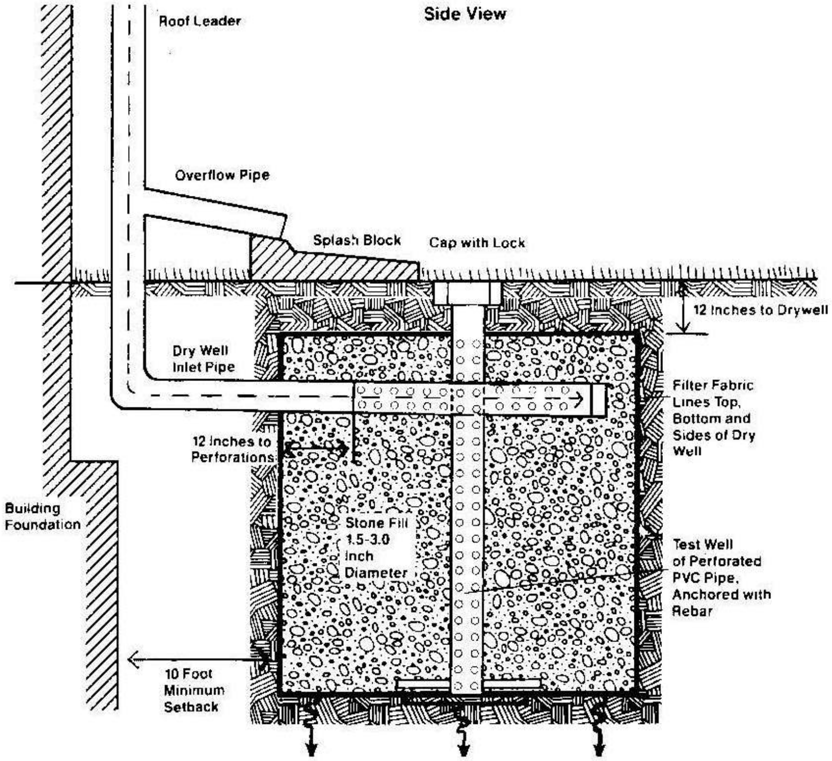


Figure 2. Infiltration Trench

Porous Pavement

Porous pavement is a type of paved surface that contains high void space compared to conventional pavement. Porous pavement consists of a permeable paving system overlying a stone bed that creates storage for storm water and allows runoff to infiltrate into soils. Porous pavement should not be used in "high pollutant loading" areas, such as gas stations and vehicle maintenance lots, to prevent pollutants from seeping into soils. Types of porous pavement include porous asphalt, pervious concrete, paving stones, and grass pavers. Porous pavement may be ideal for sidewalks, patios, plazas, driveways, parking spaces, and overflow parking areas.

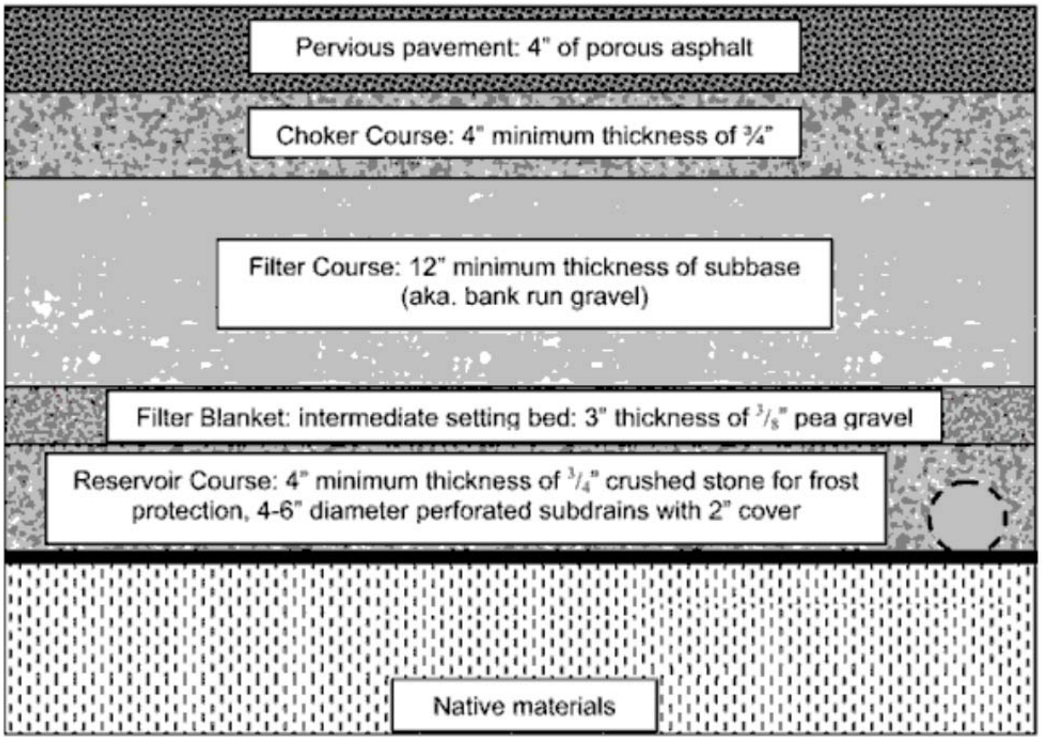


Figure 3. Porous Pavement

Rain Barrels

Rain barrels, or cisterns, are containers that store stormwater runoff from rooftops to be re-used for landscaping or other non-potable use. Downspouts are disconnected from the sewer system and redirected into the container to fill up with water during storms. An overflow system ensures that excessive storm water safely drains during a large storm.

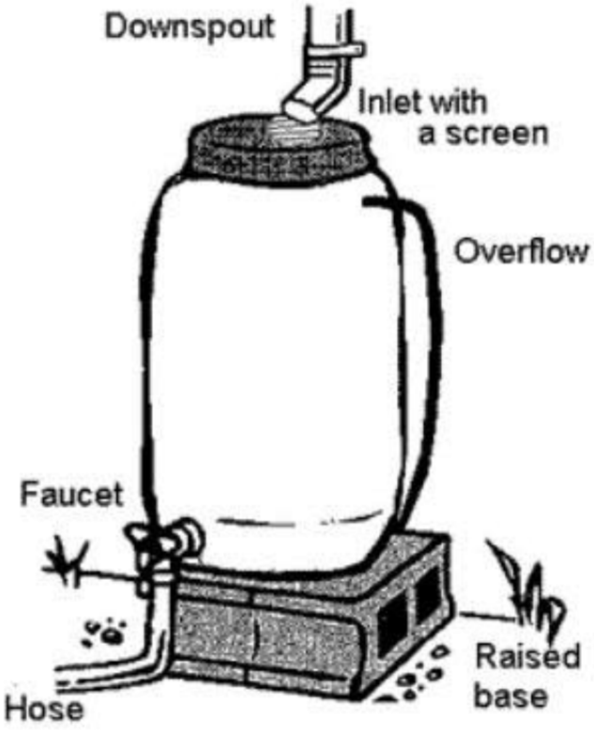


Figure 4. Rain Barrel

Blue Roofs

Blue roofs are rooftop detention systems designed to hold water until a storm passes. The detention system can involve containers weighted with stones or "dams" to hold back water. After a storm, water evaporates or excessive storm water (more than 2 inches deep) overflows to downspouts. Flat roofs or low slope roofs are ideal for this installation, and rooftops must have enough load-bearing capacity to carry the additional weight of ponded water. Blue roofs reduce the sudden impact to combined sewer systems during storms and can be relatively cheap when compared to green roofs. Coupled with light-colored roofing materials, blue roofs can provide an additional benefit of rooftop cooling (City of New York, 2008).

Figure 5. Blue Roof

(NYCDEP, 2011)

Green Roofs

Green roofs are permanent rooftop planting systems containing live plants in a lightweight engineered soil. Green roofs are designed to store storm water in a storage and soil layer. Water is then taken up by plants and transpired into the air. Overflow is directed to downspouts to prevent flooding. There are two main types of green roofs, extensive and intensive. Extensive green roofs require minimal maintenance, utilize native and easy-to-care for plants, and are resistant to frost, wind, and drought. Common plants used in extensive green roofs are sedum, herbs and grasses, and they are usually installed on flat and low sloped roofs to maximize water retention. Intensive green roofs require regular maintenance (irrigation, fertilizing, pruning, mowing), can accommodate a greater variety of plants (sod lawn grasses, perennial, annual flowers, shrubs, and small trees), and use deeper and heavier soils. In this study, extensive green roofs are assumed for use in Somerville.

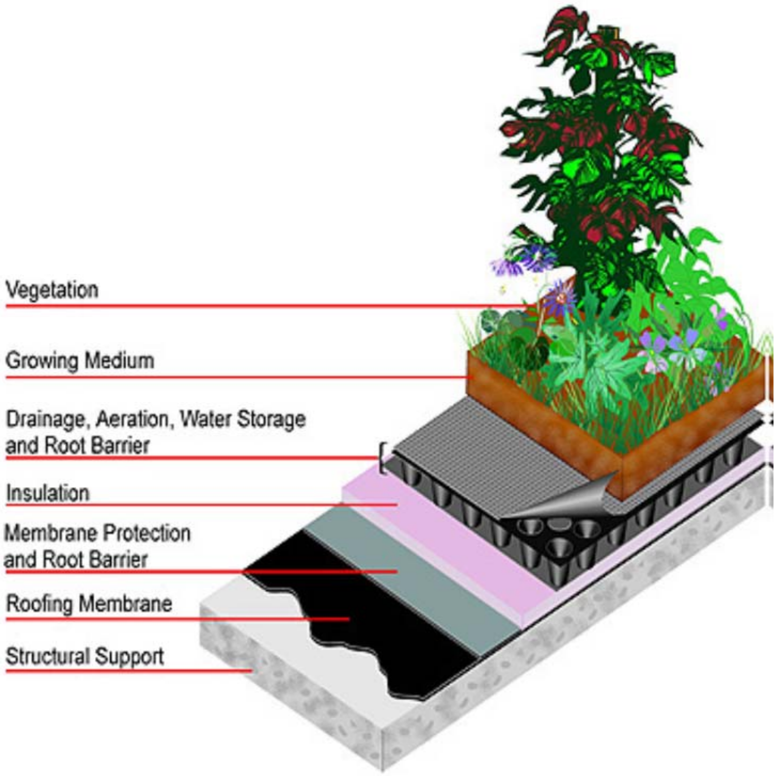


Figure 6. Green Roof

Bioretention

Bioretention is a retention or detention basin that uses soils, plants, and microbes to treat and store storm water before it infiltrates or flows downstream. Bioretention involves a gravel storage layer, soil layer, and mulch layer, planted with dense native vegetation that requires little maintenance. Stormwater runoff flows into the bioretention area through sheet flow or piping. Storm water percolates through the soils and is taken up by the plants and transpires into the air. Microbes in the soil consume many of the pollutants so storm water is cleaner as it enters soils or flows downstream. Bioretention can be designed with or without an underdrain or an impermeable liner, depending on its purpose.

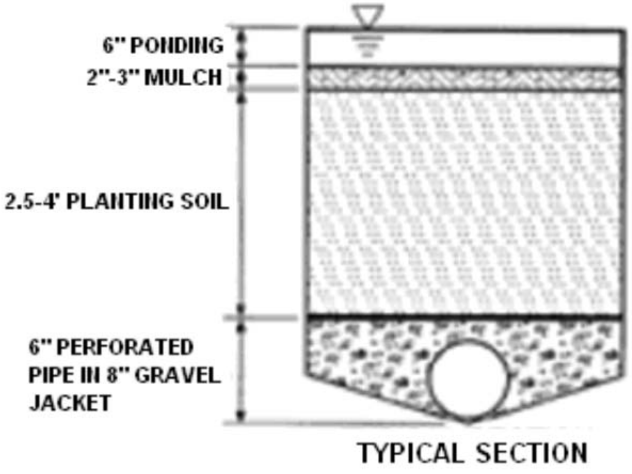


Figure 7. Bioretention

1.3 Solutions for CSO Management

Ever since EPA's CSO Control Policy was published in 1994, CSOs have been targeted for removal or, at the very least, reduction in CSO activations or improvement in CSO water quality. A common approach to CSO management is the upgrade of infrastructure to increase sewer system capacity using retention basins. Sewer separation is another option that involves separating the combined single pipe into separate pipes for sewage and stormwater flows. This section describes retention basins and sewer separation as solutions for CSO mitigation.

Retention Basins

Similar to underground storage for stormwater, retention basins for combined sewage reduce peak flows and help decrease local flooding. Retention basins capture and store some excess combined sewage during storms and then return water back to the system after the storm has passed (USEPA, Retention Basins, 1999). Retention basins can be designed for storage or water quality. Off-line retention basins must be constructed with pumping facilities to get the combined sewage back into the system after the storm has passed. Operations and maintenance is an important aspect of retention basin projects. When designed properly, retention basins can significantly reduce or eliminate CSOs in urban areas.

Sewer Separation

Sewer separation is the process of separating a combined sewage system into two piping systems, one for sewage and one for storm water. A separate stormwater system can discharge directly into surface waters (with proper pretreatment). The sewage system flows are treated at the WWTP, same as before. Sewer separation may be feasible for cities that have land use constraints, when other structural CSO methods are too costly, where complete elimination of CSOs is desired, or when the combined system is undersized (USEPA, Sewer Separation, 1999).

In some cases, sewer separation may increase pollutant loads to surface waters if stormwater runoff contains heavy metals, sediments, and nutrients. The stormwater pollutant load should be evaluated before sewer separation is performed, and stormwater BMPs should be installed during sewer separation to ensure storm water is treated to appropriate levels before entering surface waters. In other cases, aging combined sewer systems may be leaking and allowing pollutants to seep into local water resources. Separating and installing new piping for storm water and sewage may improve local water quality tremendously (USEPA, Sewer Separation, 1999).

Sewer separation may be more cost-effective if implemented at the same time as other municipality improvements such as road paving or repair/replacement of other utilities.

1.4 Literature Review: Solutions under Climate Change

The past decade has seen growing interest and subsequent research performed on the issue of how to plan our water resources within the context of potential future climate change. It is now well-accepted that “stationarity is dead” (Milly et. al., 2008) and that a “new paradigm for water resources design” (Casey, 2010) is necessary, one that enables water systems to respond dynamically to a changing world. Much research has focused on floodplain management of rivers and climate change (Schreider et al., 2000; Simonovic and Li, 2003), as well as water supply and climate change (Boland, 1997; Liverman and Merideth, 2002). However, there has been less research performed on stormwater management and CSO management under climate change. Some articles on this topic are summarized below.

Arisz et al. (2006) focuses on the design and planning of new stormwater infrastructure instead of retrofitting existing systems. Arisz et al (2006) recommend that when designing for drainage, the concept of a minor and major drainageway should be used. Minor drainage is created by smaller, more frequent storms and is served by the traditional storm sewer system. Major drainage is created by the larger, less frequent storms and is served by open channels, rivers and streams, roadways, and detention/retention ponds. Arisz et al (2006) emphasize that the minor drainage system will surcharge, and this reality should be anticipated and addressed during design. They also argue that increases in flow due to climate change are most easily accommodated by the major drainage system because open channels, rivers and streams, roadways, and detention/retention ponds have more capacity than the traditional storm sewer system.

Arisz et al. (2006) suggest that the service life of drainage infrastructure is very long (up to 100 years), thus one should expect gradual changes in the hydrology of the site over the life of the project. They argue that the cumulative effect of such changes become significant over the life of the drainage infrastructure and should be taken into account during design.

Mailhot et al. (2010) focuses on design criteria for stormwater systems and conclude that the service level of stormwater infrastructure is likely to change over time. They present a new statistical method that will determine service level of a design based on the critical return period and reference year. They determine that the longer the expected lifetime of the design, the greater the impact climate change will have on the structure. Thus the design return period will change over its lifetime leading to deterioration in performance levels and this phenomenon will be magnified as the design return period increases. Mailhot et al. (2010) concludes that it is important to take an adaptive approach and that the performance level of the system should be evaluated periodically perhaps through modeling tools.

Denault et al. (2006) analyzes climate trends in northern Vancouver and performs a case study of the major drainageways on an urban watershed in Vancouver. Using 2020 and 2050 synthetic design storms, results showed that climate change would not have a dramatic impact on the current drainage infrastructure of the watershed. Only a few elements in the minor drainage system would be inadequate to convey the 10-year storm, and about 20% of the major drainage system would be undersized to convey the 100-year storm. Denault et al. (2006) acknowledged that their case study may be unique because North Vancouver has steep topography which could overwhelm the climatic impacts. Stormwater runoff flows downstream quickly over steep slopes which may explain why climate change did not cause more surcharging in the system.

Denault et al. (2006) noted that although climate change does not have a dramatic impact on the infrastructure, it may have a dramatic impact on stream health. Increased runoff and peak flows resulting from climate change is analogous to the increased runoff which results from increases in the "equivalent percent of total impervious area (TIA)" of a watershed. The variable TIA is often used as an environmental indicator of stream health Thus increases in rainfall intensity due to climate change also imply degradation in stream health.

Damodaram et al. (2010) provide a case study for evaluating LID and BMP implementation in a highly urbanized watershed. Their literature review concluded that LID performed better (runoff volumes and peak discharges were reduced) for small, less intense storms, while conventional BMPs performed better for larger, more intense storms. Damodaram et al.'s (2010) hypothesis was that "a combined LID-BMP approach may provide control for the entire spectrum of rainfall events."

Damodaram et al. (2010) performed a case study of the watershed containing the Texas A&M University campus in College Station. A BMP scenario (implementation of a detention pond), LID scenario (retrofitted rooftops and parking lots utilizing permeable pavement, rainwater harvesting systems, and green roofs), and combined BMP-LID scenario were modeled and results were compared to existing conditions and predevelopment conditions. The results "demonstrate that the use of LID is highly effective for smaller storms and may be more effective than storage-based BMPs, and as the intensity of the rainfall event increases, the infiltration-based improvements become less effective in impacting the peak flow."

Damodaram et al. (2010) concluded that to effectively manage watersheds to meet the goals of sustainability, smaller, more frequent storms should not be ignored as they may have a significant impact on stream health and ecosystems. The case study showed that infiltration-based LID performs best for smaller storms and storage-based BMPs performs best for larger, more intense storms. "To achieve both flood control and sustainability objectives, LID and BMPs may be used in combination." Future research topics identified were to "utilize optimization methodologies to identify the best combinations of LID and BMPs that would achieve sustainability goals given limited resources."

Semadeni-Davies et al. (2008) presented a case study of the combined sewer system in Helsingbord, Sweden under the impacts of climate change and urbanization. Urbanization was modeled as an increase in sanitary sewage to represent population growth and an increase in impervious cover to represent development, and climate change was analyzed using scenario analysis. A computer model of the drainage system was developed for present climate conditions, a future high gas emission scenario (SRES A2), and a future medium gas emission scenario (SRES B2) under three different urbanization "storylines". The model was simulated for two ten-year time periods: present (1994 – 2003) and future (nominally 2081 – 2090). A total of twelve simulations were performed. Results showed that both climate change and urbanization, alone and together, will worsen current drainage problems by causing a greater volume of CSOs and higher nutrient release to surface water. The use of BMPs and stormwater disconnection from the combined sewer system could reduce the number of CSOs to a very low, if not negligible, level for present and future climate scenarios.

In summary, a review of research within the past decade reveals that research on the topic of stormwater and CSO management under climate change is in its infancy. Few new methods for developing robust adaptive strategies for dealing with future climate change in an urban setting were advanced. Every case study applied a stormwater simulation model to evaluate various stormwater management alternatives with no generalized methodology for testing robust solutions. The primary goal of this study is to introduce a new methodology for testing a strategy to manage storm water under a changing climate which is robust, in the sense that it performs well regardless of future outcomes.

Chapter 2: Stormwater Management Design Criteria and CSO Policy

Design for stormwater management is regulated on the national, state, and local levels. This section describes stormwater regulations at all levels and EPA's CSO Control Policy and speculates what actions may need to be taken for combined sewage systems to remain in compliance under climate change. This section also provides a summary of two cities on the forefront of green infrastructure.

2.1 Federal Regulations - NPDES

Stormwater discharges are regulated under the National Pollutant Discharge and Elimination System (NPDES) Program and enforced by the Environmental Protection Agency (EPA). NPDES is authorized by the Clean Water Act and controls water pollution by regulating point discharges into the waters of the United States. Stormwater point sources are direct discharges from sources such as stormwater pipes and drainage ditches. Stormwater nonpoint sources come from many diffuse sources in the watershed such as sidewalks, roads, highways, agricultural fields, etc.

Municipalities with separate storm sewers (MS4s) need to comply with NPDES Phase I and Phase II regulations. Phase I regulations, issued in 1990, require "medium and large cities or certain counties with populations of 100,000 or more" (USEPA, June 2011) to obtain NPDES permit coverage for stormwater discharges. This phase was instrumental in eliminating many of the large contributors to water pollution around the country. Phase II regulations, issued in 1999, require “small MS4s in urbanized areas as well as small MS4s outside the urbanized areas that are designated by the permitting authority” (USEPA, June 2011) and operators of small construction sites to obtain NPDES permit coverage which has improved water quality further.

The EPA administers and enforces the NPDES program, although many states are authorized to run their own NPDES program and issue NPDES permits. However, Massachusetts is not one of these states (USEPA, 2003). NPDES permits define technology-based and/or water-quality-based limits and establish pollutant monitoring and reporting requirements the MS4 must abide by. Municipalities must develop a Stormwater Management Plan (SWMP) that defines measurable goals and ways to manage storm water through BMPs as well as a monitoring and reporting plan to assess the effectiveness of their stormwater programs.

Now that the majority of point discharges have been targeted, EPA has shifted its focus toward nonpoint sources of pollution (USEPA, 1997). The EPA provides many publications and resources on how to control and minimize nonpoint source pollution (USEPA, August 2011).

Under a changing climate, NPDES permits may need to be revised to consider the effects of more intense rainfall and higher frequency of storms.

Monitoring may need to be increased and more effective stormwater controls may need to be implemented to meet the same water quality limits of the receiving water body. CSOs will occur more frequently and increased controls on combined sewage systems may be warranted. Municipalities will need to adapt their stormwater program to comply with NPDES under a changing climate.

2.2 EPA’s CSO Control Policy

Municipalities with combined sewer systems, such as Somerville, do not fall under the category of MS4s. As point sources, CSOs need to comply with the technology- and water quality-based requirements of the Clean Water Act and NPDES. However, they are not subject to the secondary treatment standards that apply to WWTPs (USEPA, December2001). Municipalities with combined sewer systems need to obtain NPDES permits with CSO conditions and develop a CSO long-term control plan (LCTP).

EPA's CSO Control Policy was published in 1994 and is the national framework for CSO control. The CSO Policy provides guidance to municipalities on how to meet requirements under the Clean Water Act in the most flexible and cost-effective manner possible. The Policy establishes four key principles to guide planning decisions by municipalities and water authorities:

1. “Providing clear levels of control that would be presumed to meet appropriate health and environmental objectives.
2. Providing sufficient flexibility to municipalities, especially financially disadvantaged communities, to consider the site-specific nature of

CSOs and to determine the most cost-effective means of reducing pollutants and meeting CWA objectives and requirements.

3. Allowing a phased approach to implementation of CSO controls considering a community's financial capability.
4. Reviewing and revising, as appropriate, water quality standards and their implementation procedures when developing CSO control plans to reflect the site-specific wet weather impacts of CSOs." (USEPA, CSO Control Policy, September 2002)

The Policy expects that NPDES permits "would require CSO communities to implement nine minimum technology-based controls by January 1, 1997 and to develop CSO LTCPs" (USEPA, CSO Control Policy, September 2002). The Nine Minimum Controls are meant to "maximize the efficiency of existing facilities in order to limit the duration and impact of CSO discharges" and are listed as follows:

1. "Proper operation and regular maintenance programs for the sewer system and CSO outfalls.
2. Maximum use of the collection system for storage.
3. Review and modification of pretreatment requirements to ensure that CSO impacts are minimized.
4. Maximization of flow to the POTW for treatment.
5. Elimination of CSOs during dry weather.
6. Control of solid and floatable materials in CSOs.
7. Pollution prevention programs to reduce containments in CSOs.
8. Public notification to ensure that the public receives adequate notification of CSO occurrences and CSO impacts.

9. Monitoring to effectively characterize CSO impacts and the efficacy of CSO controls.” (USEPA, Nine Minimum Controls, September 2002)

The LTCP must assess a range of control options, including costs and benefits, and provide a CSO control that would achieve appropriate water quality objectives and compliance with the Clean Water Act. Once the NPDES authority and municipality reach agreement on an LTCP, the CSO controls would be designed and constructed as soon as practicable.

Under the EPA CSO Policy, the LCTP should adopt one of two approaches, the “presumption” approach or “demonstration” approach. This study focuses on CSO management strategies under the presumption approach which states there should be:

> "**No more than an average of four overflow events per year**, provided that the permitting authority may allow up to two additional overflow events per year. For the purpose of this criterion an overflow event is one or more overflows from a CSS as the result of a precipitation event that does not receive the minimum treatment specified below; or… "(EPA CSO Policy, 1994)

Under a changing climate, the LTCP may need to be revised to consider the effects of more intense rainfall and higher frequency of storms. CSO overflows may occur more often and with higher volumes. A more aggressive CSO control may need to be installed for the system to remain in compliance with the Clean Water Act. More monitoring may be necessary. Municipalities will need to adapt their CSO control program to comply with NPDES under a changing climate.

2.3 Massachusetts - Stormwater Management Standards

In Massachusetts, EPA has authority of the NPDES Program but works in conjunction with the Massachusetts Department of Environmental Protection (MassDEP) to administer the program and authorize permits. The permit requires municipalities to meet six minimum control measures:

1. "Pollution Prevention/Good Housekeeping for Municipal Operations
2. Must have an Illicit Discharge Detection and Elimination (IDDE) Program
3. Construction Site Runoff Control
4. Post Construction Runoff Control
5. Public Education and Outreach
6. Public Participation and Involvement" (MassDEP, Municipal Compliance Fact Sheet: Stormwater, 2011)

In addition to the federal NPDES requirements, MassDEP has additional state standards called the Massachusetts Stormwater Management Standards that are part of regulation under the Massachusetts Wetlands Protection Act Regulations (310 CMR 10.00) and the 401 Water Quality Certification Regulations (314 CMR 9.00). The Standards are further defined and specified in the Massachusetts Stormwater Handbook with details on how to apply the Standards.

MassDEP created the Stormwater Management Standards in 1996 as part of the Stormwater Policy to "encourage recharge and prevent stormwater discharges from causing or contributing to the pollution of the surface waters and ground waters of the Commonwealth” (MassDEP, January 2008). MassDEP recognized that point and non-point discharges are the major contributor to water quality problems in the waters of Massachusetts (MassDEP, 1996). In 2008, MassDEP incorporated the Stormwater Management Standards into both 310 CMR 10.00 and 314 CMR 9.00, eliminating the need for the Stormwater Policy.

The ten Stormwater Management Standards are summarized as follows.

- **Standard 1** - “No new stormwater conveyances (e.g. outfalls) may discharge untreated stormwater directly to or cause erosion in wetlands or waters of the Commonwealth.”
- **Standard 2** - “Stormwater management systems shall be designed so that post-development peak discharge rates do not exceed pre-development rates” for the 2-year and 10-year 24-hour storm. The 100-year 24-hour storm also needs to be attenuated by the stormwater design if analysis indicates flooding will occur offsite, with all downstream impacts carefully considered.”
- **Standard 3** - “Loss of annual recharge to ground water shall be eliminated or minimized through the use of infiltration measures including environmentally sensitive site design, LID techniques, stormwater BMPs, and good operation and maintenance. At a minimum, the annual recharge from the post-development site shall approximate the annual recharge from pre-development conditions based on soil type. This Standard is met when the stormwater management system is designed to infiltrate the required recharge volume as determined in accordance with the Massachusetts Stormwater Handbook.”

- **Standard 4** - "Stormwater management systems shall be designed to remove 80% of the average annual post-construction load of Total Suspended Solids (TSS). This standard is met when:
    a) Suitable practices for source control and pollution prevention are identified in a long-term pollution prevention plan, and thereafter are implemented and maintained;
    b) Structural stormwater BMPs are sized to capture the required water quality volume as determined in accordance with the Massachusetts Stormwater Handbook; and
    c) Pretreatment is provided in accordance with the Massachusetts Stormwater Handbook."
- **Standard 5** - "For land uses with higher potential pollutant loads, source control and pollution prevention shall be implemented in accordance with the Massachusetts Stormwater Handbook to eliminate or reduce the discharge of stormwater runoff from such land uses to the maximum extent practicable…"
- **Standard 6** - "Stormwater discharges within the Zone II or Interim Wellhead Protection Area of a public water supply and stormwater discharges near or to any other critical area require the use of the specific source control and pollution prevention measures and the specific structural stormwater BMPs determined by the Department to be suitable for managing discharges to such areas as provided in the Massachusetts Stormwater Handbook."
- **Standard 7** – "A redevelopment project is required to meet the following Stormwater Management Standards only to the maximum extent practicable: Standard 2, Standard 3, and the pretreatment and structural stormwater best management practice requirements of Standards 4, 5, and 6. Existing stormwater discharges shall comply with Standard 1 only to the maximum extent practicable. A redevelopment project shall also comply

with all other requirements of the Stormwater Management Standards and improve existing conditions.”

- **Standard 8** - “A plan to control construction related impacts, including erosion, sedimentation, and other pollutant sources during construction and land disturbance activities (construction period erosion, sedimentation, and pollution prevention plan) shall be developed and implemented.”
- **Standard 9** – “A long term Operation and Maintenance (O&M) Plan shall be developed and implemented to ensure that stormwater management systems function as designed.”
- **Standard 10** – “All illicit discharges to the stormwater management system are prohibited.”

The Standards provide a straight-forward list of requirements to keep development and redevelopment projects in compliance with the Clean Water Act, NPDES, the Massachusetts Wetlands Protection Act, and the Massachusetts 401 Water Quality Certification Regulations. This study focuses on stormwater/CSO strategies that take these standards into consideration.

As patterns and frequency of precipitation change over time, the Stormwater Management Standards may need to be updated. The 2-year, 10-year, and 100-year 24-hour storms are continuously changing in a non-stationary climate which should be recognized under the Standards. Recharge volumes to ground water may need to be reconsidered. More intense storms may pick up more pollutants so water quality runoff volumes may need to be increased to accommodate the higher pollutant load. Longer dry periods in between precipitation may increase pollutant loads as well.

In summary, developers building new or retrofitted stormwater systems or water resource managers responsible for CSOs will need to adapt their approach to stormwater management under a changing climate.

2.4 Local Ordinances for Somerville

There are no additional regulations set forth by the City of Somerville for stormwater management. Projects implemented in Somerville comply with MassDep Requirements (City if Somerville, Conservation Commission, 2011). The Somerville Conservation Commission (ConCom) is charged with “preserving and protecting Somerville’s natural environment” (City of Somerville, Conservation Commission, 2011). The ConCom administers and enforces the Wetland Protection Act and River Protection Acts and has authority to review and approve applications for activities near waterfront areas of Somerville including the Mystic River.

2.5 Cities on the Forefront of Green Infrastructure

Traditional urban drainage design is driven by the Clean Water Act, NPDES, CSO Policy, and any additional state and local stormwater regulations that may apply. These regulations have helped improve water quality in urban rivers, lakes, and streams but can only do so much to address nonpoint source pollution from urban runoff. Increasingly, cities around the country have started to address the issue of stormwater quality with a term called “green infrastructure” which is stormwater management with a small-scale and large-scale component. At the small scale, green infrastructure is the same as LID and includes bioretention, porous pavement, green roofs, infiltration planters, rain barrels, etc. At the large scale, green infrastructure adds another dimension to stormwater management by including the "preservation and restoration of natural landscape features (such as forests, floodplains and wetlands); By protecting these ecologically sensitive areas, communities can improve water quality while providing wildlife habitat and opportunities for outdoor recreation." (USEPA, January 2011).

Cities that have incorporated green infrastructure can be seen as models for improving stormwater management in urban areas. The accomplishments of two of these cities, Chicago, Illinois and Philadelphia, Pennsylvania, are described below.

Chicago

Chicago is one of the nation's innovators of green infrastructure. As a combined sewer system community, the city has invested in a deep tunnel storage system to reduce combined sewer overflows during storm events which should be completed in 2019 (EPA, January 2011). However, with the uncertainty of climate change looming, Chicago is promoting LID to add robustness to its stormwater management system. LID will help reduce the "urban heat island effect" that Chicago is prone to, as well as advance its triple-bottom-line which Chicago leaders believe will "help the City stretch taxpayer funds, help residents save money on energy costs, make the City a great place to live, and contribute to increased property values for Chicago homeoweners" (EPA, January 2011).

Actions that Chicago has taken to improve stormwater management include:

- Stormwater Management Ordinance that states as of January 1, 2008 "any new development or redevelopment that disturbs 15,000 square feet or more or creates a parking lot of 7,500 square feet or more must detain at least the first half inch of rain on site" (EPA, January 2011).
- Green Streets Program promotes planting of trees throughout the city.
- Green Roof Program provides grants for green roofs on residential or small commercial buildings.
- Green Alley Program led by the Chicago Department of Transportation has installed more than 100 permeable paving systems in Chicago's public alleyways.
- Sustainable Streetscapes Program integrates LID practices into roadway improvement projects.
- Green Permit Program offers owners and developers incentive to incorporate LID by offering an expedited permitting process and lower permit fees.

As of 2010, nearly 600,000 trees have been planted and more than four million square feet of green roofs have been installed. Data collected from the City Hall's green roof indicates that the roof reduces stomrwater runoff by 50% and significantly reduces energy use, saving the city approximately $5,500 on annual heating and cooling expenses (EPA, January 2011).

Philadelphia

To manage Philadelphia's combined sewer systems (60% combined and 40% separated), the City is implementing the Green City, Clean Waters Plan (Philadelphia Water Department, 2011), passed in June 2011 (Loviglio, 2011). Implementation of the full plan will take 25 years and $2 billion to modify infrastructure and incorporate LID techniques throughout the city. After 25 years, the changes are expected to capture "85% by volume of the combined sewage collected in the Combined Sewer System during precipitation events on a system-wide annual average basis" (Philadelphia Water Department, 2011).

In addition to LID, actions that Philadelphia has taken or plans to take to improve stormwater management include:

- Promotion of LID through the Green Plan Philadelphia, the Green Roof Tax Credit, and the Green Streets program.
- Revised stormwater billing system based on amount of impervious cover. 80% of the fee is based upon a property's impervious area with the remaining 20 percent based upon the property's gross area. Up to 100% of the fee is discounted for customers who reduce impervious cover using LID (EPA, January 2011).
- Revised stormwater regulations that promote developers to build on infill lots instead of undeveloped, natural areas. Also, redevelopment projects may be exempt from Channel Protection and Flood Control Requirements if they can "reduce directly connected impervious area by at least 20 percent" (EPA, January 2011).

In the first year of the revised stormwater regulations, Philadelphia saw over one square mile built with LID features. These practices will "manage most one-inch storms, reducing CSO inputs by 25 billion gallons, which the Philadelphia Water Department estimates will save the City $170 million" (EPA, January 2011). This planned success has helped create political and public support for green infrastructure and promotion of the Green City, Clean Waters Plan.

Chapter 3: Background and Model Formulation for Case Study

This chapter presents background and details on the model formulation for the case study in Somerville. This chapter describes the existing conditions of the combined sewage system, the computer software used for the model formulation, the development of the model, the boundary conditions, the calibration and validation, and the model adjustments made for future simulations.

3.1 Existing Conditions

Somerville, Massachusetts is a highly urbanized city located in Middlesex County just north of Boston as shown in Figure 8.

Figure 8. Location of Somerville, Massachusetts

The 2010 census stated the total population of Somerville to be 75,754, and with an area of 4.2 square miles, is “the most densely populated municipality in New England” (City of Somerville, About Somerville, 2011). The city is highly urbanized, almost completely built out, and has very little open space except for greenways along the Mystic River and Alewife Brook Parkway and Somerville’s parks. Topography varies from flat along the rivers to moderate hills in several parts of the city. Somerville receives approximately 42 inches of annual precipitation. Most of the precipitation falls as rain except during the winter when it can be either rain or snow.

The city is serviced by a combined sewer system called the Somerville-Medford Branch Sewer (S-MBS) that collects sanitary flow from the neighborhoods of Somerville and stormwater runoff that is generated during storms. Sanitary flow comes from the Somerville neighborhoods of Winter Hill, Ten Hills, and East Somerville, as well as the commercial area of Assembly Square and the neighborhoods in Medford south of the Mystic River. The watersheds draining to the S-MBS cover a total area of 1.06 miles and are shown in Figure 9.

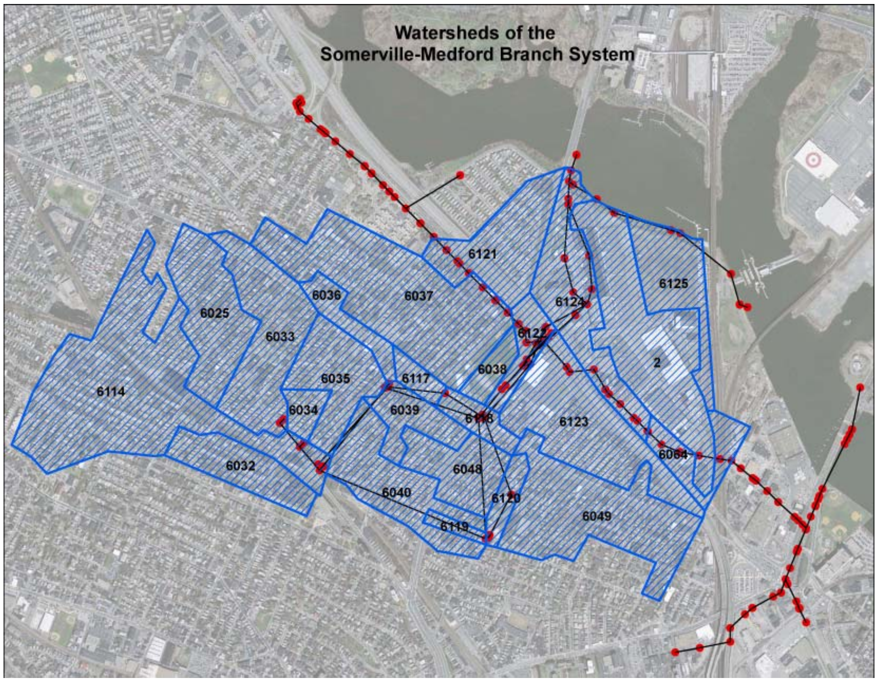


Figure 9. Watersheds of Somerville-Medford Branch Sewer (S-MBS)

A number of the watersheds have separate infrastructure for stormwater and sanitary sewage; however, all separated stormwater in the watershed drain back into the S-MBS. A separate stormwater outfall was never built. The separate and combined watersheds are shown in Figure 10.

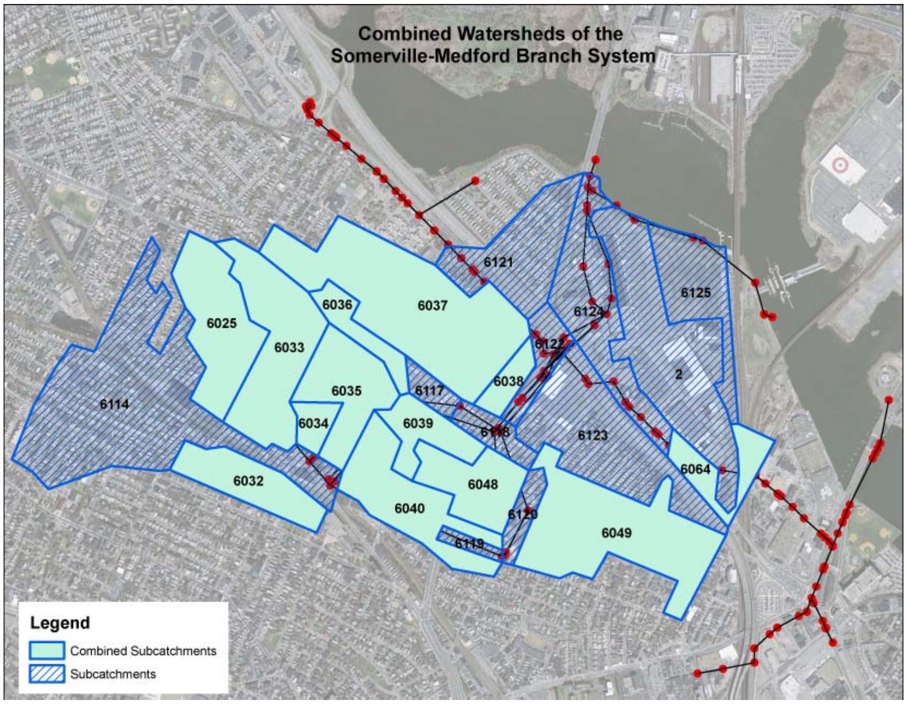


Figure 10. Separate and Combined Watersheds of the S-MBS

Under low flow conditions, storm water and combined sewage flows to the Chelsea Creak Headworks through the DeLauri Pump Station while under high flow conditions, some flow is diverted through the Somerville Marginal CSO facility, triggering a Combined Sewer Overflow (CSO), and into the Mystic River. The Somerville Marginal Facility is gravity-operated and unmanned and has a capacity of 245 million gallons per day (MGD). Water flowing through the facility is screened and chlorinated and then is discharged into the Mystic River into one of two outfalls depending on the tidal elevation. During low tide, flow discharges through the Outfall 205 located below the Amelia Earhart Dam and during high tide, flow discharges through Outfall 205A upstream of the dam. The layout of the S-MBS, locations of the MWRA flow meters, and locations of the outfalls are shown in Figure 11.

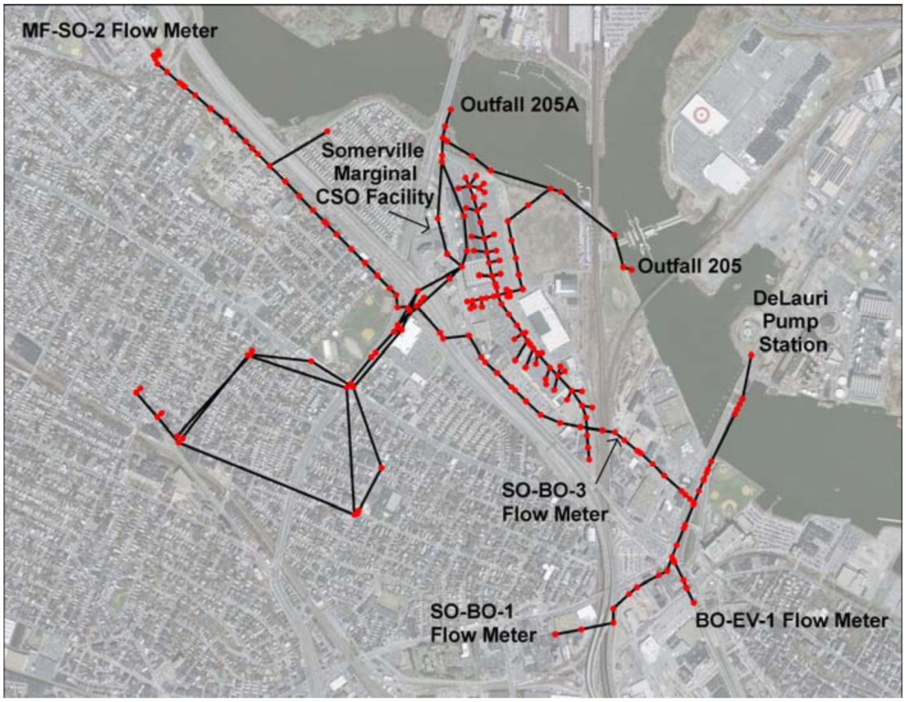


Figure 11. Layout of Somerville-Medford Branch Sewer (S-MBS)

A landuse analysis of the S-MBS watershed, summarized in Table 1, shows that the majority of area is comprised of multi-residential neighborhoods (54%), followed by much smaller areas of industrial (14.5%), commercial (11.4%), transportation (7.7%), and urban public/institutional (6.8%). There are smaller areas of recreation, open land, forest, marina, and water.

Landuse	Percentage of Watershed
Multi-Family Residential	53.9%
Industrial	14.5%
Commercial	11.4%
Transportation	7.7%
Urban Public/Institutional	6.8%
Participation Recreation	2.5%
Open Land	2.5%
Forest	0.3%
Marina	0.3%
Water	0.1%

Table 1. Landuse

In addition to landuse, the watershed was analyzed in terms of impervious cover using the Mass GIS (http://www.mass.gov/mgis/) impervious surface layer at a 1-meter scale. The watershed is 73% impervious, a very high percentage even for an urban city. The analysis assumes all impervious cover within the watershed drains to the S-MBS, because the analysis was unable to determine which areas may be disconnected from the stormwater system.

There are few existing stormwater 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., 2010). The highly urbanized watershed forces Somerville to rely heavily on its stormwater infrastructure to prevent flooding.

3.2 Storm Water Management Model (SWMM) Software

The S-MBS was modeled using the EPA StormWater Management Model (SWMM) Version 5.0.022. SWMM is a dynamic rainfall-runoff simulation model that performs hydraulic routing, hydrologic processes, and pollutant loading mainly for urban and suburban areas. It can simulate single precipitation events or continuous events over time. First developed in 1971, SWMM is a well-reputed model that continues to be used around the world for planning, analysis and design related to stormwater runoff, combined sewers, sanitary sewers, and other drainage systems in urban areas. The current version of SWMM contains the following components:

- Runoff component - generates runoff and pollutant load hydrographs based on single event or long-term precipitation data and a collection of subcatchment areas.
- Routing component - transports runoff hydrographs through a system of pipes, channels, storage/treatment devices, pumps, and regulators. SWMM tracks the quantity and quality of runoff generated within each subcatchment, and the flow rate, flow depth, and quality of water in each pipe and channel during a simulation period comprised of multiple time steps.
    - LID controls – ability to model the hydrologic performance of specific types of LID controls, including porous pavement, bio-retention areas, rain barrels, infiltration trenches, and vegetative swales.

The most recent versions of SWMM employed here integrate LID control options into the hydrologic and hydraulic processes of the software. This feature is relatively new for SWMM and has only been available since Version 5.0.019 was released in August 2010. LID controls in SWMM are designed to capture surface runoff within a subcatchment and provide some combination of detention, infiltration, and evapotranspiration. Although LID techniques can provide water quality benefits, at this time SWMM only simulates the hydrologic functions of LID. A mass balance is performed on each LID control and SWMM keeps track of how much water moves through and is stored within each LID.

Within a subcatchment, surface runoff flows into the specified LID controls, which act in parallel. LID controls cannot act in series in SWMM. LID controls replace some of the subcatchment area so that percent impervious values need to be reevaluated after they are entered in the model. Each LID control is represented by vertical layers such as a surface layer, pavement layer, soil layer, storage layer, and underdrain system. For example, the conceptual diagram of a bioretention cell in SWMM is in Figure 12.

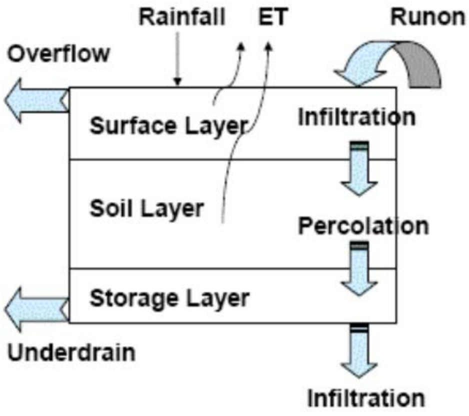


Figure 12. Conceptual Bioretention Cell in SWMM

(Rossman, 2010)

Each type of LID control (i.e. bioretention, rain barrel, infiltration trench, porous pavement, and vegetative swale) contains a combination of layers unique to that LID. Table 2 below shows which layers apply to each type of (where x = required, o = optional).

	Layers				
LID Type	Surface	Pavement	Soil	Storage	Underdrain
Bio-Retention Cell	x		x	x	o
Porous Pavement	x	x		x	o
Infiltration Trench	x			x	o
Rain Barrel				x	x
Vegetative Swale	x				

Table 2. Applicable Layers for Each LID Type in SWMM

(Rossman, 2010)

Depending on the LID type, water can leave an LID control through evaporation, infiltration into native soils according to the Curve Number infiltration model or other infiltration models, an underdrain system depending on a drain rate, or overflow out of the surface layer once storage capacity has been exceeded. Water flowing through the underdrain system or as overflow is sent directly into the drainage system to the corresponding downstream node. There is an option to send overflow from an LID control to pervious areas in the subcatchment before entering the drainage system. For this study, this option was utilized for rain barrels because it was assumed that stored water would overflow to lawn areas.

3.3 Model Development

The Massachusetts Water Resources Authority (MWRA) provided a SWMM input file of the MWRA "North System" which includes the S-MBS. MWRA models their wastewater collection system in Infoworks, commercial software that simulates hydraulic routing, hydrologic processes, and pollutant loading (similar to SWMM) but Infoworks can also perform real-time control which

SWMM cannot perform. MWRA converted the North System Infoworks model into SWMM format for use in this study. The conversion process created errors in SWMM which were addressed and listed in Appendix A.

The model configuration of the S-MBS and a section of the Cambridge Branch Sewer ending at the DeLauri Pump Station were retained in SWMM for this study. From discussions with Cambridge and Somerville officials as well as personal experience from model simulations, it was known that the S-MBS is affected by flow in the Cambridge Branch. Therefore, it was important to include a section of the Cambridge Branch for simulation and to choose the boundary conditions appropriately.

3.4 Boundary Conditions

The upstream end of the S-MBS is located at the Medford-Somerville town line. Inputs into the system at this location include a subcatchment that represents flow coming in from Medford. Flow is metered here by the MF-SO-2 meter. See Figure 11 for flow meter locations. Flow meter readings for the year 2008 were provided by MWRA for assistance in the calibration and validation of the SWMM model.

Two boundary conditions along the main branch of the S-MBS include:

1. Outfall above Amelia Earhart Dam set to a fixed water surface elevation of 105 ft MDC datum (CDM, 2003); and

2. Tidal outfall downstream of the Amelia Earhart Dam set to the corresponding historical NOAA tidal data (Boston MA Station ID 8443970) during calibration and validation efforts.

The upstream boundary condition of the Cambridge Branch was chosen at the location of the SO-BO-1 flow meter. The upstream boundary condition of a smaller branch flowing into the Cambridge Branch was chosen at the location of the BO-EV-1 meter.

The downstream boundary condition of the Cambridge Branch was chosen at the location of the DeLauri Pump Station. The pump station was included with initial modeling efforts, but due to the lack of real time controls in SWMM the complexities of the pump station were unable to be modeled accurately. The DeLauri pump station is modeled as a “free” outfall in SWMM, meaning there are no fixed water elevation constraints at this outfall. This configuration results in the assumption that flow is not throttled at the pump station during storms. In reality, flow is throttled during large storms; however, we are assuming no throttling in order to isolate the effects on the S-MBS and to keep this downstream boundary condition consistent for all simulations.

3.5 Calibration and Validation

Although the S-MBS system had been previously calibrated and validated in Infoworks, it was necessary to re-calibrate and validate the model to ensure the model performed well in SWMM for the purpose of this study. SWMM inputs that were adjusted included:

- Subcatchments parameters
    - Percent impervious
    - Width of subcatchment
    - Curve number for pervious areas
    - Manning's n values for overland flow
    - Depth of depression storage
- Dry weather flows
    - Infiltration
    - Sanitary flow

See Appendix B for calculations of the SWMM inputs. In addition to the SWMM inputs, the model was updated to run one previous day of dry weather. The model uses dynamic wave routing in order to simulate backwater effects and allows ponding at junctions to simulate flooding. The model utilizes the Curve Number infiltration model to simulate infiltration into soils in pervious areas.

MWRA flow meter data was provided at the upstream boundary of the S-MBS (meter MF-SO-2), at the upstream boundary of the Cambridge Branch (meter SO-BO-1), and at a smaller branch entering the Cambridge Branch (meter BO-EV-1). Flow data at these locations were used as direct inputs into the SWMM model for the calibration and validation storms.

The SWMM model was calibrated at the SO-BO-3 flow meter location in the main trunk for the July 19-25, 2008 storm which had a total rainfall depth of 4.70

inches over 5 days. Figures 13 and 14 compare pipe flows and depths between observed MWRA flow meter data and SWMM model results.

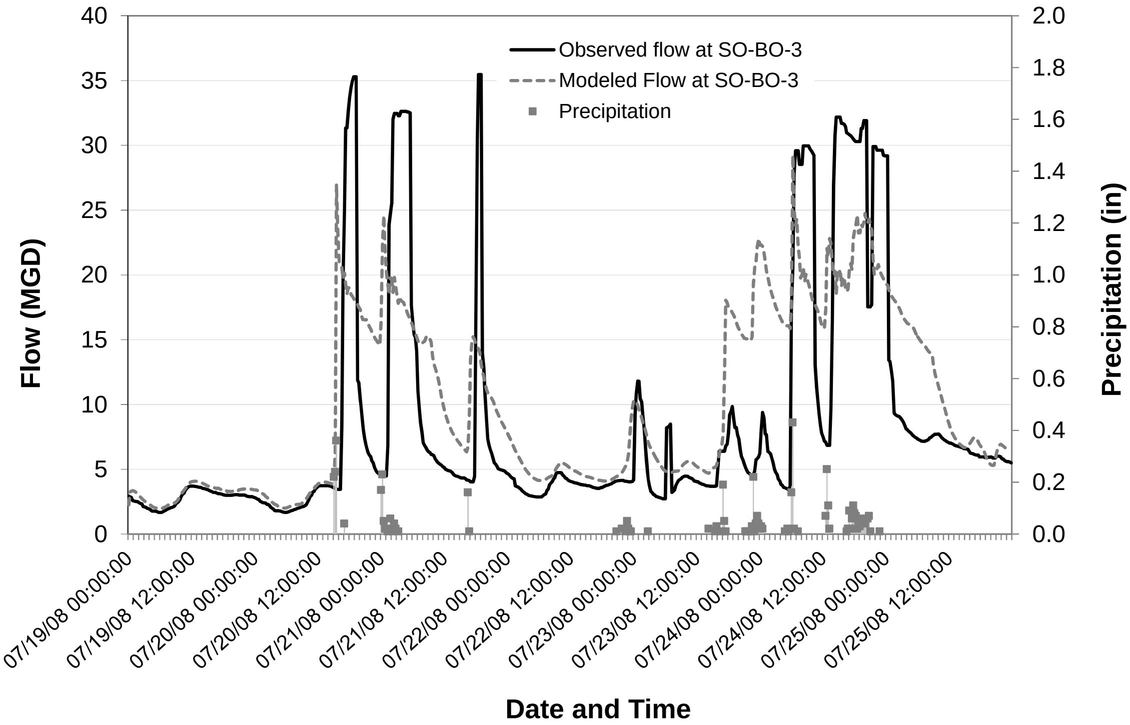


Figure 13. S-MBS Flow July 19-25, 2008

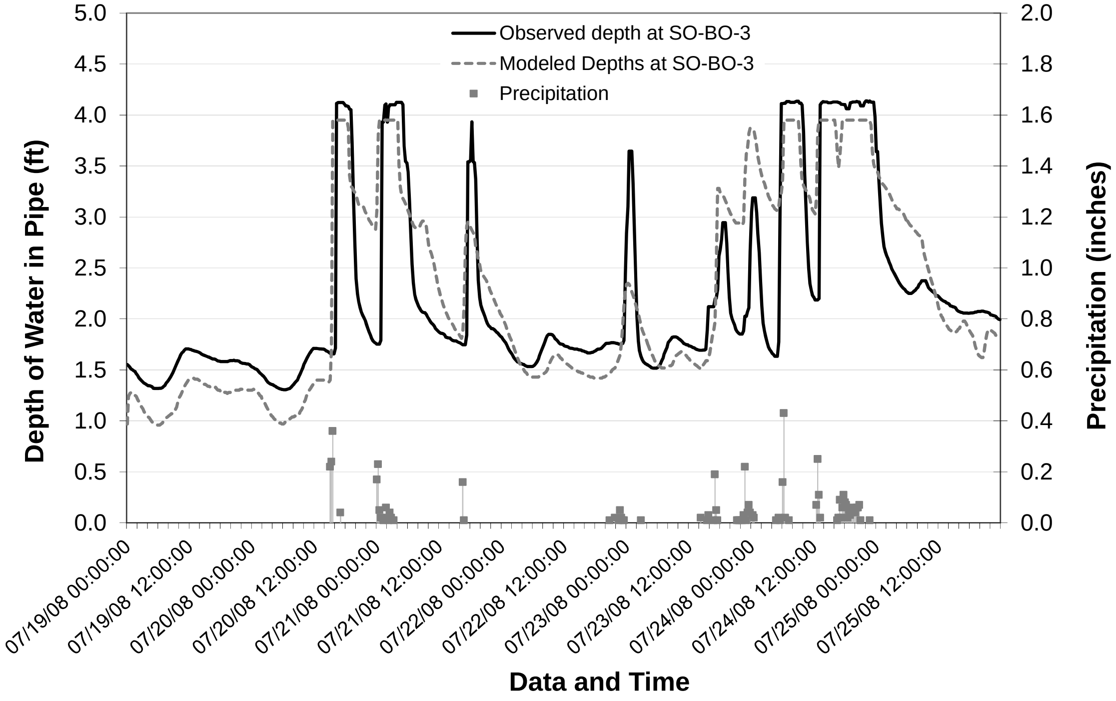


Figure 14. S-MBS Water Depths July 19-25, 2008

Figures 13 and 14 show that modeled flows and depths match relatively well with the observed flows and depths at the SO-BO-3 meter for this event. Precipitation values are graphed on the secondary axis of both figures for reference.

The SWMM model was validated for the August 10th and Sept 26th storm of that same year. The August 10th storm had a total rainfall depth of 2.57 inches over 1 day, and the September 26th storm had a total rainfall depth of 3.20 inches over 4 days. Figures 15-18 compare the pipe flows and depths at the location of SO-BO-3 between observed MWRA flow meter data and the SWMM model results for the two validation events.

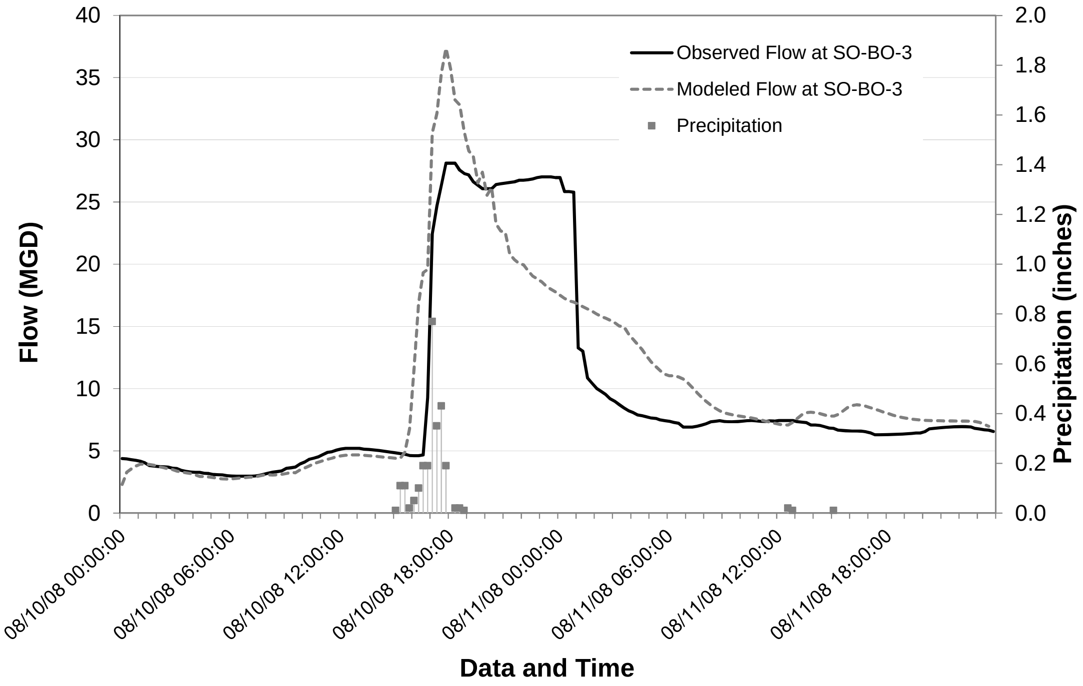


Figure 15. S-MBS Flow August 10-11, 2008

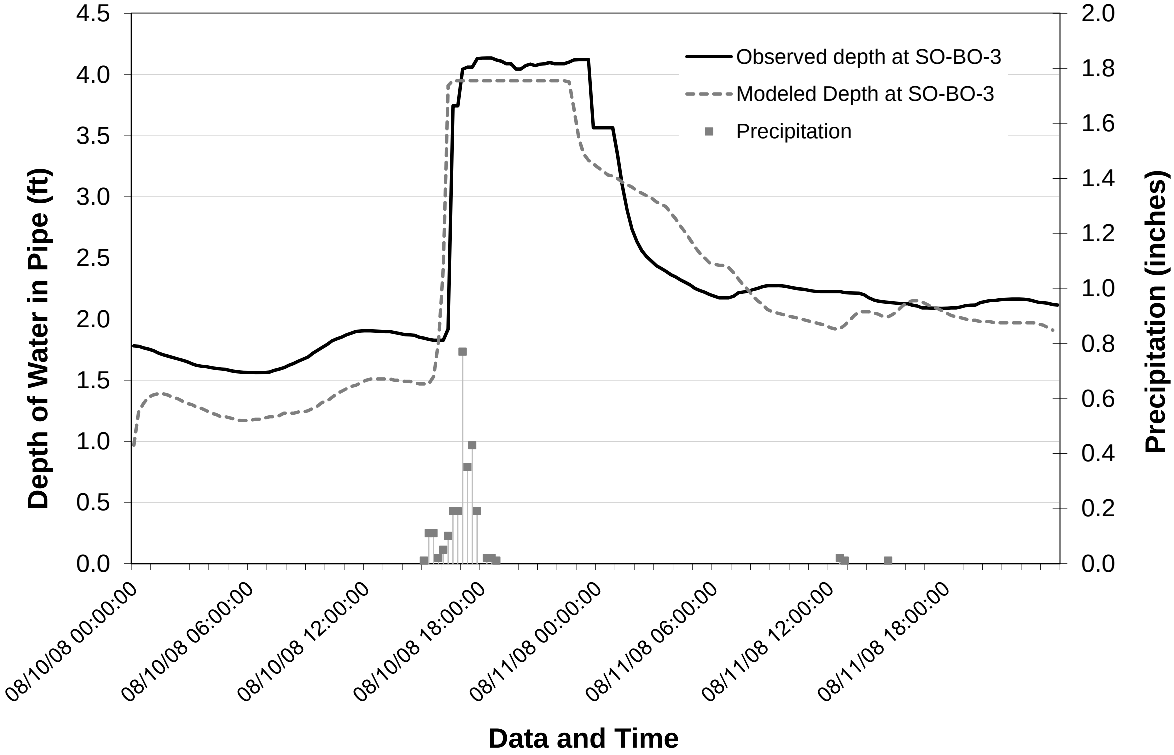


Figure 16. S-MBS Water Depths August 10-11, 2008

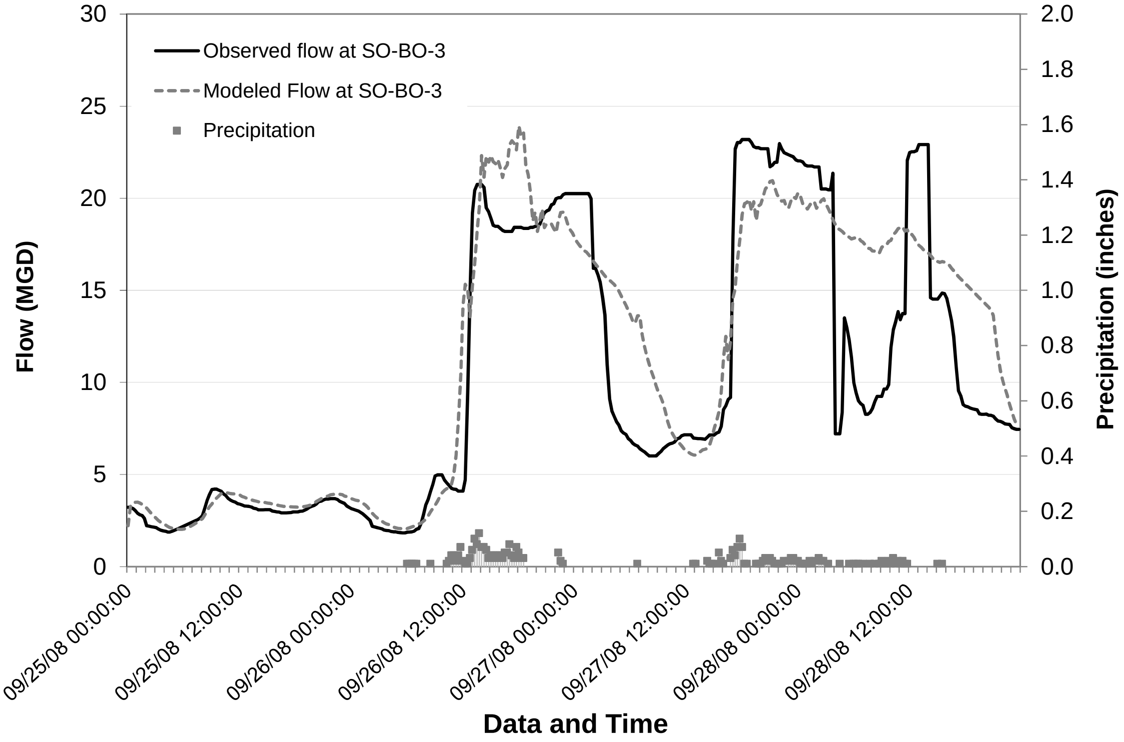


Figure 17. S-MBS Flow September 25-29, 2008

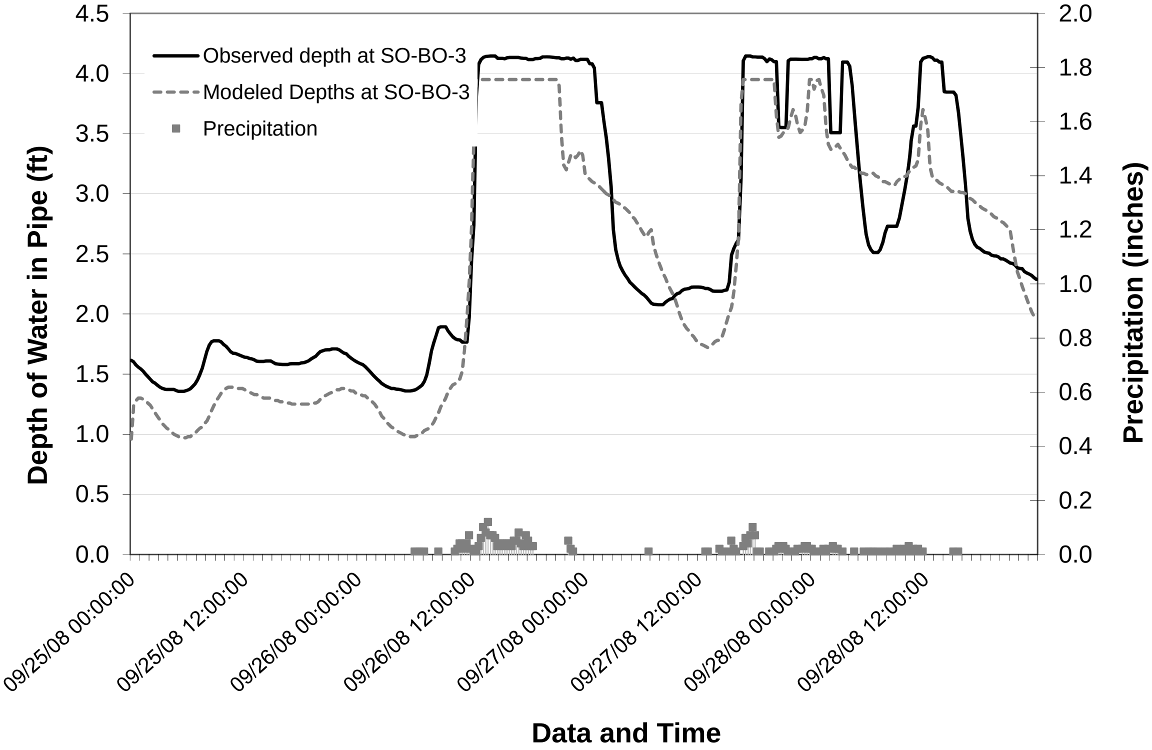


Figure 18. S-MBS Water Depths September 25-19, 2008

Figures 15, 16, 17, and 18 show that modeled flows and depths match relatively well with the observed flows and depths at the SO-BO-3 meter.

In addition to flow and water depths in the system, CSO facility and outfall discharge duration, volumes, and peak flows were analyzed during calibration and validation efforts. Table 3 compares observed MWRA data versus modeled data at the Somerville Marginal CSO Facility and Outfall 205A (upstream of the dam).

Type of Simulation	Date of Storm	Somerville Marginal CSO Facility					
		Discharge Duration (hrs)		Total Volume (Mgal)		Peak Flow (MGD)	
		Observed	Modeled	Observed	Modeled	Observed	Modeled
Calibration	July 20-21, 2008	3.6	16.3	5.1	7.0	165	57
Validation	July 23-25, 2008	8.8	11.0	13.1	18.1	120	63
Validation	August 10-11, 2008	4.8	25.5	12.1	18.5	161	152
Validation	September 26-27, 2008	8.3	23.0	14.4	12.5	82	44

Type of Simulation	Date of Storm	Outfall 205A					
		Discharge Duration (hrs)		Total Volume (Mgal)		Peak Flow (MGD)	
		Observed	Modeled	Observed	Modeled	Observed	Modeled
Calibration	July 20-21, 2008	0.1	6.5	n/a	2.9	24	24
Validation	July 23-25, 2008	0.2	21.5	n/a	10.1	74	67
Validation	August 10-11, 2008	0.6	3.8	n/a	8.6	n/a	123
Validation	September 26-27, 2008	n/a	21.5	n/a	11.7	n/a	48

Table 3. CSO Facility and Outfall 205A Calibration and Validation Data

For purposes of this study, calibration and validation efforts focused on total volume through the CSO facility, and table 3 shows that the modeled data matches relatively well with the observed data, where available.

Thus we conclude that the calibrated model parameters result in realistic model validations.

3.6 Simulation Adjustments

To prepare the SWMM model for design storm simulations, two more modifications to the model were performed. First, metered flows at the boundaries of the S-MBS and Cambridge Branch, including meters MF-SO-2, SO-BO-1, and BO-EV-1 were replaced with subcatchments in order to capture the response of the system under rainfall events different from the calibration and validation storms. This allows the model to be simulated under any possible design storm. The subcatchment draining to the upstream boundary condition of the S-MBS from the North System SWMM file replaced the metered flow at MF-SO-2 in the SWMM model. Subcatchments draining to SO-BO-1 and BO-EV-1 were created based on the known characteristics of the MF-SO-2 subcatchment. The models for these subcatchments were calibrated to the historical flow data of September 25-29, 2008 storm data. Calibration graphs are shown in Figure 19 for SO-BO-1 and Figure 20 for BO-EV-1.

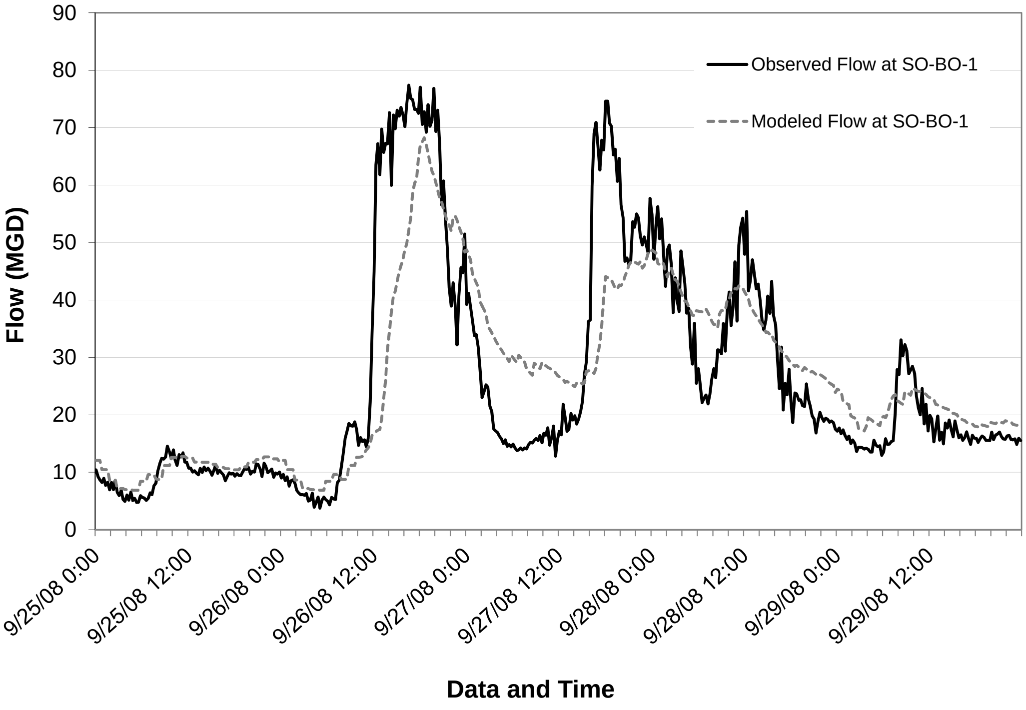


Figure 19. SO-BO-1 Flows September 25-29, 2008

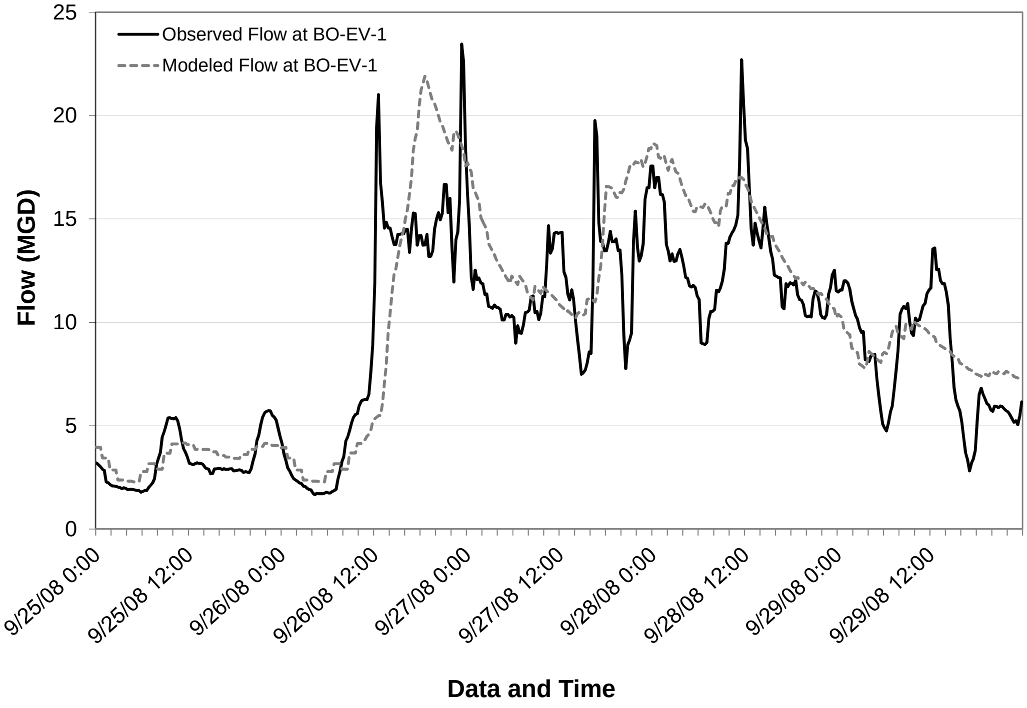


Figure 20. BO-EV-1 Flows September 25-29, 2008

Figures 19 and 20 show acceptable calibrations for meters SO-BO-1 and BO-EV-1. During the design storm simulations, no change in precipitation is applied to these subcatchments in order to isolate climate change effects on the S-MBS. This action assumes that Medford and Cambridge are doing their part to mitigate for climate change. Because the inputs from these subcatchments will remain the same for all climate change scenarios, these calibrations are acceptable for this study.

The second and last modification performed on the SWMM model was the addition of the Assembly Square drainage network. Assembly Square is currently under construction with new office space, retailers, and residential units; therefore, its drainage network was not included during calibration and validation of the model using 2008 historical data. The finished stormwater management network in Assembly Square includes some LID features including a 2-acre green roof that will be installed on a portion of the IKEA building and a sediment forebay (4,988 cubic feet) and bioretention area (15,532 cubic feet) that will treat and store storm water draining from the IKEA loading dock.

The Assembly Square stormwater management network drains into the S-MBS downstream of the Somerville CSO facility so the addition of this section has minimal influence on the S-MBS. It does not affect volume of flow through the Somerville CSO facility. However, it was included to capture the completeness of the S-MBS SWMM model.

With the addition of MF-SO-2, SO-BO-1, and BO-EV-1 subcatchments and the Assembly Square drainage network, the SWMM model is ready for design storm simulations.

Chapter 4: Methodology

This chapter presents the methodology applied to the Somerville case study. Five feasible stormwater/CSO strategies were identified and the designs were incorporated into SWMM. Each strategy was simulated under low, moderate, and high climate change scenarios for the 3-month 24-hour, 10-year 24-hour, and 100-year 24-hour design storms (hereafter identified as the 3-month, 10-year, and 100-year storms). These simulations were performed for three points in time: 2010 (present), 2040, and 2070. This methodology is shown as a tree diagram in Figure 21.

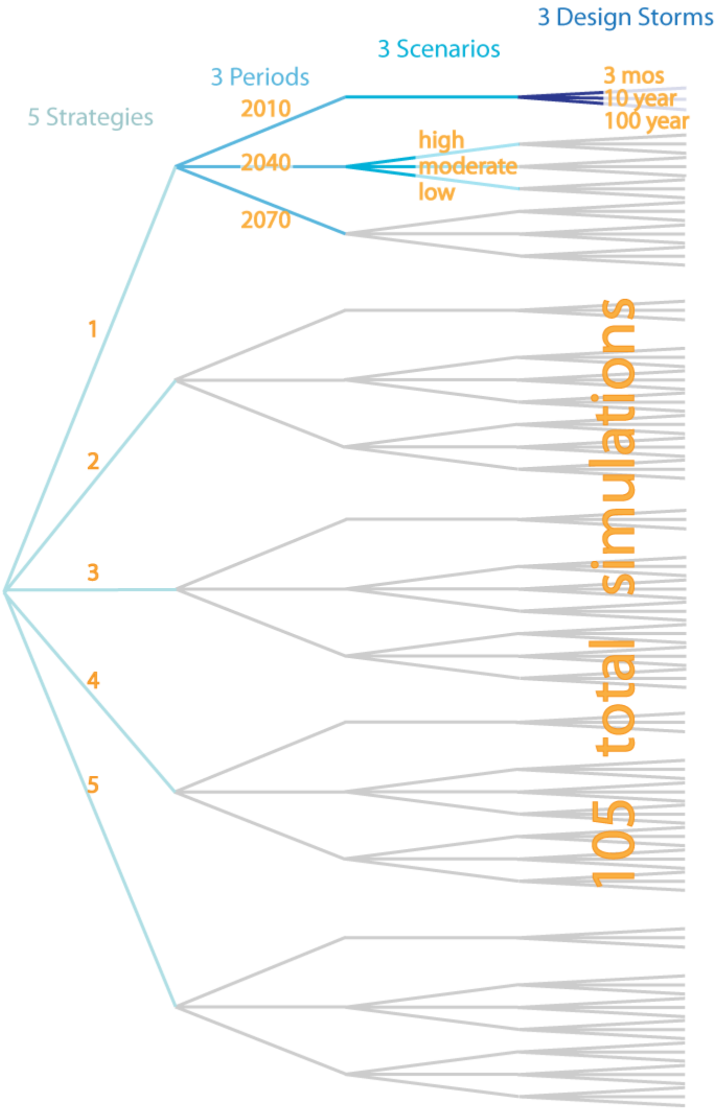


Figure 21. Tree Diagram of Methodology

The tree diagram provides a framework to show each strategy tested. A total of 105 strategies were tested in SWMM. Strategies that perform well under all climate change scenarios and for all design storms are considered robust.

This chapter explains the climate change scenarios in detail, the design storms and why they were chosen, and the two performance metrics each strategy was compared against. It also explains the five stormwater management strategies in detail.

4.1 Climate Change Scenarios

Precipitation

An important aspect of the methodology involves the definition of the climate change scenarios. One of the challenges of designing for climate change is that it is impossible to assign probabilities to possible future climate conditions. While some researchers have quantified these types of uncertainties, this study uses scenarios without assigned probabilities. A scenario is an internally consistent plausible future that might evolve from present conditions given various driving forces (Groves and Lempert, 2007). To analyze scenarios, this study uses three points in time: 2010 (present), 2040, and 2070. The years 2040 and 2070 were chosen because a sixty-year planning horizon for stormwater management is a plausible timeframe. Data from General Circulation Models (GCMs) were available for 2050 and 2100 which encompasses 2040 and 2070 and allows for interpolation of downscaled GCM data for Somerville.

GCMs are mathematical models of the general circulation of the Earth's atmosphere and are used for weather forecasting, understanding the climate, and projecting climate change (i.e. future precipitation and temperature). Global weather patterns are complex and climate change involves high uncertainty. Further uncertainty is introduced when “downscaling” techniques are used to translate GCMs into predictions for specific geographic locations such as for the city of Somerville. Powell (2008) performed analysis and downscaling of twenty GCMs for the Special Report on Emission Scenarios (SRES) of greenhouse gases (GHG), including SRES scenarios B1, A1b, and A2, to obtain estimated percent changes in annual precipitation for Somerville. B1 is a low change scenario and represents a “convergent world with an emphasis on sustainability”. A1b is a moderate change scenario. A2 is a moderate-to-high change scenario and represents a “differentiated world” (IPCC, 2001 and Solomon et al., 2007).

For each SRES scenario, twenty GCM datasets of daily precipitation were fit to a Log Pearson Type III distribution and results were displayed as box and whisker plots to show the variability in relative percent changes for annual precipitation in Somerville. Powell’s results are shown below for the 2-year design storm, 10-year design storm, and 100-year design storm respectively for 2050 and 2100. For each box and whisker plot, Q1 is defined as the 25th percentile of values, median is the 50th percentile of values, and Q3 is the 75th percentile of values.

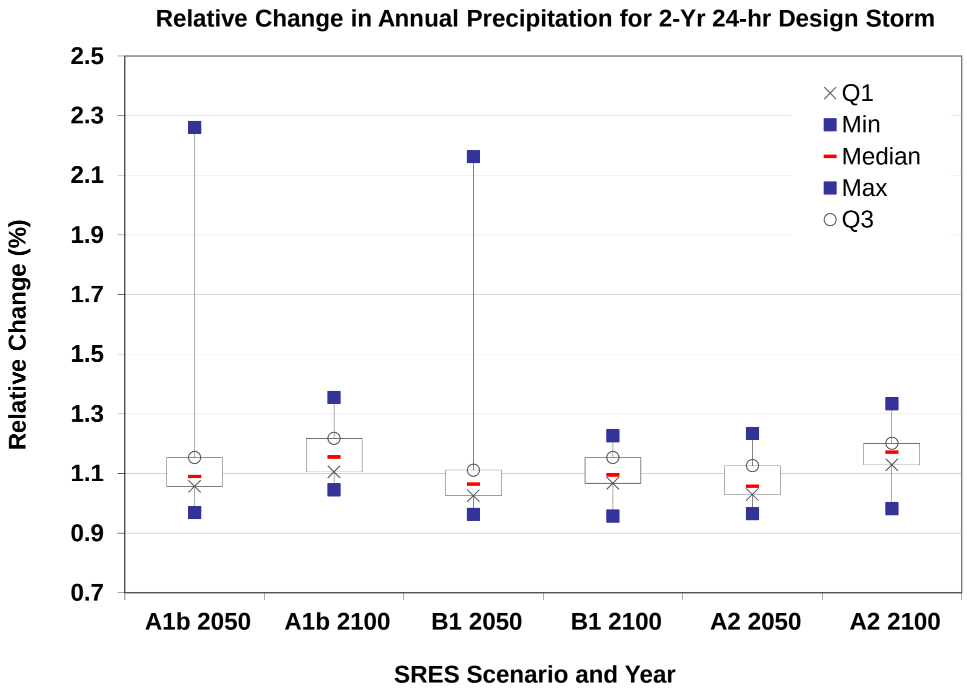


Figure 22. Relative Change in Annual Precipitation for 2-yr Design Storm

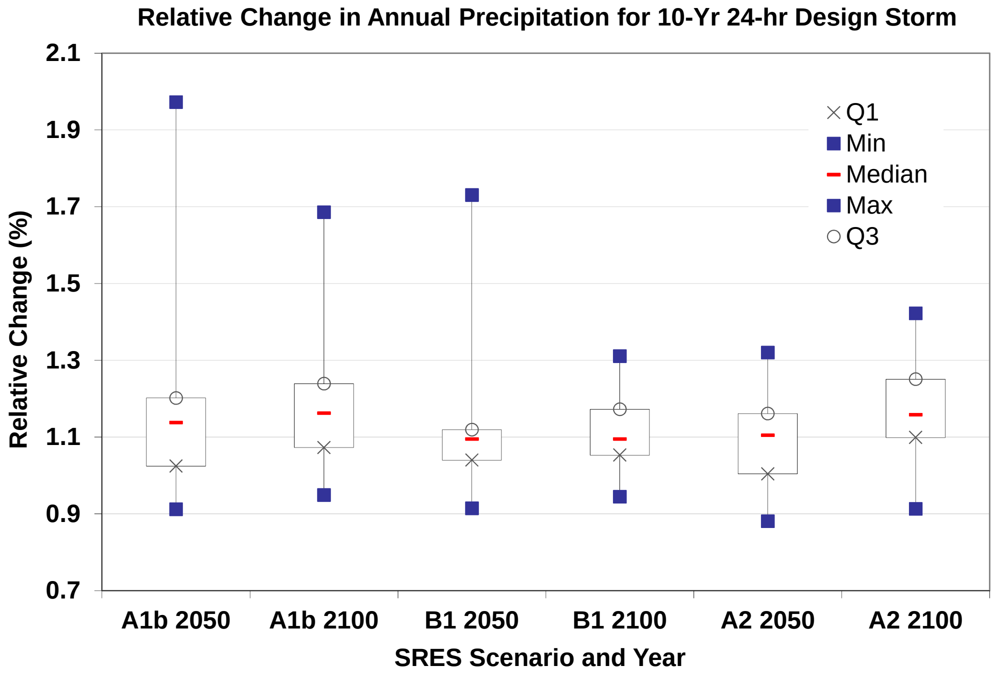


Figure 23. Relative Change in Annual Precipitation for 10-yr Design Storm

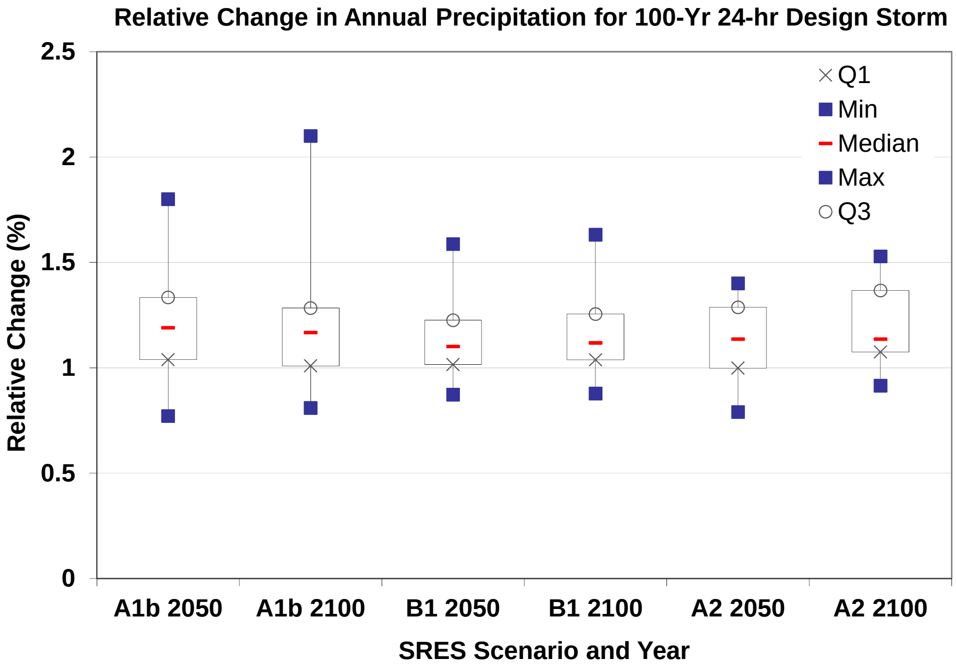


Figure 24. Relative Change in Annual Precipitation for 100-yr Design Storm

Based on the downscaled SRES scenarios shown in Figures 22, 23, and 24, three climate scenarios were defined in Table 4 for 2050 and 2100 using the terms “low, moderate, and high”.

Climate Change Scenario	Definition
Low	Minimum of the 25th % values (Q1) of the SRES
Moderate	Median of the 50th % values of the SRES
High	Maximum of the 75th % values (Q3) of the SRES

Table 4. Definition of Climate Change Scenario

In some instances, the SRES scenario (A1b, B1, or A2) defined for a climate change scenario in 2100 was different than the SRES scenario defined in 2050. For example, for the 10-year storm, the SRES scenario that had the minimum value for the 25th percentiles in 2100 (SRES B1) was different than the SRES scenario that had the minimum value for the 25th percentiles in 2050 (SRES A2).

This can be seen in Figure 23. In these instances, the SRES scenario chosen for 2100 was also chosen as the model for 2050 to ensure interpolation between values was credible for the years 2040 and 2070. For example, SRES scenario B1 was chosen for use in the low climate change scenario for the 10-year design storm in 2100 and 2050.

The smallest design storm Powell analyzed was the 2-year storm. In addition to the 10-year and 100-year storm, this study focused on the 3-month storm because it is an approximation for a low-flow storm that would occur four times in any one year which is the number of CSOs the EPA CSO Policy strives for (see Section 4.2 for further detail). Because no data were available on the 3-month storm, the relative change percentages calculated for the 2-year storm were used as the relative change percentages for the 3-month storm for the purposes of this study. Annual relative percent changes identified for each climate change scenario for each design storm are shown below. The SRES scenario used for each scenario is in parentheses.

24-hour Design Storm	Annual Relative Percent Change for each Climate Change Scenario (%)					
	2050			2100		
	Low	Moderate	High	Low	Moderate	High
3-mo	1.06 (A1b)	1.09 (A1b)	1.15 (A1b)	1.10 (A1b)	1.15 (A1b)	1.22 (A1b)
10-year	1.04 (B1)	1.10 (A2)	1.16 (A2)	1.05 (B1)	1.16 (A2)	1.25 (A2)
100-year	1.04 (A1b)	1.14 (A2)	1.29 (A2)	1.01 (A1b)	1.13 (A2)	1.37 (A2)

Table 5. Annual Relative Percent Changes for CC Scenarios in 2050 and 2100

Values for the high, moderate, and low scenario in 2050 and 2100 were then linearly interpolated to find high, moderate, and low scenarios for 2040 and 2070. Interpolation was performed between 2010 and 2050 to obtain percent change in precipitation for 2040, and interpolation was performed between 2050 and 2100 to obtain percent change in precipitation for 2070. Interpolated relative percent change values for each climate change scenario are shown below.

24-hour Design Storm	Annual Relative Percent Change for each Climate Change Scenario (%)					
	2040			2070		
	Low	Moderate	High	Low	Moderate	High
3-mo	1.05	1.08	1.14	1.08	1.12	1.18
10-year	1.04	1.09	1.14	1.05	1.13	1.20
100-year	1.04	1.14	1.27	1.03	1.14	1.32

Table 6. Annual Relative Percent Changes for CC Scenarios in 2040 and 2070

Finally, the percent change for each scenario was multiplied by existing design storm totals for Somerville to obtain future design storm totals. Future design storm values for 2040 and 2070 are shown below.

24-hour Design Storm		Storm Total for each Climate Change Scenario (inches)					
	2010	2040			2070		
		Low	Moderate	High	Low	Moderate	High
3-mo	1.69	1.76	1.80	1.88	1.82	1.89	1.99
10-year	4.88	5.03	5.26	5.47	5.10	5.49	5.84
100-year	8.84	9.10	9.74	10.74	9.08	10.03	11.66

Table 7. Storm Total for each Climate Change Scenario

Existing design storm totals for the 10-year and 100-year storms in 2010 were obtained from the Cornell University interactive web tool for extreme precipitation analysis (Cornell, 2011). The 3-month storm is an approximation for a low-flow storm that would occur four times in any one year and was determined based on analysis of the daily precipitation record at Boston Logan International Airport. The complete set of daily precipitation data at Logan Airport from 1973 through 2010 was downloaded from the National Climatic

Data Center. The largest storm in each 3-month period of every year (Jan – March, April – June, July – September, October – Dec.) was identified and used to create a new data series. This data series was fit to a lognormal distribution and the median value was identified as 1.69 inches, the “typical” 3-month storm. Design storms are discussed in further detail in Section 4.2.

Surface Water Elevations

In addition to precipitation, the surface water elevations of the Mystic River needed to be adjusted for climate change. 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 upstream flooding in the future (i.e. increased pumping). The water surface level would remain constant behind the dam at the present elevation of 105 feet MDC datum.

At the downstream outfall below the Amelia Earhart dam, tidal data were adjusted for the years 2040 and 2070 due to sea level rise. The tidal cycle observed during the July 21 – 24, 2008 calibration storm was used as a typical tidal cycle for the design storms because the pattern represented an average tidal cycle. High tide was set to occur one hour after the rainfall peak for each design storm to coincide with high flows in the S-MBS and create a worst-case scenario for drainage. The small amount of subsidence in the region which is approximately 7.8 inches/100 years (Kirshen, 2008) was ignored. Sea level rise estimates were based on results from Vermeer and Rahmstorf (2009) and are shown below according to the corresponding climate change scenario.

Climate Change Scenario	2040	2070
Low	0.66 ft.	1.64 ft.
Moderate	0.98 ft.	1.97 ft.
High	1.31 ft.	2.62 ft.

Table 8. Climate Change Scenarios for Sea Level Rise

(Vermeer and Rahmstorf, 2009)

4.2 Design Storms

To capture variability of the system's response to small, frequent storms and larger, infrequent storms, the 3-month, 10-year, and 100-year design storms were chosen for simulation. All three design storms were input as 15-minute precipitation data into SWMM according to the Soil Conservation Service (SCS) Type III distribution, the typical distribution of a storm in the Northeast U.S. (Chow et. al., 1998). Design storms were simulated using one previous day of dry weather, 24 hours of precipitation, and one latter day of dry weather.

The 3-month storm was chosen as a small, frequent storm for evaluation. This storm is typically exceeded four times in one year. This storm was chosen specifically to evaluate the S-MBS against the EPA CSO Policy that states there should be no more than an average of four overflow events per year under the presumption approach. Currently, the Somerville Marginal CSO Facility activates more than four times per year on average. Between 1999 and 2008, the

Somerville Marginal CSO Facility experienced 24 activations each year on average (Wu, 2009). MWRA has a variance through Sept 1, 2013 that authorizes limited CSO discharges to the Alewife Brook and the Upper Mystic River (section of the river above the dam) (Haas, 2010). The variance states:

> "CSO discharges to the Upper Mystic River Basin, not including Alewife Brook, are now limited to infrequent, treated discharges from the Somerville Marginal facility through the high tide outfall (SOM007A/MWR205A) upstream of the Amelia Earhart Dam." (Haas, 2010 and MassDEP, 2010)

This statement acknowledges that CSOs through Outfall 205A are treated with basic screening and chlorination. However, the Long-term CSO Control Plan sets a target of three overflows at Outfall 205A (upstream of the dam) (MassDEP, 2010). A target of three overflows at Outfall 205A implies that the Somerville Marginal CSO Facility would activate approximately six times in a year, assuming that high tide occurs 50% of the time during a significant storm. A high tide is necessary to force a CSO at Outfall 205A (see Section 3.1 for detail). A reduction in number of CSOs would bring the Mystic River closer to compliance with "Class B water quality criteria 98.5 percent of the time," the LCTP's water quality goal for the Alewife Brook and Upper Mystic River (MassDEP, 2010).

The 10-year and 100-year storms were chosen for evaluation as larger, more infrequent storms because these storms must be evaluated under Standard 2 of the Massachusetts Stormwater Rules for stormwater management design. The

10-year storm is defined as a storm that has a 10% chance of being exceeded in any one year, and the 100-year storm is defined as a storm that has a 1% chance of being exceeded in any one year. These storms were also chosen because they provide data to determine the expected value of costs during the decision-making processes.

4.3 Definition of Performance Metrics

Two performance metrics were considered for this study, including hazardous volume of flooding in streets and volume of flow through Somerville Marginal CSO Facility. Both metrics are defined below.

Hazardous Flooding

Hazardous flooding was chosen as a metric because there is an existing flooding problem in Somerville. 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 Somerville dropped approximately 3.5 inches of rain in an hour which caused combined sewage to surcharge into the streets. One woman needed to be rescued from the Route 28 underpass on McGrath Highway near Assembly Square because the water rose too quickly for her to drive out of the tunnel (TheBostonChannel.com, 2010).

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 according to the following equation: Nuisance flooding = pipe length x average road width x average curb height

Values for nuisance flooding were very small compared to total flooding during model simulations, so nuisance flooding was ignored when determining hazardous flooding.

Volume of Flow through Somerville Marginal CSO Facility

Volume of flow through the CSO facility was calculated as the total inflow over the storm event in million gallons (MG) entering node SM6315E in the model which is representative as the point where flow leaves the CSO facility. CSO volumes at the upstream outfall above the dam (Outfall 205A) and at the downstream outfall below the dam (Outfall 205) were not used because storm water enters the system downstream of the CSO facility at two points, at node SM6315ETG and node 1008799 as shown in Figure 25.

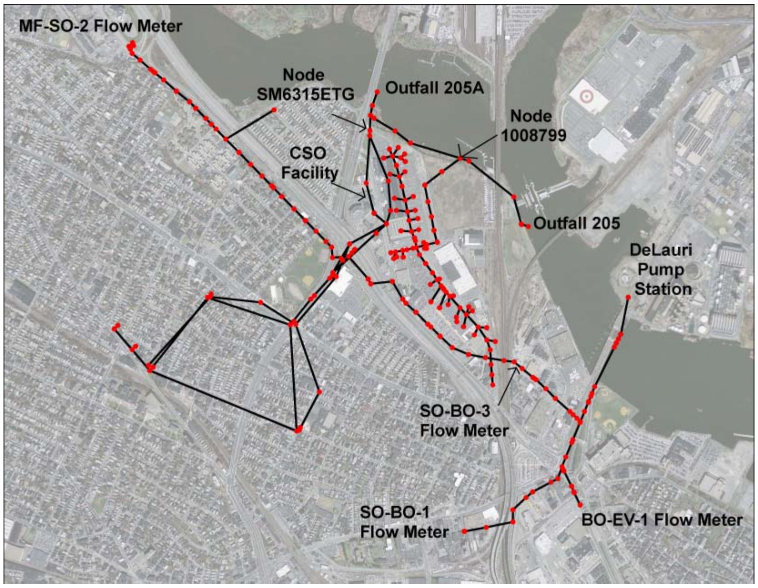


Figure 25. Layout of S-MBS with node IDs

Node SM6315ETG is where stormwater runoff from the Ten Hills neighborhood enters the S-MBS and node 1008799 is where stormwater runoff from Assembly Square enters the system. Evaluating flow at the outfalls would not give an accurate representation of combined sewage entering the Mystic because additional separated stormwater from these two locations would be included in volume totals.

In addition to analyzing hazardous flooding and volume of flow through the CSO facility, an investigation was made to ensure peak flows in the main trunk line at the intersection of the S-MBS with the Cambridge Branch were equal to or less than existing peak flows. Peak flows were reduced for all simulations that met the performance metric targets, so peak flows are no longer included in discussions.

4.4 Stormwater Management Strategies

Stormwater management strategies were chosen based on their perceived feasibility for the city of Somerville. Strategies were designed for two performance metric targets:

- No increase in volume of flow through the CSO facility under all design storms and for all climates compared to the present; and
- Practically no hazardous flooding (less than total of 0.5 MG) under all design storms and for all climates compared to the present. We chose 0.5 MG as the threshold because it was a relatively small value compared to existing flooding.

Both performance metric targets need to be met under all climate change scenarios for all design storms. Therefore, strategies were designed to meet performance metric targets for the worst-case scenario which is the 100-year storm under the high climate change scenario (except for strategy 3 described below in more detail). The designs for each strategy were created to accommodate the 100-year storm under the high climate change scenario in 2010, 2040, and 2070 and results were evaluated for the remaining scenarios. It should be understood that there are many other designs that could be created to meet the performance metric targets of other scenarios, but this was too intensive for this study. The strategies chosen for Somerville include:

1. No action
2. Underground storage
3. LID throughout the watershed
4. Sewer separation
5. Combination of sewer separation and LID

A detailed description of each strategy is described below.

Strategy 1 - No action

Strategy 1 employs no action to the Somerville-Medford Branch Sewer (S-MBS). This strategy acts as a “baseline scenario” to compare against Strategy 2, 3, 4, and 5.

Strategy 2 - Underground Storage

Strategy 2 employs the conventional approach of using detention in the form of retention basins to manage combined sewage in urban areas. In addition to retention basins, there are other ways to provide detention in sewer systems such as deep tunnels. However, a deep tunnel has been deemed too costly for Somerville in the past (CDM, 1974). This strategy incorporates retention basin storage throughout the S-MBS as a flexible, distributed design. It should be understood as a conceptual design for the purpose of this study, not a hard-engineered design.

To design retention basins for the S-MBS, hazardous flooding volumes in 2010, 2040, and 2070 under the baseline scenario were simulated and used to size the necessary storage to keep total flooding below 0.5 MG. Results showed the majority of hazardous flooding occurred at approximately the same twenty nodes for all design storms. Preliminary simulations showed that creating storage at the twenty junctions would mitigate almost all hazardous flooding in the S-MBS.

Twenty retention basins were incorporated in the S-MBS in SWMM. At each of the twenty nodes, an orifice located 5 feet below the ground surface was connected to an offline storage node sized to accommodate hazardous flooding volume. Enough underground storage is installed in 2010 to accommodate the present 100-year storm. In 2040, additional storage is installed to accommodate the increase in hazardous flooding that occurs under increased precipitation for the 100-year storm for the high climate change scenario in 2040. Then again in 2070, additional storage is installed to accommodate the increase in hazardous flooding for the 100-year storm, high climate change scenario.

Strategy 3 - LID throughout the watershed

Strategy 3 employs LID throughout the watershed draining to the S-MBS. As described in Section 4.1, the majority (54%) of the watershed area is multi-residential neighborhood and 73% of the watershed is impervious. In addition, GIS analyses show that 2.7% of the watershed area of lots is municipality-owned and the remaining 97.3% of the watershed area is privately-owned. This information presents complications for stormwater management in Somerville.

The majority of the watershed is owned by homeowners, not the City of Somerville, which makes employing LID techniques more difficult. There must be incentive for homeowners to install LID on their property, or else a majority of the land may be ignored. In addition, the high amount of impervious area means that typical LID options such as bioretention, vegetated swales, vegetated filter strips, and constructed wetlands might need to be overlooked, unless paved surface is removed specifically for these applications.

Through research and 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. (These LID techniques are defined in Section 1.2).

Because many of these LID techniques utilize storm water drained from rooftops and impervious area, a zoning analysis was performed on the watershed to determine the area of rooftop in each subcatchment as well as other impervious and pervious areas. The zoning datalayer and impervious surface layer at a scale of 1-meter for Somerville were downloaded from Mass GIS (http://www.mass.gov/mgis/) and intersected with the subcatchments. Using Mass GIS orthophotos at a scale of 1:5,000 m, the percent of impervious area that was comprised of rooftops was estimated for each zone. Using these estimates, the percentage of rooftop area in each subcatchment was calculated. The total amount of impervious, pervious, and rooftop areas for residential and non-residential areas were calculated and used to determine the maximum area that could drain to each type of LID.

The LID strategy did not meet the performance metrics and therefore, did not meet design conditions. The LID techniques used in this study cannot treat more than a 2-inch storm, and therefore, cannot handle the 10-year or 100-year storm. Instead, this strategy focused on feasible LID techniques that would perform well for each zoning area. LID was modeled in SWMM based on assumptions about the maximum amount of LID that could be installed in each zoning area. This was achieved by using conservative estimates about the total amount of land that would be converted to LID or drained to LID. This approach provided the maximum impact that LID could have on the S-MBS watershed.

In residential areas, impervious area was broken down into two categories: rooftops and driveways/pathways/roadways. LID techniques that homeowners may install to store storm water from rooftops include drywells, rain barrels, green roofs, and blue roofs. LID techniques available to store storm water from driveways/pathways/roadways include porous pavement. Maximum feasible amount of area (in percentages) assumed to be converted to LID as well as a summary of design values input to SWMM is shown below. Percentages were chosen based on what seemed realistic to this study's authors, and a variety of LID techniques were chosen for diversity. Feasible LID techniques were determined based on common stormwater BMPs used in the Boston area, except for blue roofs which is a relatively new stormwater BMP. Design for LID was determined using the Massachusetts DEP Stormwater Handbook (MassDEP, 2008). Design for blue roofs was determined based on knowledge received from the engineering firm currently piloting blue roof projects.

Residential Areas

Rooftop

- 60% of roofs drain to on-site drywells – each drywell is modeled as an infiltration trench, 50.3 cubic feet in volume
- 10% of roofs drain to rain barrels – each rain barrel is modeled as a rain barrel, 9.4 cubic feet in volume
- 10% of roofs are converted to green roofs – each green roof is modeled as bioretention cell, 1 inch surface storage depth, 4 inches soil thickness, 1 inch storage height, 2000 sq. feet
- 10% of roofs are converted to blue roofs – each blue roof is modeled as rain barrel, 2 inches high, 2000 sq. feet
- 10% of roofs make no changes in existing drainage

Driveways/pathways

- 25% of area is converted to porous pavement – each porous pavement cell is modeled as porous pavement, 4 inches thick pavement, 23 inches thick storage, 1,000 sq. feet

The commercial, business, and industrial areas were broken into three categories: rooftops, parking lots/sidewalks/pathways/roadways, and grass/shrubs. LID techniques that may be installed 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/roadways include porous pavement. LID that may be installed to store storm water from grass and shrub areas include bioretention.

Maximum feasible amount of area (in percentages) assumed to be converted to LID as well as a summary of design values input to SWMM is shown below.

Commercial, Business, Industrial Areas, and Public Buildings

Rooftop

- 50% of roofs drain to on-site drywells - each drywell is modeled as an infiltration trench, 50.3 cubic feet in volume
- 20% of roofs are converted to green roofs - each green roof is modeled as bioretention cell, 1 inch surface storage depth, 4 inches soil thickness, 1 inch storage height, 2000 sq. feet
- 20% of roofs are converted to blue roofs - each blue roof is modeled as rain barrel, 2 inches high, 2000 sq. feet
- 10% of roofs make no changes in existing drainage

Parking lots/sidewalks/pathways

- 75% of impervious area is converted to porous pavement - each porous pavement cell is modeled as porous pavement, 4 inches thick pavement, 23 inches thick storage, 1000 sq. feet

Grass/shrubs

- 15% of pervious area is converted to bioretention – each bioretention cell is modeled as bioretention with an underdrain (drain coefficient, C = 0.20 in/hr), 6 inches surface depth, 18 inches soil thickness, 12 inches storage, 1000 sq. ft.

Parks

- All areas - no change

Under strategy 3, LID was implemented as a time varying process. Under strategy 3, the staged actions look like this:

- 2010
    - Install 30% of the maximum amount of LID planned to be installed
- 2040
    - Install additional 50% of the maximum amount of LID
- 2070
    - Install remaining 20% of LID

The SWMM LID models were simulated under 2010 conditions, 2040 climate change scenarios, and 2070 climate change scenarios for all design storms.

Strategy 4 - Sewer Separation

This strategy employs sewer separation in the watershed. To meet the performance metric target of 0.5 MG 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 pipe lines. In reality, many of the subcatchments draining to the S-MBS are already separated but they drain into the combined sewer system because no separate stormwater outfall was ever built to the Mystic River or a nearby water body. Combined sewer watersheds are shown in Figure 10.

To represent complete disconnection from the combined sewer system in SWMM, all subcatchments except for two, subtcatchment 6124 and 2 (Assembly Square), are removed from the model. Subcatchment 6124 and 2 are not removed because they drain into the system downstream of the CSO facility and have no impact on the volume out of the CSO facility or hazardous flooding. Under strategy 4, the staged actions look like this:

- 2010
    - Perform sewer separation in all combined subcatchments
    - Build new stormwater outlet for new stormwater system
- 2040
    - No action necessary
- 2070
    - No action necessary

The SWMM sewer separation models were simulated under 2010 conditions, 2040 climate change scenarios, and 2070 climate change scenarios for all design storms.

Strategy 5 – Combination of sewer separation and LID

Strategy 5 employs a combination of sewer separation and LID. LID techniques were eliminated that were deemed costly and did not provide much storage/retention (green roofs, rain barrels, and bioretention) and the remaining LID techniques of blue roofs, dry wells, and porous pavement were incorporated into SWMM. Similar to strategy 3, maximum amounts of these LID techniques were chosen and incorporated into the model based on zoning. Maximum feasible amount of area (in percentages) assumed to be converted to LID as well as a summary of design values input to SWMM is shown below. Dry wells were increased in volume in comparison to strategy 3 to accommodate more runoff.

Residential Areas

Rooftop

- 50% of roofs drain to on-site drywells – each drywell modeled as an infiltration trench, 113 cubic feet in volume
- 50% of roofs are converted to blue roofs – each blue roof modeled as rain barrel, 2 inches high, 2000 sq. feet

Driveways/pathways

- 25% of area is converted to porous pavement – each porous pavement cell modeled as porous pavement, 4 inches thick pavement, 23 inches thick storage, 1,000 sq. feet

Commercial, Business, Industrial Areas, and Public Buildings

Rooftop

- 50% of roofs drain to on-site drywells - each drywell modeled as an infiltration trench, 113 cubic feet in volume
- 50% of roofs are converted to blue roofs - each blue roof modeled as rain barrel, 2 inches high, 2000 sq. feet

Parking lots/sidewalks/pathways

- 75% of impervious area is converted to porous pavement - each porous pavement cell modeled as porous pavement, 4 inches thick pavement, 23 inches thick storage, 1000 sq. feet

Parks

- All areas - no change

After preliminary simulations, it was determined that sewer separation needed to be performed to meet the performance metric targets, specifically the target of less than 0.5 MG of hazardous flooding. Subcatchments were removed from the model one by one until the performance metric targets were met.

Under strategy 5, the staged actions look like this:

- 2010
    - Perform sewer separation in all but four subcatchmets (numbers 6025, 6038, 6039, 6064, and 6134)
    - Build new stormwater outlet for new stormwater system
    - Install 100% of LID in the 4 combined subcatchments
- 2040
    - Separate subcatchment 6025
- 2070
    - No action necessary

Using this staged strategy, the SWMM combination models were simulated under 2010 conditions, 2040 climate change scenarios, and 2070 climate change scenarios for all design storms.

Chapter 5: Results

This chapter presents results from the 105 simulations performed according to the tree diagram as shown in Figure 21. It also discusses the quantification of the results according to two decision-making approaches and the determination of most robust strategy for each approach.

In summary, the performance of each strategy is evaluated under two metrics. Next, two decision-making approaches are used to quantify results: a design cost approach and a net benefits approach. Both approaches utilize risk analysis for each climate change scenario to determine the expected values of costs, and in the case of net benefits, the benefits of management. Costs to meet design criteria are compared for each climate change scenario to identify the most cost-effective robust strategy. Similarly, net benefits are compared and the most beneficial robust strategy is identified.

5.1 Simulation Results

The graphs below summarize the system's performance for each strategy. One graph is provided for each performance metric including volume out of the CSO facility and hazardous flooding.

Strategy 1 - No action

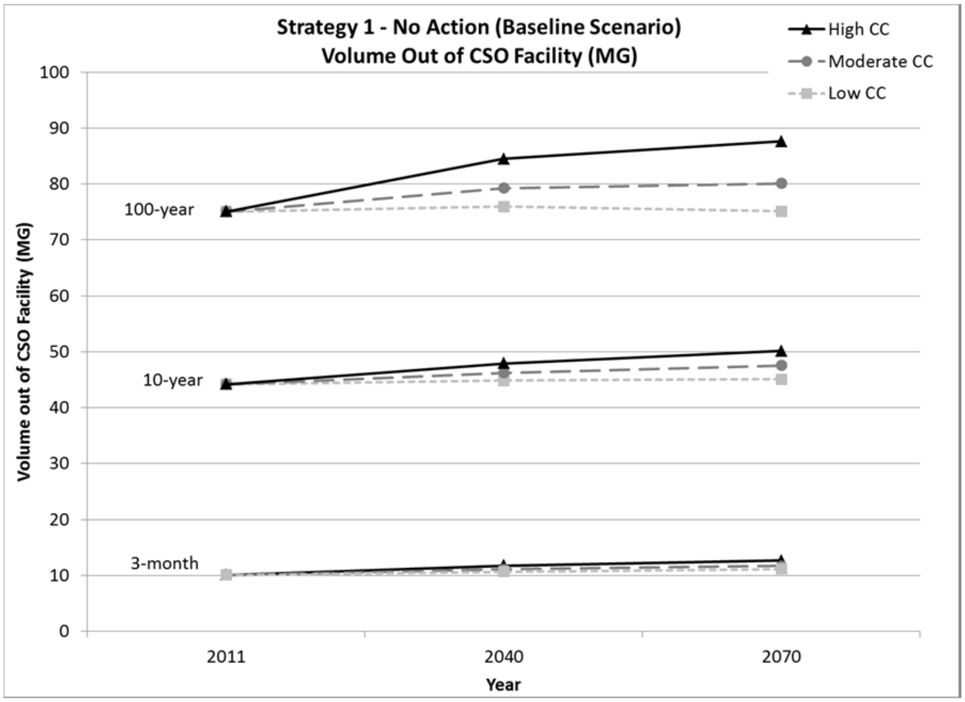


Figure 26. Strategy 1 - No Action - Volume out of CSO Facility

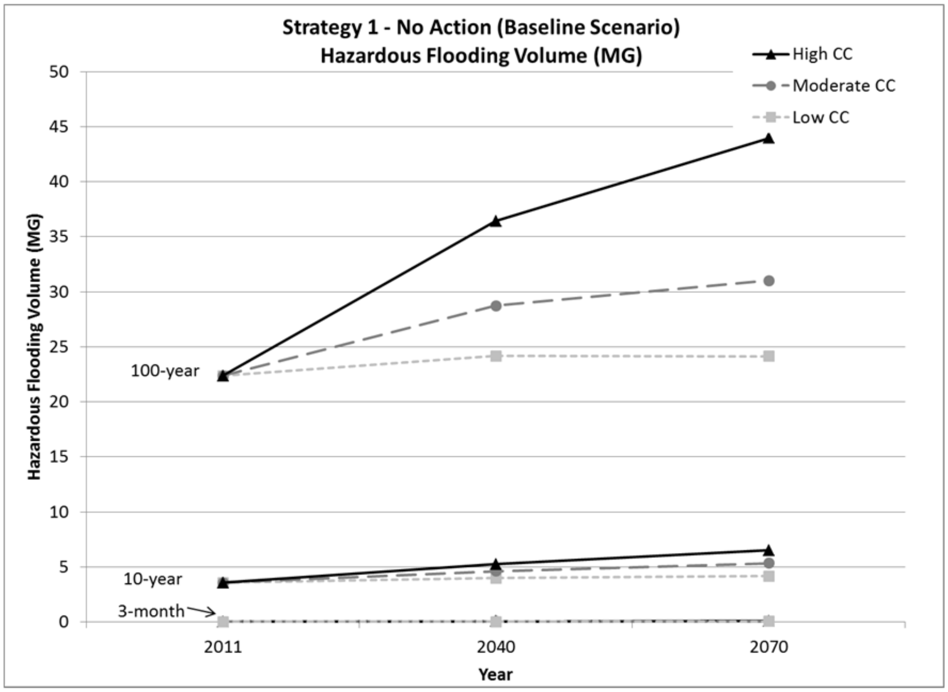


Figure 27. Strategy 1 - No Action - Hazardous Flooding

Strategy 2 - Underground Storage

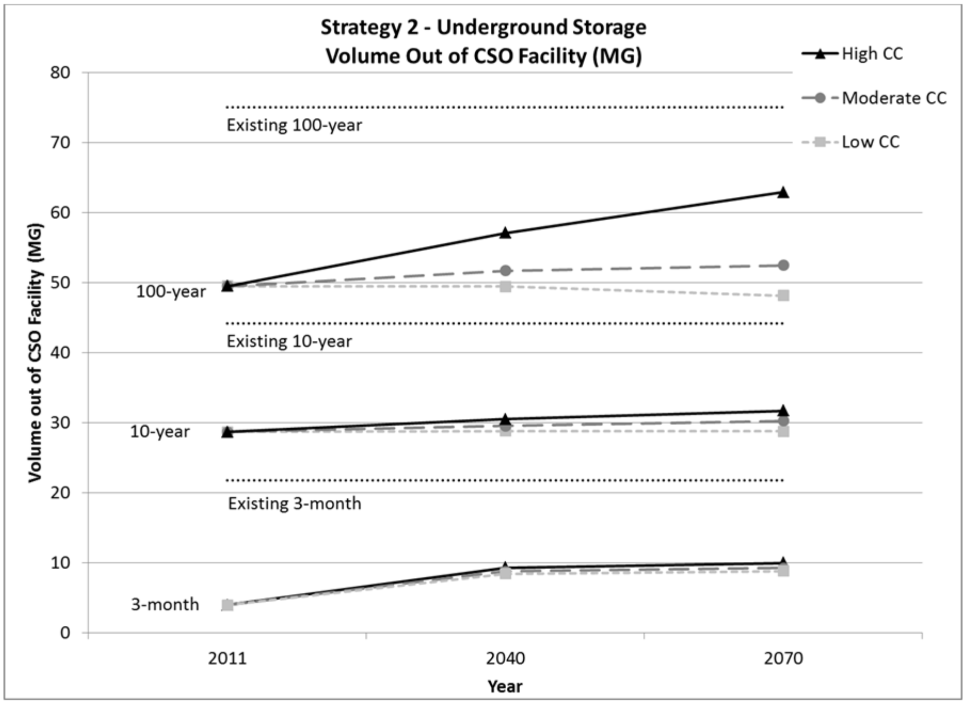


Figure 28. Strategy 2 - Underground Storage - Volume out of CSO Facility

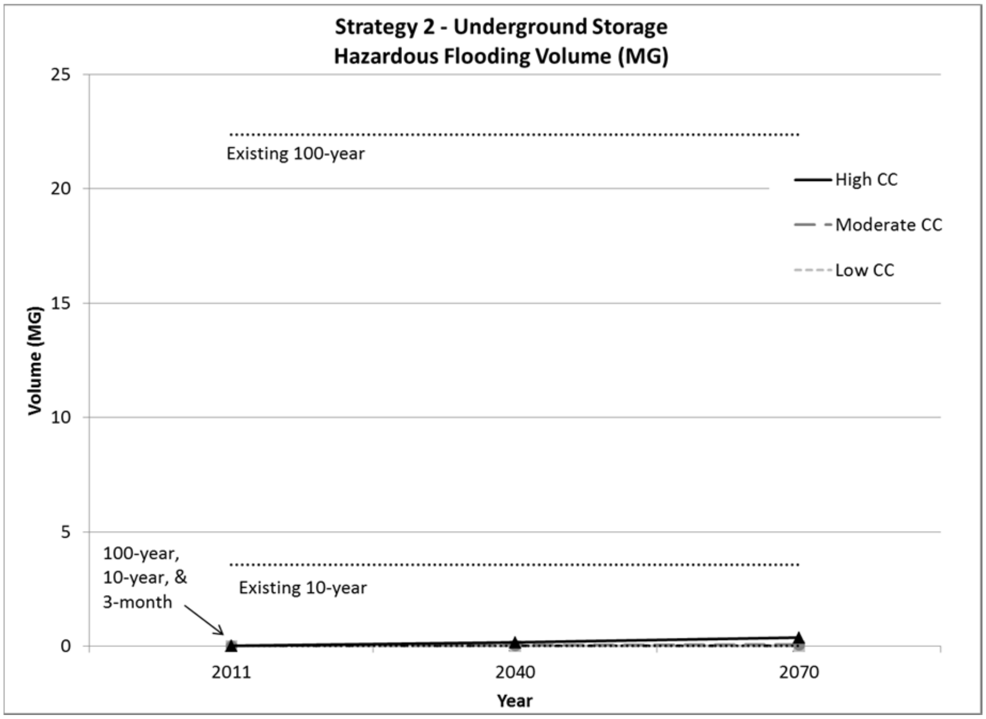


Figure 29. Strategy 2 - Underground Storage - Hazardous Flooding

Strategy 3 - LID throughout the watershed

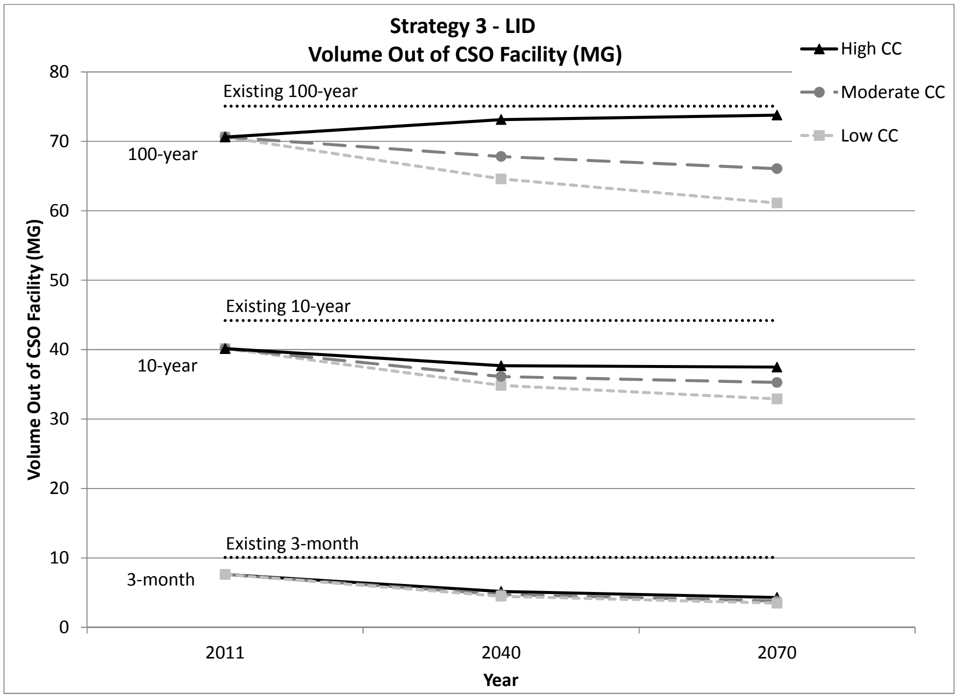


Figure 30. Strategy 3 - LID - Volume out of CSO Facility

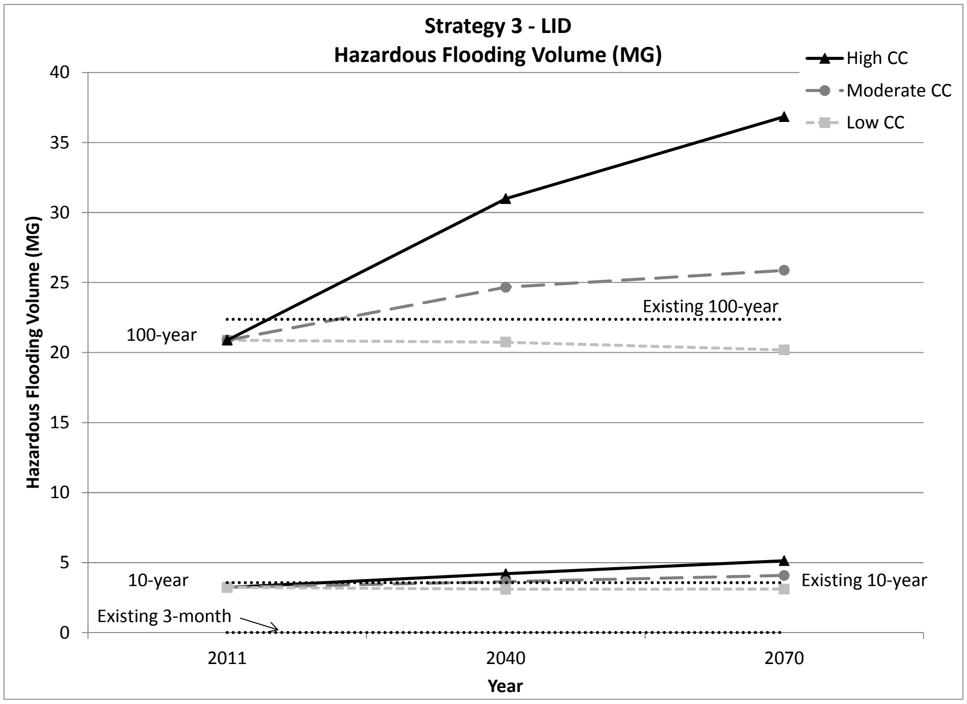


Figure 31. Strategy 3 - LID - Hazardous Flooding

Strategy 4 - Sewer Separation

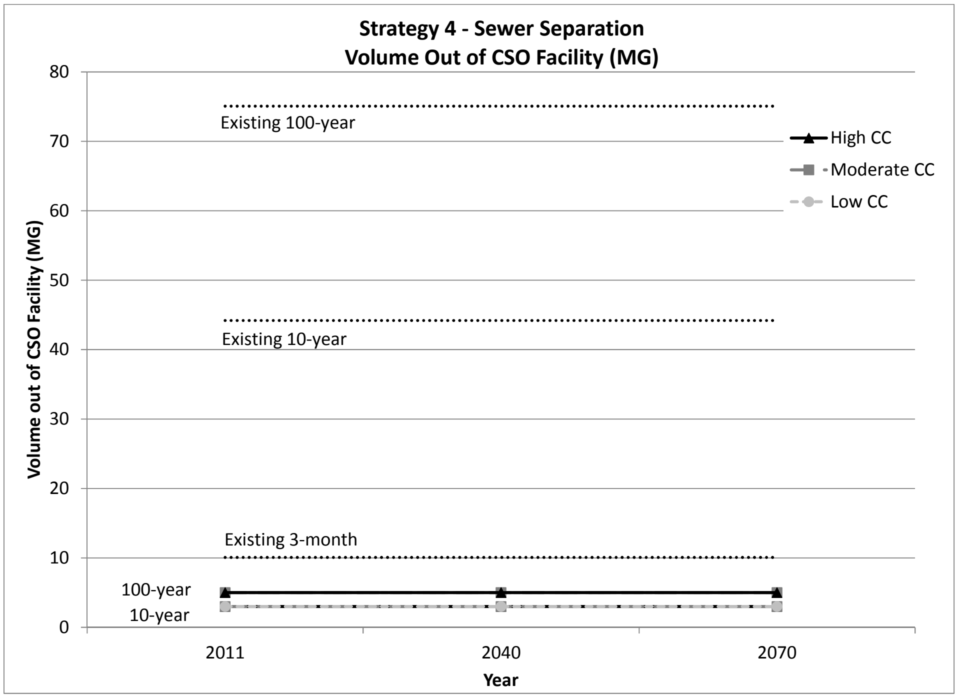


Figure 32. Strategy 4 - Sewer Separation - Volume out of CSO Facility

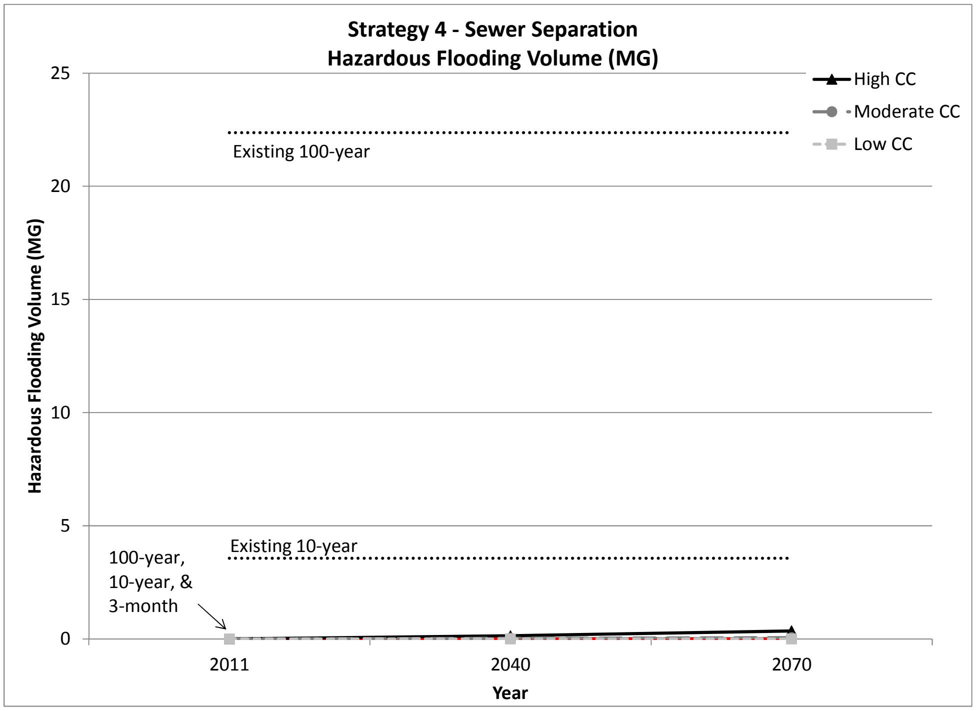


Figure 33. Strategy 4 - Sewer Separation - Hazardous Flooding

Strategy 5 – Combination of sewer separation and LID

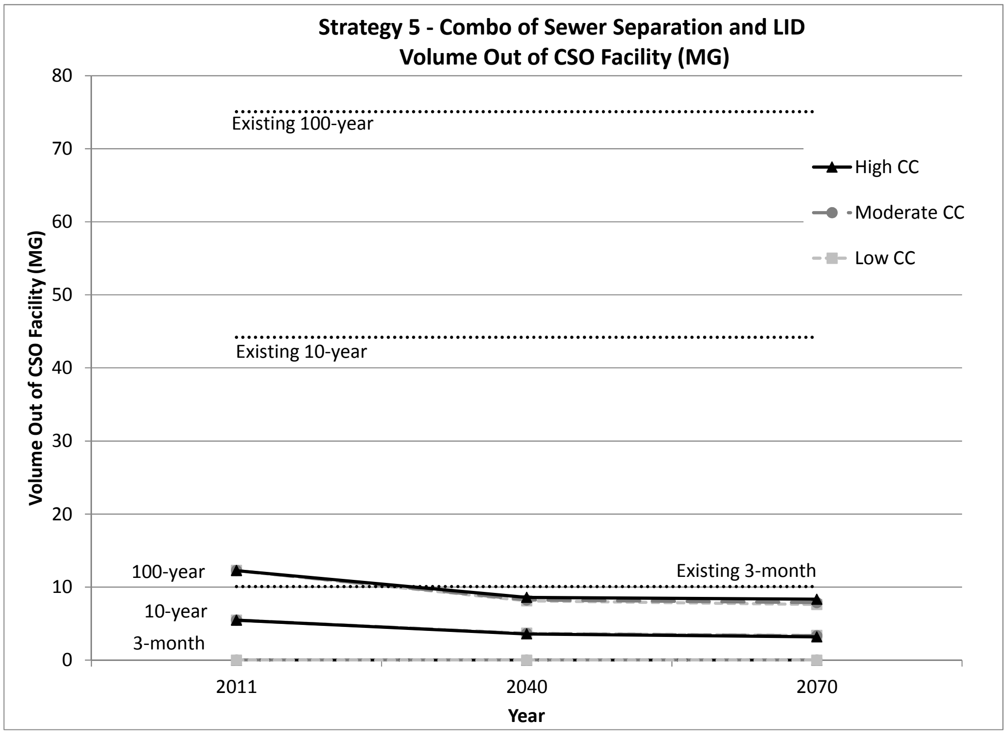


Figure 34. Strategy 5 - Combo - Volume out of CSO Facility

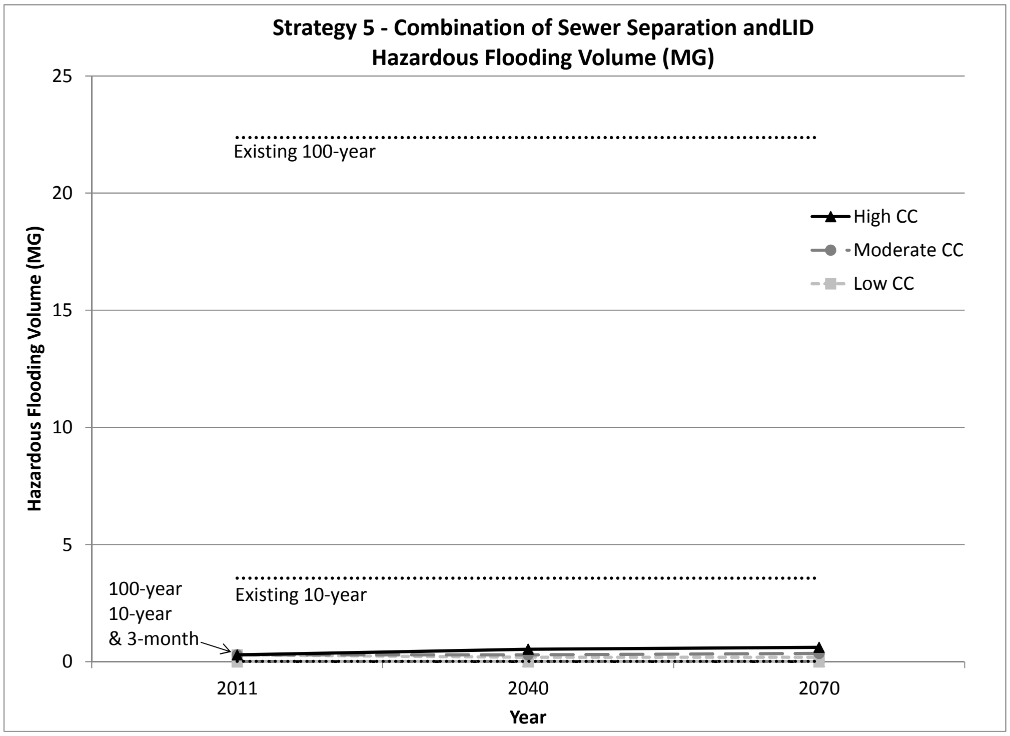


Figure 35. Strategy 5 - Combo - Hazardous Flooding

The simulation results show that Strategies 2, 4, and 5 are the only viable strategies for implementation because they meet both performance metric targets, no increase in flow volumes through the CSO facility and no hazardous flooding. Strategy 3, LID, does not meet both performance metric targets. It does not meet the "no hazardous flooding" metric to reduce flooding below 0.5 MG for all scenarios. This can be seen in Figure 31. Interestingly, Strategy 3 does reduce hazardous flooding below existing levels for the low climate change scenario, and Figure 30 shows it does meet the "no increase in CSO volumes" metric for all scenarios. However, Strategy 3 is not considered to be robust because it does not meet both performance metrics for all scenarios.

5.2 Design Cost Approach

A design cost approach was used to quantify results by estimating each strategy's constant and variable costs. For the purposes of this study, constant costs cover construction, design and engineering (D&E), life-cycle considerations, and operations and maintenance (O&M). Variable costs cover the treatment of water flowing downstream to Deer Island and treatment of water flowing through the Somerville Marginal CSO facility. The volume of water ultimately being treated at Deer Island does not include water stored in pipes at the end of a storm because this volume was considered negligible, nor does this volume include dry weather flow during the storm. (Dry weather flow was subtracted manually after simulations.)

The design cost approach is useful only for strategies that meet the performance metrics as described in Section 5.1. Therefore, only strategies 2, 4, and 5 are analyzed in this section. The design cost approach is summarized below and then it is explained in detail for strategy 2. The same approach is repeated for Strategies 4 and 5, but only results are provided to avoid redundancy.

First, constant costs for each strategy were estimated and converted into present values using present worth formulas (Revelle et. al., 2004). Next, variable costs were addressed which includes three steps.

1. Variable costs were estimated and converted into present values.
2. Expected values were calculated which uses the concept of risk analysis. That is, the expected value is the weighted average of all possible values that the variable costs could be, and it is calculated by summing the product of cost and the probability that it will occur. Expected values were calculated for 2010 and for each of the low, moderate, and high climate change scenarios in 2040 and 2070.
3. Expected value present value (EVPV) costs were calculated which uses the same method as step 2, except it is calculated over the lifetime of the strategy instead of over a range of probabilities. This is performed for the low, moderate, and high climate change scenario.

Finally, the values calculated for constant present values and variable EVPV costs were added together to obtain total costs. This approach is presented in Figure 36.

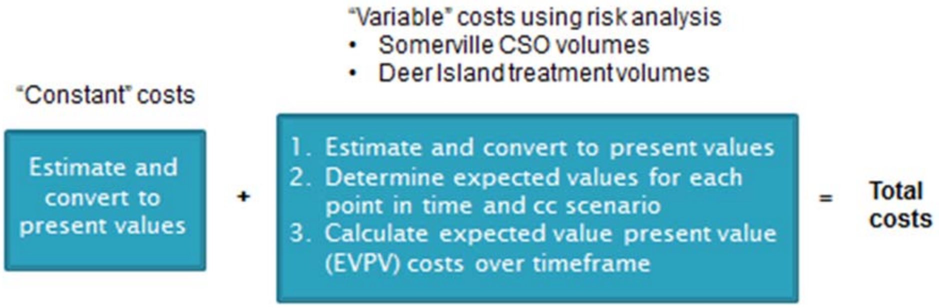


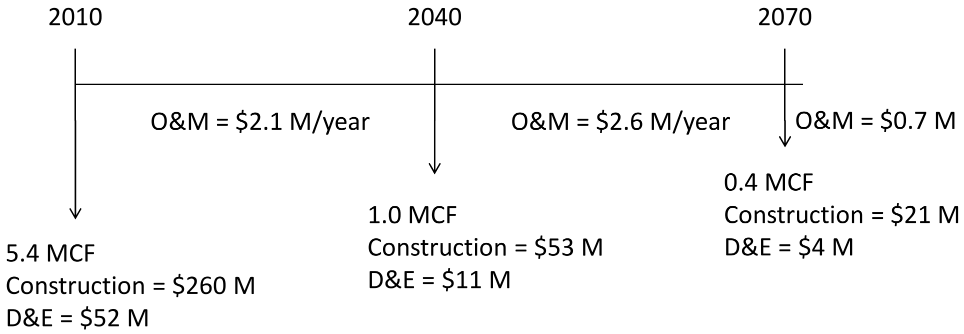
Figure 366. Design Cost Approach

After total costs were determined for strategies 2, 4, and 5, they were compared for each climate change scenario to identify the most cost-effective robust strategy. This approach is explained in detail for strategy 2.

Strategy 2 - Underground storage

Constant Costs

Under strategy 2, as described in Section 4.4, underground storage is installed in 2010 to accommodate the present 100-year storm. Then in 2040 and 2070, additional storage is installed to accommodate the increase in hazardous flooding that occurs under increased precipitation for the 100-year storm under the high climate change scenario. Figure 37 shows the estimated constant costs of the strategy.



- Construction costs based on $49.16/CF and O&M costs based on $0.40/CF/year(EPA, 1999).
- Values were adjusted based on Engineering News-Record (ENR) construction cost index.
- D&E costs were calculated as 20% of construction costs.

Figure 377. Estimated Constant Costs of Strategy 2 - Underground Storage

Over the 61-year timeframe with a discount rate of 2.3%, the present value cost of the strategy is $430 M.

Somerville currently experiences hazardous flooding so the cost to control hazardous flooding using underground storage for the present 100-year storm was evaluated as well. Without taking climate change into account, it would cost $340 M to control the existing hazardous flooding problems in the city over a 61-year time frame with a discount rate of 2.3%.

Variable Costs

Variable costs include costs for CSO treatment in Somerville and wastewater treatment at Deer Island. These terms are defined further below.

Costs for CSO treatment include all expenses for treatment of combined sewage flowing through the Somerville Marginal CSO Facility. No cost data was available for the CSO facility, so engineering judgment was used to estimate that costs for CSO treatment would be 1/100th the cost of treatment of Somerville's combined sewage that is treated at Deer Island. Using this ratio, the cost is $100/MG to treat water at the CSO facility.

Wastewater treatment costs include all expenses for combined sewage that flows from Somerville downstream through the MWRA system and ultimately through the Deer Island treatment plant. The total volume of water treated includes water in retention basins at the end of a storm that would need to be pumped back into the MWRA system. Based on review of the Somerville sewer rates, it was determined that Somerville residents pay approximately $0.01/gallon (or $10,000/MG) for MWRA to treat their combined sewage (Somerville Water and Sewer Department, 2011).

Variable costs were estimated, converted into present values, and are listed in Table 9.

Scenario	CSO Volume (MG)	To Deer Island (MG)	Cost ($)	Present Value Cost ($)
3mo	4	20	$199,000	$199,000
3mo 2040 L	8	20	$205,000	$104,000
3mo 2040 M	9	21	$211,000	$107,000
3mo 2040 H	9	21	$215,000	$109,000
3mo 2070 L	9	21	$214,000	$55,000
3mo 2070 M	9	22	$219,000	$56,000
3mo 2070 H	10	23	$229,000	$59,000
10yr	29	58	$579,000	$579,000
10yr 2040 L	29	60	$599,000	$303,000
10yr 2040 M	30	62	$621,000	$314,000
10yr 2040 H	30	64	$646,000	$326,000
10yr 2070 L	29	61	$613,000	$157,000
10yr 2070 M	30	65	$653,000	$167,000
10yr 2070 H	32	69	$695,000	$178,000
100yr	49	104	$1,046,000	$1,046,000
100yr 2040 L	49	108	$1,082,000	$547,000
100yr 2040 M	52	115	$1,151,000	$582,000
100yr 2040 H	57	124	$1,245,000	$629,000
100yr 2070 L	48	109	$1,094,000	$280,000
100yr 2070 M	52	118	$1,189,000	$304,000
100yr 2070 H	63	131	$1,311,000	$335,000

Table 9. Present Values of Strategy 2 for each Scenario

Expected Values

Once present values were calculated, the expected value costs were determined using the concept of risk analysis as described below. Variable costs for each scenario were plotted against the probability of each scenario and linear interpolation was assumed between data points. Functions could have been fit to the date; however, linear interpolation was assumed to simplify the process. Figure 38 shows climate change scenarios in 2040 as an example.

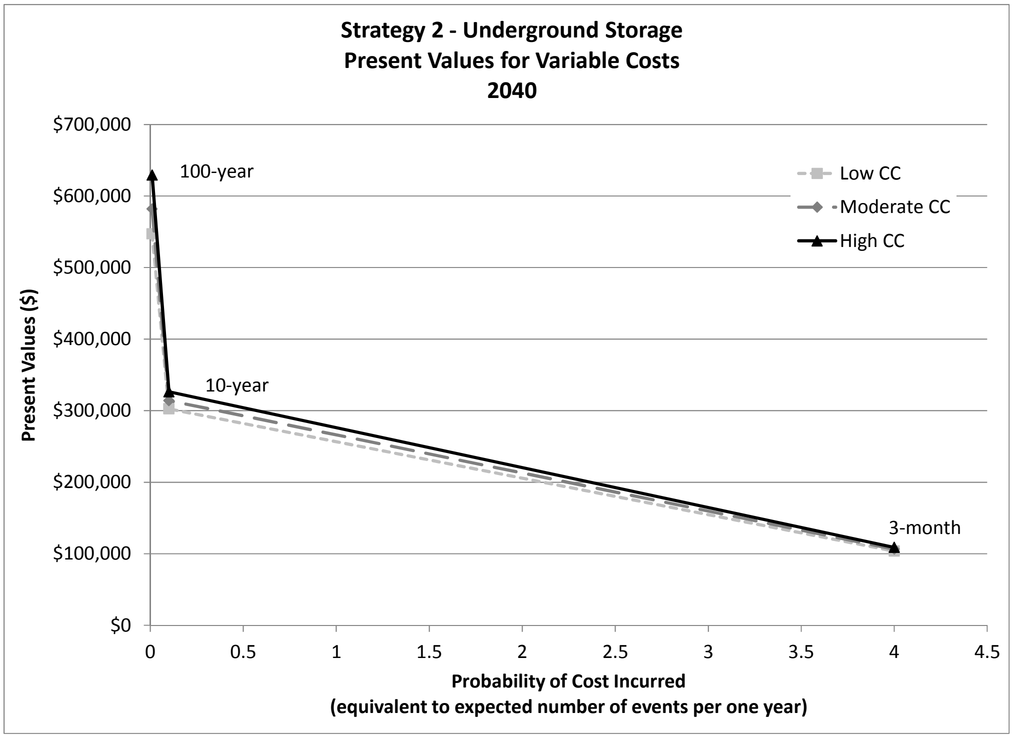


Figure 388. Strategy 2 - Present Values for Variable Costs in 2040

This figure shows the present values for variable costs for the 100-year, 10-year, and 3-month storms in 2040 plotted against the probability of cost incurred (or essentially the frequency of occurrence). Expected values were calculated by summing the area underneath the curve for the low, moderate, and high climate change scenarios for 2040. The same process was repeated for present and 2070. Expected values are shown in Table 10.

CC Scenario	Year	Expected Value
-	2010	$1,592,000
Low	2040	$831,000
Moderate	2040	$860,000
High	2040	$892,000
Low	2070	$432,000
Moderate	2070	$456,000
High	2070	$483,000

Table 10. Strategy 2 - Expected Values of Variable Costs

Expected Value Present Value Costs for Each Scenario

Next, expected values were plotted for each climate change scenario over the 61-year timeframe as shown in Figure 39.

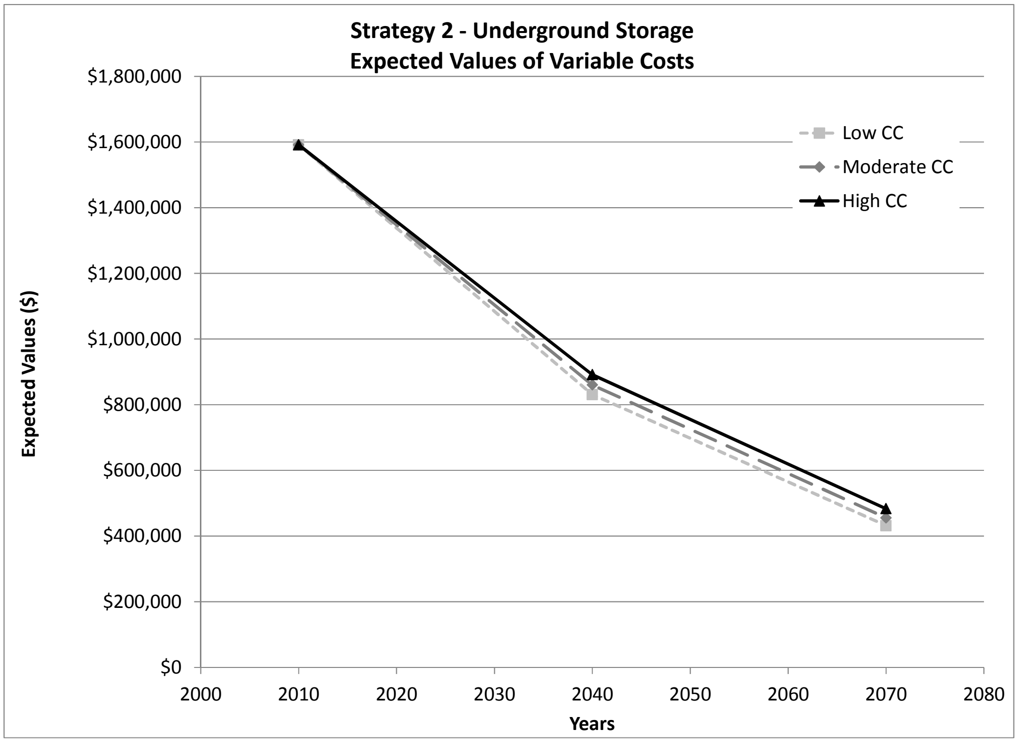


Figure 399. Strategy 2 - Expected Values for Variable Costs

Expected value present value costs were calculated by summing the area underneath each curve and are shown in Table 11.

CC Scenario	EV PV Variable Costs
Low	$55,300,000
Moderate	$56,500,000
High	$57,900,000

Table 11. Strategy 2 - Expected Value Present Value Costs

Finally, constant and variable costs were summed to obtain a final cost estimate of using underground storage under climate change scenarios as shown in Table 12.

CC Scenario	EV PV Total Costs
Low	$485,000,000
Moderate	$486,200,000
High	$487,600,000

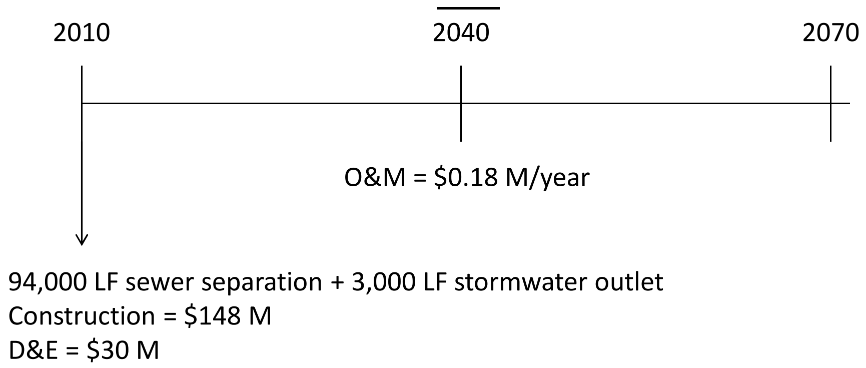
Table 12. Strategy 2 - Expected Value Present Value Total Costs

Strategy 4 - Sewer separation

Constant Costs

Under strategy 4, sewer separation is performed in all combined subcatchments draining to the Winter Hill pipelines or the main trunk of the S-MBS in 2010. As explained in Section 4.4, it is necessary to perform complete separation all at once in order to meet the performance metrics. Costs for sewer separation were estimated based on personal communication with an engineering firm experienced in sewer separation projects. For planning level estimates in an urban city similar to Somerville, a value of $1250/ linear foot of pipeline was used for sewer separation in dense urban commercial areas. Sewer separation costs were determined for thirteen of the twenty-four subcatchments, because the rest of the subcatchments draining to the S-MBS have already been separated. Detailed piping information in the combined sewer subcatchments were unavailable, so total linear feet of roadway was used to obtain a piping length estimate. A factor of 1.25 was multiplied to the total linear feet to obtain a conservative estimate to assure that there is greater length of combined sewer pipe than roadway.

In addition, an estimated value of $1.1 M was used for the construction of a separate stormwater pipe to the Mystic River. This calculation assumed an RCP pipe, 3,000 feet in length, 6 feet in diameter, 20% D&E costs, and used the Capital Cost Function in Table 1 provided by Sample (2003). Figure 40 shows the estimated constant costs of the strategy.



- Construction costs for sewer separation based on $1250/LF.
- Construction costs for stormwater outlet based on Capital Cost Function in Table 1 (Sample, 2003).
- O&M costs were estimated 0.25% of total cost of separation in entire watershed (CDM, 1974).
- D&E costs were calculated as 20% of construction costs.

Figure 40. Estimated Constant Costs of Strategy 4 - Sewer Separation

Over the 61-year timeframe with a discount rate of 2.3%, the present value cost of the strategy is $180 M. Because there is no future construction costs for this strategy, $180 M is also the price to control hazardous flooding for the present 100-year storm.

Variable Costs

Damages for strategy 4 include costs for CSO treatment and wastewater treatment at Deer Island. The same process applied to strategy 2 was applied to strategy 4. Variable costs were estimated and converted into present values, expected value costs were calculated using present values, and expected value present value costs were calculated. These results are shown in Table 13.

CC Scenario	EV PV Variable Costs
Low	$7,620,000
Moderate	$7,620,000
High	$7,620,000

Table 13. Strategy 4 - Expected Value Present Value Variable Costs

Finally, constant and variable costs were summed to obtain a final cost estimate of using sewer separation under climate change scenarios.

CC Scenario	EV PV Total Costs
Low	$191,200,000
Moderate	$191,200,000
High	$191,200,000

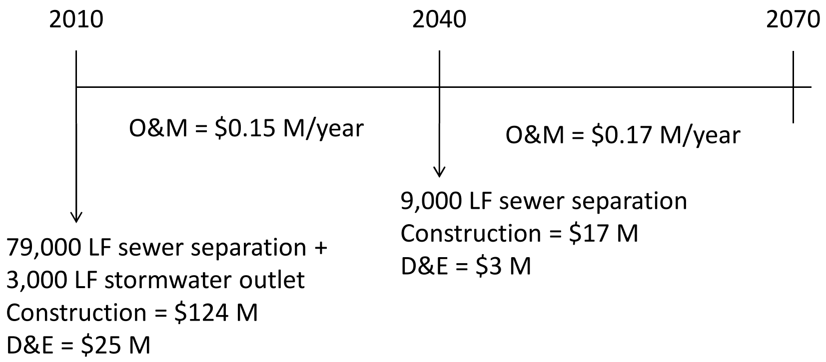
Table 14. Strategy 4 - Expected Value Present Value Total Costs

Costs are the same for all climate change scenarios because all precipitation falling on the watershed previously drained by the S-MBS is now managed by a new separate stormwater system. Climate change has no effect on the S-MBS because it is now a separate sanitary sewer.

Strategy 5 - Combination sewer separation and LID

Constant Costs

Under strategy 5, sewer separation is performed for all combined subcatchments except for five (numbers 6025, 6038, 6039, 6064, and 6134) and 100% of LID is implemented in 2010. In 2040, subcatchment 6025 is separated to meet performance targets. In 2070, no further sewer separation is necessary. Constant costs were estimated using the same sewer separation and stormwater outlet values as strategy 4 and are shown in Figure 41.



- Construction costs for sewer separation based on $1250/LF.
- Construction costs for stormwater outlet based on Capital Cost Function in Table 1 (Sample, 2003).
- O&M costs were estimated 0.25% of total cost of separation in entire watershed (CDM, 1974).
- D&E costs were calculated as 20% of construction costs.

Figure 401. Estimated Constant Costs of Strategy 5 - Combo of SS and LID

Variable Costs

Damages for strategy 5 include costs for CSO treatment and wastewater treatment at Deer Island. The same process applied to strategy 2 was applied to strategy 5. Variable costs were estimated and converted into present values, expected value costs were calculated using present values, and expected value present value costs were calculated. Results are shown in Table 15.

CC Scenario	EV PV Variable Costs
Low	$9,450,000
Moderate	$9,570,000
High	$9,660,000

Table 15. Strategy 5 - Expected Value Present Value Variable Costs

Finally, constant and variable costs were summed to obtain a final cost estimate of using sewer separation under climate change scenarios.

CC Scenario	EV PV Total Costs
Low	$217,240,000
Moderate	$217,360,000
High	$217,450,000

Table 16. Strategy 5 - Expected Value Present Value Total Costs

Once expected value present value total costs were calculated, strategies 2, 4, and 5, can be compared. Table 17 shows total costs for the strategies.

	CC Scenario		
Strategy	**Low**	**Moderate**	**High**
2 - underground storage	$485,000,000	$486,200,000	$487,600,000
4 - sewer separation	$191,200,000	$191,200,000	$191,200,000
5 - sewer separaion and LID	$217,240,000	$217,360,000	$217,450,000

Table 17. Comparison of Strategy Costs

Results show that strategy 4, sewer separation, is the most cost-effective robust strategy for all climate change scenarios because it is the cheapest. In review, there is little difference between climate change scenarios within each strategy because the cost of the strategy outweighed the costs related to the change in stormwater runoff.

5.3 Net Benefits Approach

A second decision-making approach was used to quantify results by estimating each strategy's net benefits. Net benefits are defined as benefits subtracted by costs. Costs are the constant and variable costs described in the previous section. Benefits are defined as the difference in variable costs if the strategy performed better than Strategy 1, the baseline scenario. For example, benefits occur for a strategy when there is less volume flowing through the CSO facility, when there is less volume flowing to Deer Island, or when there is less hazardous flooding. If the strategy performed "worse" than Strategy 1, the baseline scenario, then this difference would be considered an additional cost. The net benefits approach is presented in Figure 42. The details of variable costs and benefits are provided below in this section.

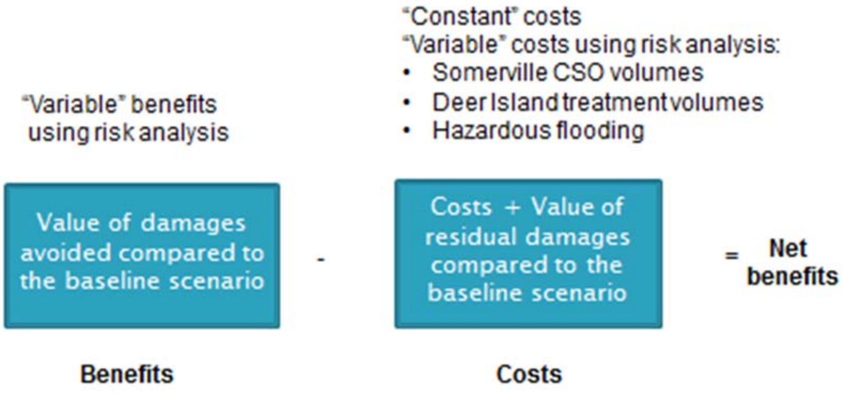


Figure 412. Net Benefits Approach

Variable Costs and Benefits

In addition to CSO treatment in Somerville and wastewater treatment at Deer Island, variable costs and benefits under this approach also include hazardous flooding damages. Hazardous flooding damages are defined further below.

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 structure damage and content damage are based on the Army Corps of Engineers relationship tables (ACOE, 2003). Pump-out, cleaning, and disinfection costs are based on research performed on available commercial services. Assumptions were made to estimate the number of houses affected by flooding and how much flooding occurred. Based on the zoning analysis, it was assumed that 4,175 buildings are located in combined sewerage watersheds. For the 100-year storm, it was assumed that 25% of buildings (1,044 buildings) were affected by hazardous flooding, and for the 10-year storm, it was assumed that 12.5% of buildings (522 buildings) were affected. No hazardous flooding occurs under the 3-month storm so no percentage was assigned to this design storm. Each building was assumed be 2,000 square feet in foot-print area. It was conservatively assumed that hazardous flooding flows into basements, and therefore, the volume of hazardous flooding was converted into depth of combined sewage in each basement based on these assumptions. Using the ACOE tables, depth of combined sewage was related to structural damage cost and content damage cost based on a percentage of the average assessed value of a house in Somerville which was estimated to be $423,000 (Boston.com, 2008). Pump-out, cleaning, and disinfection costs were determined to be approximately $10,000 per building regardless of depth of basement flooding. (All depths were less than 3 feet for all scenarios).

Benefits and additional costs for CSO treatment, wastewater treatment at Deer Island, and hazardous flooding were estimated for strategies 2, 4, and 5. Benefits and costs were also estimated for strategies 1 and 3. The same process using the concept of risk analysis to estimate variable costs in the design cost approach was again utilized to quantify benefits and cost in the net benefits approach. Finally, net benefits were calculated and compared among strategies. Results are described below.

Strategy 1 - No action

Costs

Under strategy 1, no action is taken so there are no constant costs. However, there are variable costs including CSO treatment, wastewater treatment at Deer Island, and hazardous flooding. Variable costs were estimated and converted into present values, expected value costs were calculated using present values, and expected value present value costs were calculated. Results are shown in Table 18.

CC Scenario	EV PV Variable Costs
Low	$746,200,000
Moderate	$756,200,000
High	$769,100,000

Table 18. Strategy 1 - Expected Value Present Value Costs

Benefits

Strategy 1 provides no benefits because it is the baseline scenario with no action. Benefits are $0.

Net Benefits

Net benefits equal benefits subtracted by costs. Results are shown in Table 19.

CC Scenario	Benefits	Costs	Net Benefits
Low	$0	$746,200,000	-$746,200,000
Moderate	$0	$756,200,000	-$756,200,000
High	$0	$769,100,000	-$769,100,000

Table 19. Strategy 1 - Net Benefits

Strategy 2 - Underground storage

Costs

Under strategy 2, costs in addition to those already determined in Section 5.1 are the additional wastewater treatment costs at Deer Island compared to Strategy 1, the baseline scenario. Water that is retained through underground storage is pumped back into the MWRA system after a storm. Under the baseline scenario, this water usually becomes hazardous flooding that flows into basements causing property and content damage before getting pumped back into the MWRA system so the costs are different. The additional cost to treat water at Deer Island compared to the baseline scenario was determined and is shown in Table 20.

CC Scenario	EV PV Variable Costs
Low	$51,700,000
Moderate	$53,900,000
High	$56,300,000

Table 20. Strategy 2 - Expected Value Present Value Additional Costs

Benefits

Strategy 2 provides less CSO volumes and less hazardous flooding volumes than the baseline scenario (no action) which can be quantified as benefits. The difference in costs between strategy 2 and the baseline strategy were estimated and converted into present values. Expected values were calculated and expected value present values were calculated. Benefits are shown in Table 21.

CC Scenario	EV PV Variable Benefits
Low	$721,500,000
Moderate	$731,300,000
High	$744,000,000

Table 21. Strategy 2 - Expected Value Present Value Benefits

Net Benefits

Results are shown in Table 22.

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

Table 22. Strategy 2 - Net Benefits

Strategy 3 – LID throughout the watershed

Costs

Under strategy 3, LID was implemented over time. In 2010, 30% of maximum LID was implemented throughout the watershed. In 2040, 50% more of maximum amount of LID was implemented. In 2070, the remaining 20% of maximum amount of LID was implemented. Figure 43 shows the estimated constant costs of the strategy.

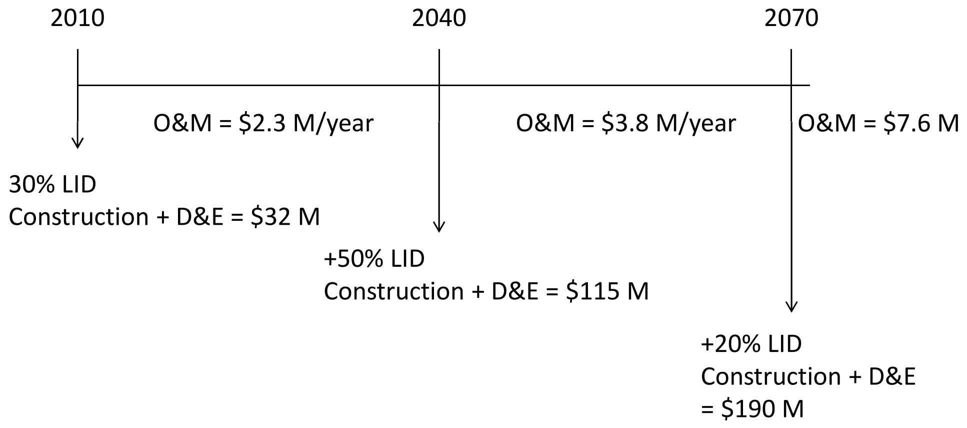


Figure 423. Constant Costs of Strategy 3 – LID

Over the 61-year timeframe with a discount rate of 2.3%, the present value cost of the strategy is $231 M. Costs were determined according to Table 23.

BMP	Area (sq ft)	Unit Volume (CF)	Incremental Construction Cost ($/sq ft or $/unit)[1]	Design & Engineering Costs (assume 20% of construction cost)	Construction Cost	Annual O&M Costs[2,3] (% of installation)	Lifetime (years)[2,4,1]	# of times needing re-installation every 30 years
Bioretetion	1000	-	$37	$7,362	$44,172	6%	3	10
Dry Well	7.07	167.1	$5,000	$1,000	$6,000	12.5%	30	1
Porous Pavement	1000	-	$8	$1,626	$9,756	1.5%	8	4
Green Roof	2000	-	$24	$9,780	$58,680	8.5%	36	1
Blue Roof	2000	-	$4	$1,600	$9,600	1%	20	2
Rain Barrel	0.79	7.4	$200	$40	$240	1%	25	1

Sources:
1. (City of New York, 2008)
2. (Montalto, 2007)
3. (US EPA, Fact Sheet: Bioretention, September 1999)
4. (US EPA, Fact Sheet: Infiltration Trench, September 1999)

Table 23. LID Costs

Variable costs include CSO treatment, wastewater treatment at Deer Island, and hazardous flooding. Variable costs were estimated and converted into present values, expected value costs were calculated using present values, and expected value present value costs were calculated. Variable costs are shown in Table 24.

CC Scenario	EV PV Variable Costs
Low	$730,100,000
Moderate	$741,600,000
High	$749,600,000

Table 24. Strategy 3 - Expected Value Present Value Total Costs

Constant and variable costs were summed to obtain a final cost estimate of implementing maximum LID under climate change scenarios.

CC Scenario	**EV PV Total Costs**
Low	$960,900,000
Moderate	$972,400,000
High	$980,400,000

Table 25. Strategy 3 - Expected Value Present Value Total Costs

Benefits

Strategy 3 provides less CSO volumes, less volume treated at Deer Island, and less hazardous flooding volumes than the baseline scenario which can be quantified as benefits. The difference in costs between strategy 3 and the baseline strategy were estimated and converted into present values. Expected values were calculated and expected value present values were calculated. Benefits are shown in Table 26.

CC Scenario	EV PV Variable Benefits
Low	$16,600,000
Moderate	$18,100,000
High	$20,700,000

Table 26. Strategy 3 - Expected Value Present Value Benefits

Net Benefits

Results are shown in Table 27.

CC Scenario	Benefits	Costs	Net Benefits
Low	$16,600,000	$960,900,000	-$944,300,000
Moderate	$18,100,000	$972,400,000	-$954,300,000
High	$20,700,000	$980,400,000	-$959,700,000

Table 27. Strategy 3 - Net Benefits

Strategy 4 - Sewer separation

Costs

Under strategy 4, there are no additional costs to consider because there is no hazardous flooding.

Benefits

Strategy 4 provides less CSO volumes, less volume treated at Deer Island, and less hazardous flooding volumes than the baseline scenario which can be quantified as benefits. The difference in costs between strategy 4 and the baseline strategy were estimated and converted into present values. Expected values were calculated and expected value present values were calculated. Benefits are shown in Table 28.

CC Scenario	EV PV Variable Benefits
Low	$740,200,000
Moderate	$750,400,000
High	$763,500,000

Table 28. Strategy 4 - Expected Value Present Value Benefits

Net Benefits

Results are shown in Table 29.

CC Scenario	Benefits	Costs	Net Benefits
Low	$740,200,000	$191,200,000	$549,000,000
Moderate	$750,400,000	$191,200,000	$559,200,000
High	$763,500,000	$191,200,000	$572,300,000

Table 29. Strategy 4 - Net Benefits

Strategy 5 - Combination of sewer separation and LID

Costs

Under strategy 5, there are no additional costs to consider because there is no hazardous flooding.

Benefits

Strategy 5 provides less CSO volumes, less volume treated at Deer Island, and less hazardous flooding volumes than the baseline scenario which can be quantified as benefits. The difference in costs between strategy 5 and the baseline strategy were estimated and converted into present values. Expected values were calculated and expected value present values were calculated. Benefits are shown in Table 30.

CC Scenario	EV PV Variable Benefits
Low	$736,700,000
Moderate	$746,700,000
High	$759,400,000

Table 30. Strategy 5 - Expected Value Present Value Benefits

Net Benefits

Results are shown in Table 31.

CC Scenario	Benefits	Costs	Net Benefits
Low	$736,700,000	$217,200,000	$519,500,000
Moderate	$746,700,000	$217,400,000	$529,300,000
High	$759,400,000	$217,400,000	$542,000,000

Table 31. Strategy 5 - Net Benefits

Finally, net benefits can be compared for strategies 1, 2, 3, 4, and 5. Table 32 shows net benefits for the strategies.

	CC Scenario		
Strategy	Low	Moderate	High
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 separaion and LID	$519,500,000	$529,300,000	$542,000,000

Table 32. Comparison of Strategy Net Benefits

Results are also displayed as a graph in Figure 44 below.

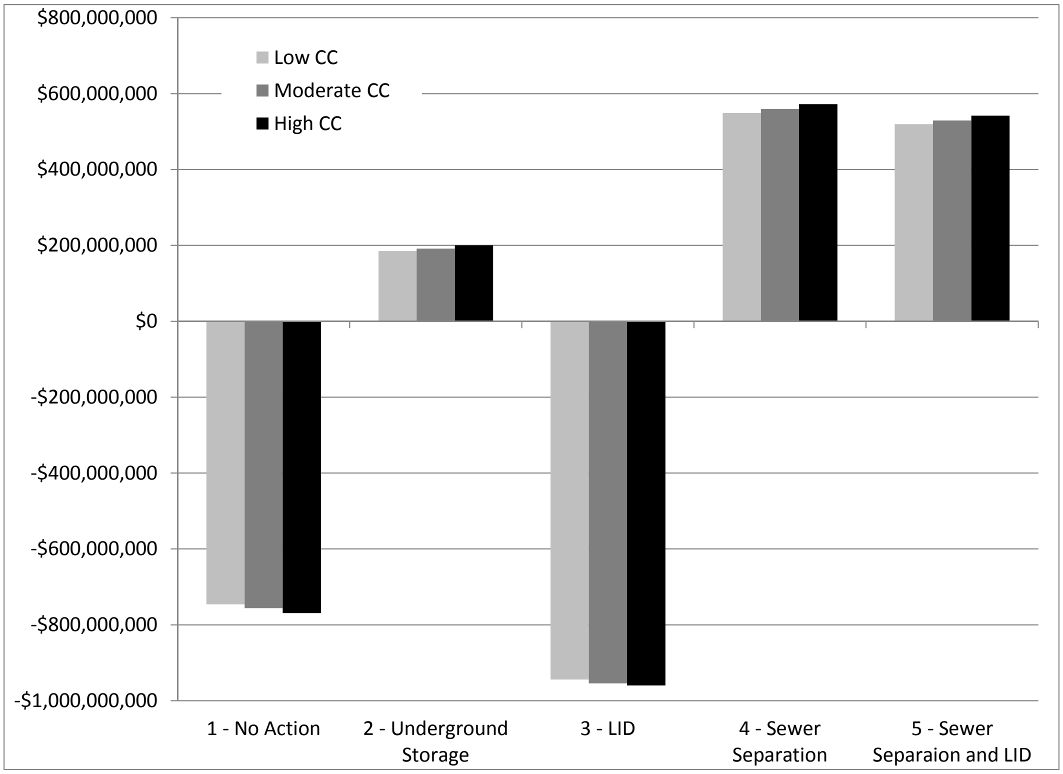


Figure 434. Net Benefit Results

Results show that strategy 4, sewer separation, is the most beneficial robust strategy because it has the highest net benefits for all climate change scenarios.

Chapter 6: Summary

6.1 Conclusion

In today's society, planning for stormwater management should incorporate planning for climate change; however climate change introduces uncertainty into the design process that traditional engineering methods do not consider. This study introduces and tests a methodology to determine robust strategies to manage stormwater under a changing climate. It provides a more holistic approach that includes expected values of costs and benefits over a specified timeframe and takes discount rates into consideration.

The application of this methodology to Somerville indicated that sewer separation as the best robust strategy under both decision-making methods, the design cost approach and the net benefits approach. The critical performance metric was "no hazardous flooding" as it much harder to control than the performance metric of reducing the volume of flow through the CSO facility. To be considered robust, a strategy needed to control all hazardous flooding under all climate change scenarios for all design storms. This translated into the need to control the 100-year high climate change scenario in 2010, 2040, and 2070 which helps explain why the stormwater management strategy of sewer separation was most effective and LID was the least effective among the alternatives considered. If a different performance metric target was chosen, for example, 85% reduction in the CSO volumes under the 1-year storm, then results may have identified a different robust strategy.

6.2 Limitations

Many assumptions were made throughout the case study that were necessary but that also introduced approximation. As stated previously, some assumptions related to the configurations of the SWMM models (i.e. no DeLauri Pump Station), designs of the strategies (i.e. amount of LID), the feasibility of the strategies, the amount of hazardous flooding that flows into basements, the cost calculations to determine hazardous flooding damage, and the values used to treat combined sewage at the Somerville Marginal CSO facility and to treat Somerville's wastewater at Deer Island. These assumptions were necessary to apply the methodology and to provide the most accurate representation of reality as possible.

Only water quantity was considered in this study; however, in reality, water quality should be included to provide a more realistic view on costs and benefits to society. LID provides more benefits in terms of water quality than quantity which may be part of the reason strategy 3, LID, did not perform better. To obtain accurate expected value present value costs and benefits, a whole range of environmental, societal, and economic benefits should be considered such as those shown in Table 33.

Benefit	Type
Environmental	Increase carbon sequestration
	Improve air quality
	Additional recreational space
	Efficient land use
	Improve human health
	Flood protection
	Drinking water source protection
	Replenish groundwater
	Improve watershed health
	Protect or restore wildlife habitat
	Reduce sewer overflow events
	Restore impaired waters
	Meet regulatory requirements for receiving waters
Economic	Reduce hard infrastructure construction costs
	Maintain aging infrastructure
	Increase land values
	Encourage economic development
	Reduce energy consumption and costs
	Increase life cycle cost savings
Social	Establish urban greenways
	Provide pedestrian and bicycle access
	Create attractive streetscapes and rooftops that enhance livability and urban green space
	Educate the public about their role in stormwater management
	Urban heat island mitigation

Table 33. Green Infrastructure Benefits by Type

(EPA, January 2011)

Finally, this study did not consider the value of flexibility for each strategy. This could have a significant impact on the results of the net benefits.

6.3 Future Work

There is much to research on the topic of stormwater management under the uncertainty of climate change. A methodology has been defined that quantifies expected values of the variable costs and benefits, but this study only represents an initial step on analyzing different combinations of designs and performance metrics. A performance metric focusing only on CSO volume through the Somerville Marginal CSO Facility may warrant exploration. In addition, tolerating flooding for any storm larger than the 10-year storm may also warrant consideration. Incorporating environmental, social, and economic benefits such as those listed in Table 33 is another area that has much research potential.

Appendix

A. Infoworks to SWMM Conversion Errors

An MWRA InfoWorks model was used to create a SWMM input file. There were a number of errors associated with the conversion process. The notes below list the changes and assumptions made in the process of creating a functioning SWMM model of the system.

The following conduits located in the upstream side of the Medford-Somerville branch have cross-sections that were described in InfoWorks using a 2-parameter "Gothic" shape, apparently a height and width measure. These were replaced by the SWMM "Gothic" shape which requires only a height parameter. Both of the InfoWorks parameters have been retained in the input file, however only the first parameter is relevant to SWMM. Notes have been made in the input file.

1001507.1
1001509.1
1001511.1
1001513.1
1001515.1
1001517.1
1001519.1
1001521.1
1001523FG.1
1001525.1
1001527.1
1001529.1
1001531.1
1001533.1
1001535FG.1
1001537.1
1001539.1
1001541.1
1001543.1
1001545.1
1001547.1
1001549FG.1
1001551.1
1001553.1
1001565.1
1001567.1
1001569.1
1001571.1
1001573.1
1001575.1
1001577FG.1
1001579.1
1001581.1
1001583.1

Similarly, the conduit S6331.1 and SM6393.1 with an 2-parameter InfoWorks "Egg" shape was replaced with a 1-parameter SWMM "Egg" shape. Both geometry parameters were retained in the input file and a note was made.

Dry-weather flow patterns were referred to in the SWMM file generated from InfoWorks however these patterns were not included. Alternate inflow patterns were used. The rain gage CH-BO-1 was used for precipitation input.

The outlets below had tables to define flow in the original InfoWorks file. Since these tables were not available, they were replaced with a functional relationship.

```
; Name Node1 Node2 Height TABULAR Qtable ( FlapGate )
SM6315A.1 SM6315A SM6315C 0.000000 TABULAR SM6315A.1 NO
SM6315B.1 SM6315B SM6315D 0.000000 TABULAR SM6315B.1 NO
```

Outlets SM6315A.1 and SM6315B.1 had an associated table for stage and discharge in the original IW file. This table was not available with the input file.

These nodes were converted to weirs with an assumed 1-foot crest height (offset) and a length of 5 feet to match the dimension of the upstream orifice, and a vertical opening of 5 feet to match the dimension of the upstream orifice. Default discharge coefficient of 3.33 was assumed.

For Weir 1008805SLG.1 no vertical opening was available in the input file. A height of 6.967 feet was assumed based on weir crest height (offset) of 0.0328 feet and the upstream conduit height of 7 feet.

Initial depths were set as follows (may be different in some versions of model):

- Main branch of Medford-Somerville set at 1 foot.
- Combined sewer conduits in Winter Hill Area (Medford, Pearl, Marshall, and Cross) set to 0.2 feet.

- Lower combined sewer conduits in Winter Hill Area (Broadway, McGrath) set to 0.4 feet.
- Storm sewer in Winter Hill Area, 0.1 ft.
- Assembly square area, 0.1 ft.

There were errors in the following link cross-sections due to a missing geometry parameter:

SM6315.1 RECT_CLOSED 0.0 5.0 (orifice) corrected to 6.0 x 5.0, 60 second time to open/close gate
SM6315.2 RECT_CLOSED 0.0 5.0 (orifice) corrected to 6.0 x 5.0, 60 second time to open/close gate
1008805SLG.1 RECT_OPEN 0.0 9.0 (weir) corrected to 0.083 (1-inch) x 9 ft

Added tide gate to 1008807 at Earhart dam.

For Weir 1001387.1 no vertical opening was available in the input file. A height of 1 foot was assumed based on the upstream conduit height of 1 foot.

Converted from Basket to Baskethandle for the following conduits:
1000569.1 – 1000573.1
1000577.1 – 1000591.1
1000989.1 – 1001027.1

Converted from Oval to Vert_Ellipse for the following conduit:
1000575.1
Converted all flushing gates in the model to 5 foot pipes.

B. SWMM Inputs

Below is a description of the SWMM inputs that were modified for the re-calibration and validation of the Somerville SWMM model.

Subcatchment Parameters

The subcatchment parameters that were adjusted include percent impervious, width of subcatchment, curve number for pervious areas, Manning's n values for overland flow, and depth of depression storage. MWRA provided a watershed map that was imported into GIS, georeferenced, and watershed boundaries were drawn directly on top of the map. Impervious area and hydrologic soil group (HSG) information were downloaded from MassGIS (http://www.mass.gov/mgis/) and watersheds were overlaid on top of this information to determine the percent impervious for each subcatchment.

Watershed	% Impervious
Medford	63.3%
6025	62.2%
6032	65.2%
6033	86.9%
6034	92.6%
6035	94.5%
6036	94.4%
6037	87.1%
6038	11.1%
6039	93.0%
6040	96.3%
6048	95.9%
6049	92.6%
6064	85.8%
6114	66.6%
6117	95.6%
6118	88.2%
6119	99.5%
6120	95.4%
6121	86.8%
6122	84.2%

6123	94.4%
6124	91.3%
6125	88.7%

Soils in the area were determined to be mainly urban soils corresponding to HSG C soils (USDA NRCS, 2011). Curve numbers for pervious areas were assigned a value of 79 which corresponds to open space in fair condition (grass cover 50% – 75%) for HSG C soils (USDA NRCS, 1986).

Values for width of subcatchments were estimated to be between 27 feet and 875 feet depending on the subcatchment. The width values from the North System SWMM file were reduced to 25% of their original values to maintain the variability between the subcatchments.

Watershed	Width (ft)
Medford	27
6025	309
6032	272
6033	408
6034	159
6035	334
6036	460
6037	875
6038	124
6039	283
6040	371
6048	334
6049	291
6064	550
6114	866
6117	223
6118	237
6119	283
6120	407
6121	223
6122	477
6123	327
6124	346
6125	569

Manning's n values for overland flow were estimated to be 0.015 for impervious areas and 0.30 for pervious areas. These values fell within the range of typical values provided by SWMM.

Values for depth of depression storage were determined to be 0.05 inches for impervious areas and 0.20 inches for pervious areas. These values fell within the range of typical values provided by SWMM. Impervious areas were suggested to range between 0.05 and 0.10 inches, and lawns/grass areas were suggested to range between 0.10 and 0.20 inches.

Dry Weather Flows

Dry weather flows contributing to the S-MBS were determined through hydrograph separation. The first step involved identifying at least seven days of consecutive dry weather (less than 0.01 inches every 15-minutes) at the CH-BO-1 rain gage located at the MWRA Chelsea Creek Headworks. Two weeks of dry weather were identified as August 23 – 29, 2008 and August 30 – September 5, 2008. The August 23 – 29th dry weather period had six days of previous dry weather.

Flows at the upstream of S-MBS (flow meter MF-SO-2) and flows at the downstream end of the S-MBS (flow meter SO-BO-3) were plotted for these two dry weather periods. Infiltration was identified as the minimum flow for each period at each meter. Infiltration for each dry weather period was averaged to get a final average infiltration value.

To obtain sanitary flow, infiltration was subtracted from flow at each meter during each period. Then, to determine amount of sanitary flow draining in from the local combined sewer system, sanitary flow at SO-BO-3 was subtracted from MF-SO-2. Sanitary flow for each dry weather period was averaged to get a final average value.

Next, multipliers were determined for each hour of the day. Two typical weekdays (Tuesday, August 26th and Wednesday, August 27th) were chosen to calculate the multipliers. The 15-minute sanitary flow values were averaged over each hour and then divided by the average sanitary flow over the two days to obtain a multiplier at each hour.

Finally, the infiltration and average sanitary flows were applied to the model based on subcatchment area. All nodes that the subcatchments drained to within the combined sewer system between MF-SO-2 and SO-BO-3 were identified, and the percentage of contributing watershed area was calculated for each subcatchment. This percentage of contributing watershed area was multiplied by the infiltration value and the average sanitary flow value to obtain infiltration and sanitary flow inputs at each node. In some instances, more than one subcatchment drained to a node so infiltration and sanitary flows were summed at these nodes.

Subcatchment	Node ID	Contributing Area (acres)	% of area	San Flow (MGD)	Infiltration (MGD)	Node ID	SF (MGD)	Infiltration (MGD)
Medford	1001505	860.4	-	0.770	1.130	1001505	0.770	1.130
6037	1001555	73.1	11%	0.080	0.071	1001555	0.080	0.071
6064	1001583	21.9	3%	0.024	0.021	1001583	0.154	0.136
6125	1001583	70.9	10%	0.078	0.069			
6124	SM6315ETG	47.5	7%	0.052	0.046			
6121	SM6319	31.8	5%	0.035	0.031	SM6319	0.046	0.041
6122	SM6319	10.4	2%	0.011	0.010			
6038	SM6321	6.9	1%	0.008	0.007	SM6321	0.060	0.053
6039	SM6325	14.1	2%	0.015	0.014	SM6325	0.031	0.027
6040	SM6329	32.1	5%	0.035	0.031	SM6329	0.129	0.114
6048	SM6329	20.5	3%	0.022	0.020			
6049	SM6329	54.9	8%	0.060	0.053			
6032	SM6331	20.7	3%	0.023	0.020	SM6331	0.137	0.121
6034	SM6331	6.0	1%	0.007	0.006			
6035	SM6403	25.6	4%	0.028	0.025	SM6403	0.039	0.034
6036	SM6403	9.9	1%	0.011	0.010			
6025	SM6411	33.3	5%	0.037	0.032	SM6411	0.037	0.032
6033	SM6415	40.1	6%	0.044	0.039	SM6415	0.044	0.039

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