Management Planning for Combined Sewer Systems in Urban Areas under Climate Change

By

Thomas M. Renaud

A Thesis

Submitted to the Faculty of

WORCESTER POLYTECHNIC INSTITUTE

In partial fulfillment of the requirements for the

Degree of Master of Science

In

Environmental Engineering

By

Thomas Renaud

April 2012

APPROVED:

Professor Paul P. Mathisen, Ph. D., Major Advisor

Professor John Bergendahl, Ph. D., Committee Member

Professor Paul Kirshen, Ph. D., Committee Member

Abstract

Management of urban stormwater is becoming increasingly difficult due to an anticipated increase in precipitation and extreme storm events that are expected under climate change. The goal of this research is to develop an approach that effectively accounts for the uncertain conditions that may occur under climate change and to develop best management practices to manage stormwater in urban areas. This presentation focuses on management of stormwater and combined sewage in Worcester, MA, where approximately four square miles of the downtown area is serviced by a combined sewer system.

The EPA's Stormwater Management Model was used to determine the impacts of storms on the urban environment for future conditions. This model was used to simulate discharges of selected design storms associated with a range of climate change scenarios. Various design storms were simulated in SWMM for 2010, 2040, and 2070 under high, moderate, and low climate change scenarios. Alternative best management practices were assessed in terms of specific metrics that included flood volumes and combined sewer overflow volumes through the Worcester sewer system.

Cost evaluations were used to identify appropriate best management strategies for managing the combined sewer system under future scenarios. A design cost approach and net benefits approach were used to analyze different options for managing stormwater under climate change. Both of these approaches utilize the concept of risk analyze to determine expected values of both costs and benefits for different options under different climate change scenarios. Results for the design cost approach indicate that providing upstream underground storage in select locations throughout the Worcester combined sewer system is the most cost-effective strategy. In addition, increased pumping capacity at the Quinsigamond Avenue Combined Sewer Overflow Storage and Treatment Facility (QCSOSTF) should be included for this option.

However, it was determined that only select upstream storage is the most beneficial option under the net benefits approach as increased pumping capacity at the QCSOSTF was determined to be too costly due to the additional costs of CSO treatment required at the facility.

The Worcester case study provides an ideal context for assessing the relative advantages of full treatment at the wastewater treatment facility, limited treatment at a centralized CSO treatment facility, decentralized storage options, and low impact stormwater controls. It also allows for an assessment of decision making methods for controlling flows and loads from the Worcester system. Comparisons between Worcester and other case studies provide a foundation for understanding how stormwater and combined sewer systems can be managed given climate change uncertainty.

Acknowledgements

I would like to acknowledge the following people who have assisted me the past two years with this study:

To my advisor, Paul Mathisen, who introduced me to this study and was always there for assistance and encouragement throughout my time at Worcester Polytechnic Institute. Professor Mathisen always provided guidance and introduced further ideas to help me improve my research. I am truly grateful to have had an advisor who continued to push me and help me at points along the way when I needed it.

To Professor John Bergendahl and Professor Paul Kirshen for their mentorship and participation as committee members for my study.

To all the students and professors from Tufts University who I collaborated with for this study: Paul Kirshen, Rich Vogel, Lauren Caputo, and Ana Rosner. The research participants from Tufts University provided great insight for this study and were a great source of assistance and support throughout. This study is based on previous research performed by Paul Kirshen and Rich Vogel, and I greatly appreciate their advice and guidance throughout.

To Matt Gamache and CDM Smith for providing the SWMM model for Worcester and their willingness to assist me with any questions and concerns I had with the model during the calibration and simulation stages of my research.

To Joe Buckley, Phil Guerin, and Dave Harris of the Worcester Department of Public Works for providing me with necessary data for my model and information on the Worcester CSO system. Their assistance and ideas were imperative in my ability to explore realistic considerations for stormwater management options.

To Al Charbonneau from the Quinsigamond CSO Storage and Treatment Facility for providing necessary data and background on the QCSOSTF necessary for this study.

To Mark Johnson of the Upper Blackstone Water Pollution Abatement District for providing necessary data for modeling and for his guidance and assistance throughout this study.

Note: The research presented in this thesis was completed for academic purposes and was not completed under the direction of the City of Worcester or CDM Smith. This work does expand upon previous work completed by the City of Worcester and CDM Smith, and the assistance of these organizations is gratefully acknowledged. It is emphasized that the views, opinions, conclusions and any recommendations presented in this thesis are solely those of the author and do not necessarily reflect the views of the City of Worcester or CDM Smith.

Table of Contents

Abstract……………………………………………………………………………………2

Acknowledgements……...4

List of Tables………………………………………………………………………...9

List of Figures……………………………………………………………………....12

1.0 INTRODUCTION……………………………………………………………...15

1.1 Problem Statement…………………………………………………………...15

1.2 Goals and Objectives………………………………………………………...17

1.3 Project Approach ……………………………………………………….......19

1.4 Project Significance …………………………………………………………20

2.0 BACKGROUND………………………………………………………………….21

2.1 Federal Regulations…………………………………………………………….21

2.1.1 Stormwater Discharges……………………………………………….21

2.1.2 CSO Control…………………………………………………………….23

2.2 State and Local Regulations………………………………………………….26

2.3 Stormwater Management Solutions…………………………………………….29

2.3.1 Best Management Practices…………………………………………..30

2.3.2 Low Impact Development…………………………………………….32

Infiltration Trenches and Dry Wells……………………………..33

Porous Pavement…………………………………………………34

Rain Barrels…………………………………………………...35

Green Roofs…………………………………………………...36

Blue Roofs……………………………………………………….38

Bioretention………………………………………………………39

2.4 CSO Management Solutions…………………………………………………40

2.5 Literature Review…………………………………………………………….42

2.5.1 Urban Drainage Solutions under Climate Change…………………………42

2.5.2 Green Infrastructure……………………………………………………..........47

Philadelphia, Pennsylvania……………………………………………48

Seattle, Washington…………………………………………………...49

2.6 Existing Conditions…………………………………………………………………51

2.6.1 Combined Sewer System………………………………………….........52

2.6.2 Quinsigamond Avenue Combined Sewer Overflow Storage and Treatment Facility (QCSOSTF)…………………………………………………..58

2.6.3 Upper Blackstone Wastewater Treatment Facility (UBWWTF)……..........60

2.6.4 Flow Metering Program………………………………………………61

3.0 METHODOLOGY…………………………………………………………………..67

3.1 EPA Stormwater Management Model (SWMM)……………………………67

3.2 Model Development…………………………………………………………70

3.3 Calibration and Validation……………………………………………………...73

3.4 Climate Change Scenarios……………………………………………….......87

3.5 Design Storms…………………………………………………………………..93

3.6 Performance Metrics…………………………………………………………94

3.6.1 Hazardous Flooding…………………………………………….........95

3.6.2 Volume of flow through QCSOSTF……………………………….95

3.6.3 Volume of flow through UBWWTF……………………………….96

3.7 Stormwater Management Options………………………………………...97

3.7.1 Option 1 – No Action……………………………………...............98

3.7.2 Option 2 – Underground storage throughout the watershed……………….98

3.7.3 Option 3- Underground storage upstream of QCSOSTF…………………100

3.7.4 Option 4 - Underground storage upstream of QCSOSTF and increased QCSOSTF pumping…………………………………………...102

3.7.5 Option 5 – Sewer Separation………………………………………......104

3.7.6 Option 6 – Low Impact Development (LID) throughout the watershed……………………………………………………………………106

3.7.7 Option 7 – Combination of LID and sewer separation…………………...110

4.0 RESULTS……………………………………………………………………………..111

4.1 Calibration Results………………………………………………………………….111

4.2 Model Simulation Results…………………………………………………………119

4.3 Cost Analysis – Design Cost Approach…………………………………………….129

Constant Costs…………………………………………………………….129

Variable Costs……………………………………………………………..130

4.3.1 Option 2 – Underground storage throughout the watershed……………...131

Constant Costs…………………………………………………….131

Variable Costs……………………………………………………..133

4.3.2 Option 4 – Underground storage upstream of QCSOSTF and increased QCSOSTF pumping………………………………………...139

Constant Costs…………………………………………………….139

Variable Costs……………………………………………………..141

4.3.3 Option 5 – Sewer Separation……………………………………….....142

Constant Costs…………………………………………………….142

Variable Costs……………………………………………………..144

4.4 Cost Analysis - Net Benefits Approach…………………………………….146

4.4.1 Option 1 – No Action………………………………………………...149

Costs…………………………………………………………………….149

Net Benefits…………………………………………………………….150

4.4.2 Option 2 – Underground storage throughout the watershed…………150

Costs…………………………………………………………………….150

Net Benefits…………………………………………………………….151

4.4.3 Option 3- Underground storage upstream of QCSOSTF…………………152

Costs………………………………………………………………….152

Net Benefits…………………………………………………………153

4.4.4 Option 4 – Underground storage upstream of QCSOSTF and increased QCSOSTF pumping………………………………………..............154

Costs………………………………………………………………….154

Net Benefits…………………………………………………………155

4.4.5 Option 5 – Sewer Separation……………………………………..156

Costs………………………………………………………………….156

Net Benefits…………………………………………………………156

4.4.6 Option 6 – Low Impact Development (LID) throughout the watershed…157

Costs………………………………………………………………….157

Net Benefits…………………………………………………………160

4.4.7 Option 7 – Combination of LID and sewer separation…………………...160

Costs…………………………………………………………………160

Net Benefits…………………………………………………………162

4.5 Discussion of Results……………………………………………………….164

5.0 CONCLUSION………………………………………………………………..168

5.1 Summary…………………………………………………………………....168

5.2 Limitations…………………………………………………………………170

5.3 Further Study………………………………………………………………172

List of References…………………………………………………………...........175

Appendix……………………………………………………………………………..179

Appendix A: Model Calibration Results………………………………………..179

Appendix B: Model Simulation Results………………………………………..187

List of Tables

Table 1: Flow meter information for June 2001 storm analysis……………………………...63

Table 2: Key boundary conditions of Worcester CSO System…………………………………72

Table 3: Total QCSOSTF stormwater flow volumes……………………………………………74

Table 4: QCSOSTF control rules (updated in 2001)……………………………………………80

Table 5: Control curve information (updated in 2001)…………………………………………81

Table 6: Comparison of model results and observed data for various parameters (old control depths: 13’, 15’, and 17’)……………………………………………………………………...83

Table 7: Comparison of model results and observed data for various parameters (new control depths: 10’, 13’, and 15’)……………………………………………………………………...84

Table 8: Comparison of model results and observed data for various parameters (final control depths: 8’, 10’, and 17’)………………………………………………………………………86

Table 9: Relative percent changes for each climate change scenario in 2050 and 2100………..91

Table 10: Relative percent changes for each climate change scenario in 2040 and 2070………92

Table 11: Summary of storm totals for each climate change scenario in 2040 and 2070………93

Table 12: Worcester CSO underground storage tank locations and design for 2070 (option 2)...100

Table 13: Worcester CSO underground storage tank locations and design for 2070 (option 3)...102

Table 14: LID inputs for residential areas……………………………………………………..108

Table 15: LID inputs for public, commercial, and industrial areas……………………………109

Table 16: Summary of BMP options and design goal performance…………………………...121

Table 17: Total constant costs for underground storage………………………………………132

Table 18: Present value costs for underground storage……………………………………….134

Table 19: Expected value cost results for underground storage (Shape 1)……………………136

Table 20: Expected value cost results for underground storage (Shape 2)………………….....136

Table 21: Expected value cost results for underground storage (Shape 3)………………….....136

Table 22: Expected value cost results for underground storage (Shape 4)……………………137

Table 23: Expected value costs for underground storage……………………………………...137

Table 24: EVPV variable costs for underground storage……………………………………...139

Table 25: EVPV total costs for underground storage…………………………………………139

Table 26: Total constant costs for upstream storage and increased QCSOSTF pumping……..141
Table 27: EVPV variable costs for upstream storage and increased QCSOSTF pumping…….141
Table 28: EVPV total costs for upstream storage and increased QCSOSTF pumping………..142
Table 29: Total cost of sewer separation of Canton St. and Northbridge St. catchments……...143
Table 30: Sewer separations costs of separated catchments under option 5…………………...144
Table 31: EVPV variable costs for sewer separation………………………………………..145
Table 32: EVPV total costs for sewer separation…………………………………………...145
Table 33: Final design cost results…………………………………………………………..146
Table 34: Present value costs for hazardous flooding damages for no action………………....148
Table 35: EVPV variable costs of CSO treatment for no action………………………………149
Table 36: EVPV variable costs of hazardous flooding damages for no action………………...150
Table 37: Total costs for no action……………………………………………………………150
Table 38: Total net benefits for no action……………………………………………………...150
Table 39: EVPV variable costs of hazardous flooding damages for underground storage……151
Table 40: Total costs for underground storage………………………………………………...151
Table 41: Total benefits for underground storage……………………………………………..152
Table 42: Total net benefits for underground storage…………………………………………152
Table 43: EVPV variable costs of hazardous flooding damages for upstream storage……….153
Table 44: Total costs for upstream storage……………………………………………………153
Table 45: Total benefits for upstream storage…………………………………………………153
Table 46: Total net benefits for upstream storage……………………………………………...154
Table 47: EVPV variable costs of hazardous flooding for upstream storage and increased QCSOSTF……………………………………………………………………………………155
Table 48: Total costs for upstream storage and increased QCSOSTF pumping………………155
Table 49: Total benefits for upstream storage and increased QCSOSTF pumping……………155
Table 50: Total net benefits for upstream storage and increased QCSOSTF pumping……….155
Table 51: EVPV variable costs of hazardous flooding for sewer separation…………………..156
Table 52: Total costs for sewer separation……………………………………………………..156
Table 53: Total benefits for sewer separation…………………………………………………157
Table 54: Total net benefits for sewer separation……………………………………………...157
Table 55: Low Impact Development (LID) costs……………………………………………...158

Table 56: Total constant costs for LID……………………………………………………………...159
Table 57: Total EVPV variable costs for LID…………………………………………………159
Table 58: Total costs for LID…………………………………………………………………..159
Table 59: Total benefits for LID………………………………………………………………160
Table 60: Total net benefits for LID…………………………………………………………...160
Table 61: Total constant costs for LID and sewer separation…………………………………161
Table 62: Total EVPV variable costs for LID and sewer separation…………………………161
Table 63: Total costs for LID and sewer separation…………………………………………...162
Table 64: Total benefits for LID and sewer separation……………………………………..162
Table 65: Total net benefits for LID and sewer separation……………………………………162
Table 66: Final net benefits results for Worcester……………………………………………..163
Table 67: Final net benefits results for Somerville…………………………………………….166

List of Figures

Figure 1: Infiltration trench plan view (left) and profile view (right)…………………………..34

Figure 2: Porous Pavement……………………………………………………………...35

Figure 3: Rain Barrel……………………………………………………………………36

Figure 4: Green Roof…………………………………………………………………....37

Figure 5: Blue Roof……………………………………………………………………..38

Figure 6: Bioretention Basin…………………………………………………………….39

Figure 7: Map of Worcester, MA………………………………………………………….51

Figure 8: Aerial view of Worcester……………………………………………………..52

Figure 9: Separated sewer system…………………………………………………………53

Figure 10: Combined sewer system…………………………………………………..54

Figure 11: Worcester CSO System Schematic…………………………………………….58

Figure 12: Quinsigamond Avenue Combined Sewer Overflow Storage and Treatment Facility (QCSOSTF)…………………………………………………………………………...60

Figure 13: Photograph of Upper Blackstone Wastewater Treatment Facility (UBWWTF)……61

Figure 14: Map of Worcester CSO System watershed area………………………………...62

Figure 15: Stormwater management model (SWMM) interface………………………………..68

Figure 16: Dry Weather Flows July 19-25, 2008………………………………………………77

Figure 17: Wet Weather Flows July 19-25, 2008………………………………………………77

Figure 18: Effluent Discharge July 19-25, 2008……………………………………………...77

Figure 19: Dry Weather Flows August 10-11, 2008……………………………………………78

Figure 20: Wet Weather Flows August 10-11, 2008……………………………………………78

Figure 21: Effluent Discharge August 10-11, 2008……………………………………………..78

Figure 22: Dry Weather Flows September 25-29, 2008…………………………....................79

Figure 23: Wet Weather Flows September 25-29, 2008………………………………………..79

Figure 24: Effluent Discharge September 25-29, 2008………………………………………79

Figure 25: Relative change in annual precipitation for 2-year 24-hour design storm…………..89

Figure 26: Relative change in annual precipitation for 10-year 24-hour design storm…………90

Figure 27: Relative change in annual precipitation for 100-year 24-hour design storm………..90

Figure 28: Map of Worcester CSO System showing proposed areas for sewer separation…...105

Figure 29: Meter 2 Flows June 2-4, 2001……………………………………………...113

Figure 30: Meter 2 Water Depths June 2-4, 2001…………………………………………...113
Figure 31: Meter 2 Rainfall June 2-4, 2001……………………………………………………113
Figure 32: Meter 12 Flows June 2-4, 2001…………………………………………………….114
Figure 33: Meter 12 Water Depths June 2-4, 2001…………………………………………….114
Figure 34: Meter 12 Rainfall June 2-4, 2001…………………………………………………..114
Figure 35: Meter 15 Flows June 2-4, 2001…………………………………………………….115
Figure 36: Meter 15 Water Depths June 2-4, 2001…………………………………………….115
Figure 37: Meter 15 Rainfall June 2-4, 2001…………………………………………………..115
Figure 38: QCSOSTF Flows June 2-4, 2001…………………………………………………..116
Figure 39: QCSOSTF Water Depths June 2-4, 2001…………………………………………..116
Figure 40: QCSOSTF Rainfall June 2-4, 2001………………………………………………...116
Figure 41: Effluent Discharge July 19-25, 2008 (New Control Rules) ……………………….118
Figure 42: Effluent Discharge August 10-11, 2008 (New Control Rules) ……………………118
Figure 43: Effluent Discharge September 25-29, 2008 (New Control Rules) ………………...118
Figure 44: Hazardous flooding for option 1…………………………………………………...122
Figure 45: Volume out of QCSOSTF for option 1…………………………………………….122
Figure 46: Volume out of UBWWTF for option 1…………………………………………….122
Figure 47: Hazardous flooding for option 2…………………………………………………...123
Figure 48: Volume out of QCSOSTF for option 2…………………………………………….123
Figure 49: Volume out of UBWWTF for option 2…………………………………………….123
Figure 50: Hazardous flooding for option 3…………………………………………………...124
Figure 51: Volume out of QCSOSTF for option 3…………………………………………….124
Figure 52: Volume out of UBWWTF for option 3…………………………………………….124
Figure 53: Hazardous flooding for option 4…………………………………………………...125
Figure 54: Volume out of QCSOSTF for option 4…………………………………………….125
Figure 55: Volume out of UBWWTF for option 4…………………………………………….125
Figure 56: Hazardous flooding for option 5…………………………………………………...126
Figure 57: Volume out of QCSOSTF for option 5…………………………………………….126
Figure 58: Volume out of UBWWTF for option 5…………………………………………….126
Figure 59: Hazardous flooding for option 6…………………………………………………...127
Figure 60: Volume out of QCSOSTF for option 6…………………………………………….127

Figure 61: Volume out of UBWWTF for option 6……………………………………………….127

Figure 62: Hazardous flooding for option 7……………………………………………………...128

Figure 63: Volume out of QCSOSTF for option 7……………………………………………….128

Figure 64: Volume out of UBWWTF for option 7……………………………………………….128

Figure 65: Present value variable cost for option 2 under 2040 high climate change scenario………………………………………………………………………………………135

Figure 66: Expected value for high climate change scenario (option 2)………………………138

Figure 67: Expected value for moderate climate change scenario (option 2)………………....138

Figure 68: Expected value for low climate change scenario (option 2)………………………139

Figure 69: Final net benefits results for Worcester……………………………………………….163

Figure 70: Final net benefits results for Somerville……………………………………………...166

1.0 INTRODUCTION

Over the years, the world has continued to become more urbanized as people are living in more populated areas with more impervious surfaces. As a result, the challenges of managing urban drainage systems have increased. Drainage systems are used to manage excess water from storm events before they reach major stream channels that can lead to downstream flooding, property damage, public health issues, and overall problems with water quality (Kirshen et al., 2010). There is increased pressure for urban water managers to improve urban drainage systems so they safely and effectively manage stormwater. Present and future management of urban stormwater has become increasingly more difficult by the awareness of long-term climate change. Several experts have reported that they expect the number of extreme storm events in most regions of the world to increase under climate change (Kirshen et al., 2010). This section describes the challenges with the impacts of climate change on urban drainage systems and presents the main goals and objectives for this study. The overall approach for the project is described as well as its significance in meeting the goals and objectives.

1.1 Problem Statement

The assessment of the potential impacts of climate change on urban drainage systems is one of the major challenges faced by cities and government agencies. From the growing interest in climate change research, it has been predicted that precipitation events will become more extreme (IPCC, 2001). Heavily urbanized areas like Worcester, MA are expected to experience possible flooding due to increased runoff from extreme storm events. Although low impact development techniques (LID) have been used and help improve stormwater management in urban areas, these techniques have been implemented too slowly at the local level.

In the future it is expected that the world will continue to urbanize. In 2010, it was estimated that 82 percent of the population of North America live in urban areas compared to only 43 percent in 1990 (UNESCO, 2006). The increase of urbanization and impervious surfaces will lead to hydrologic changes that will cause further flooding in these areas. In addition to street and river flooding, increased inflow and infiltration into sewer systems should be expected along with increased nonpoint source pollution and overflows from combined sewer systems. Costs of improving stormwater drainage systems in urban areas can be extremely high. It may cost hundreds of millions of dollars to completely mitigate CSO systems in a particular city.

Local government officials are under increased pressure by regulatory agencies to better manage stormwater. In particular, EPA issued Phase 1 and II regulations in 1990 and 1999 to specifically improve stormwater management systems in urban areas (EPA, 2011a). These regulations involve requiring cities to obtain permits for managing storm sewers and applying best management practices (BMPs) to improve their systems by improving the quality of urban runoff while also decreasing its quantity (EPA, 2011a). While present and future stormwater management is greatly affected by changing land use and regulations, it is also greatly affected by long-term climate change. Increased precipitation in extreme storm events has become a consistent result in most regions of the world from model analyses, especially in urban areas of New England. The importance of adapting water resources projects has been recognized to prepare for long-term uncertainty in climate and their effects on urban drainage systems. One of the biggest challenges today is to recognize short-term solutions for adapting to long-term uncertainty. Another challenge that has been discussed is the need to particularly develop the capacity to adjust to climate change not only in the United States but in developing countries around the world.

The challenges of climate change and its effects on urban drainage are particularly significant for the city of Worcester, MA, which was the focus for this research. The city of Worcester is located in Central Massachusetts and is one of the largest cities in New England. The city manages three distinct sewer infrastructure components: the sanitary sewer system, the stormwater system, and the combined sewer overflow system. The sanitary sewer system carries both domestic and industrial wastewater throughout the city to the Upper Blackstone Wastewater Treatment Facility (UBWWTF), where it is treated before being discharged to the Blackstone River. The stormwater piping system collects rainfall runoff from city streets to the nearest waterway. However, during heavy rain events the amount of stormwater entering the system can become overwhelming for the stormwater system and the wastewater treatment plant. The heavy rain events can lead to combined sewer overflows, which pollute rivers and streams that receive the stormwater. As a result, a combined system was developed in Worcester to treat the sewer overflows from major storm events. Most large cities have older sewer infrastructure with combined sewer systems. USEPA and MassDEP have worked to help minimize and treat combined sewer overflows so they don’t impair the quality of water bodies.

1.2 Goals and Objectives

The primary objective of this project is to develop effective ways to respond to uncertainty in extreme conditions under climate change to better manage urban stormwater systems. This study has been carried out for the combined sewer system in Worcester, MA to determine how the stormwater management system will change under the uncertainties of climate change. For this research project, actual observed data from the city of Worcester were provided. Observed flows were compared to modeled flows from a stormwater modeling program known as the Stormwater Management Model (SWMM). One objective of this project was to use SWMM to evaluate past storm events. After comparing observed flow data to results from the model, these results were used to help develop future storms and model their impacts under climate change scenarios. Finally, best management practices (BMPs) were determined for better managing urban drainage systems. Best management practices include different strategies to effectively manage stormwater runoff (Guitierrez, 2006). EPA regulations have required the application of both structural and non-structural BMPs. Most structural BMPs include building additional structures that will trap and detain runoff before they enter receiving waters (Guitierrez, 2006). Nonstructural BMPs include measures that will help control pollutants at the source of sewer runoff (Guitierrez, 2006). One of the main goals of this project was to develop a set of guidelines applicable to different areas in the U.S. on planning for future urban drainage management under the uncertainty of climate change, and these guidelines will be established through further research on observed data and future storm predictions along with the development of best management practices.

1.3 Project Approach

Our research aims to effectively respond to conditions of climate change and develop best management practices to manage stormwater in urban areas. Case studies in Massachusetts and Colorado were carried out to determine how the performance of a stormwater management system currently in the planning stages will change under climate change adaption strategies that consider the uncertainty of future storms. Three different systems were analyzed for stormwater management under climate change, including systems located in Worcester, MA, Somerville, MA, and Aurora, CO. This project involves working in collaboration with students from Tufts University who are analyzing urban drainage systems in Somerville and Aurora.

Earlier storm events were modeled from Worcester, MA in order to determine how to best manage flows from future storms. These storms include one storm in June of 2001 and three storms in July, August, and September of 2008. These storms were modeled using an EPA modeling program known as the Stormwater Management Model (SWMM). SWMM is a dynamic rainfall-runoff simulation model that can be used for both single event and continuous long-term simulations for runoff and from mainly urban areas (EPA, 2012a). After completing calibration of past storms, experimental simulations were modeled for future storms under different climate change scenarios. Different design storms were modeled in order to determine the variability of climate change scenarios.

In addition, different best management practice (BMP) options were determined and evaluated using the SWMM model. Best management practices offer a variety of different ways to improve urban stormwater management systems. Effective management of stormwater runoff offers a great deal of potential benefits. These benefits include protection of wetlands and ecosystems, improved quality of receiving waters, conservation of water resources, protection of public health, and flood control (USEPA, 2007). These BMP options were all analyzed using two cost analysis approaches: a design cost approach and a net benefits approach. Design costs and net benefits for each CSO management option were compared to determine the most cost-effective and beneficial option for Worcester. Cost and benefits results for Worcester were compared to results from the Somerville model to be able to compare the two systems. Similar cost analysis approaches were used for both systems, as cost approaches for Worcester were based on analyses performed in Somerville by Lauren Caputo of Tufts University (Caputo, 2011).

1.4 Project Significance

As the world continues to urbanize, more and more impervious surfaces are being created and the challenge of managing urban drainage systems continues to increase. In addition, the uncertainty of climate change and its lasting effects on extreme storm events in the future are becoming important issues that must be addressed. For these reasons it is becoming extremely important to better manage stormwater systems in urban areas. This project involves evaluating past and future storm events in Worcester, MA in order to help improve the management of the Worcester combined sewer system to prepare for future storm events. For the proposed research, storm events in 2001 and 2008 were evaluated using EPA SWMM. Using past modeled storm events, future storms were modeled for different storms in the future under varying climate change scenarios. These future storms were evaluated for different BMP options in order to make future recommendations. This project is intended to help gain further recognition of climate change and its effects on urban drainage systems, not only in Worcester but in developing urban areas in the United States and around the world. The end results of the proposed research include a set of guidelines for improving urban areas in the United States for urban drainage system management under climate change. The results of this study were also compared to results from Somerville in order to determine the effects of climate change on different urban areas specifically in Massachusetts. A set of best management practices for the management of flows in the Worcester CSO system were reviewed and are presented in this report. All steps of the project, including final results, are presented in the chapters that follow.

2.0 BACKGROUND

This section provides an overview of important information that is relevant to the research project. It includes information on climate change and how it expects to have a major impact on the frequency of extreme storms and the design of urban drainage systems in the future. In addition, information is provided on the importance of stormwater modeling and how EPA SWMM is used to model past and future storms in the Worcester, MA combined sewer system. Furthermore, this section provides a review of best management practices and how they have been used to improve drainage systems in urban areas. A number of case studies are also included in this section and have been studied in order to provide a comparison of Worcester, MA to other areas in the United States. Adaptation planning is also an important aspect of this project, as statistical techniques were explored in order to mathematically determine how to best prepare for uncertainty in the future. In this case, adaptation planning is used to determine the risk of managing stormwater under the uncertainty of future storm events under climate change scenarios. Finally, this chapter provides background of the Worcester CSO system along with important information about CSO policies and regulations.

2.1 Federal Regulations

2.1.1 Stormwater Discharges

Stormwater discharges in the United State are federally regulated by the Environmental Protection Agency (EPA) under the National Pollutant Discharge and Elimination System (NPDES). NPDES is a permitting program that was authorized by the Clean Water Act that protects the nation’s water and directs EPA to develop and enforce new regulations to control water pollution (EPA, 2002). The Clean Water Act was established in 1972 and the NPDES program implemented from this act provides the basic structure for regulating the discharge of pollutants from point sources to American waters (EPA, 2012b). EPA implemented pollution control programs to set standards for industrial and municipal wastewater and also for surface waters. EPA's NPDES program focuses on direct point sources, which are direct discharges from sources like stormwater pipes or man-made ditches. Individual homes that are connected to a municipal system but have their own septic systems do not need to comply with NPDES regulations. However, industrial and municipal facilities along with other facilities connected to a municipal system are required to obtain permits to directly discharge surface waters. Stormwater nonpoint sources can come from many different sources in a watershed, including roads, highways, sidewalks, fields, parks, forests, etc. (EPA, 2002). In addition to the national government, the Clean Water Act allowed EPA to authorize the NPDES Permit Program to state governments, which allowed the states to perform many of the permitting, administrative, and enforcement acts set up by the NPDES program. Massachusetts is one of the states that runs their own NPDES program and issues its own permits authorized by EPA. However, EPA still retains the main oversight responsibilities in Massachusetts and other states that have been authorized to implement the NPDES program (EPA, 2002).

Polluted stormwater runoff is usually transported though Municipal Separate Storm Sewer Systems (MS4s), where it is often untreated and discharged into local waters. In order to prevent pollutants from being discharged into an MS4, operators are required to obtain a NPDES permit and develop a program to manage stormwater. Municipalities must comply with Phase I and Phase II regulations of the NPDES program (EPA, 2011a). Phase I regulations were issued in 1990, and they require "medium and large cities or certain counties with populations of 100,000 or more to obtain NPDES permit coverage for their stormwater discharges" (EPA, 2011a). This phase of the regulations was crucial to eliminating the large contributors to water pollution in the United States. Phase II regulations were issued in 1999, and they require "regulated small MS4s in urbanized areas, as well as small MS4s outside the urbanized areas that are designated by the permitting authority, to obtain NPDES permit coverage for their stormwater discharges" (EPA, 2011a). This phase has helped operators of smaller cities and areas outside of larger cities and counties to regulate what they discharge, which has helped to further improve water quality in these areas.

The NPDES program regulates stormwater discharges from municipal separate storms systems, construction activities, and industrial activities. In addition, over the past few years more attention has been given to regulating stormwater pollutants from nonpoint sources. Under a changing climate it is important that EPA look to possibly revise its current NPDES program to consider the effects of possible extreme storms and more frequent rainfall in the future. Possible changes may include increased monitoring and improvements to current stormwater controls. It is expected that more combined sewer overflows will occur in the future, so it is important that increased controls and further stormwater regulations be considered. In addition, treatment facilities and industries will need to adapt to new regulations and change their stormwater management program to better prepare for more frequent intense storms under climate change (EPA, 2011a).

2.1.2 CSO Control

In addition to the NPDES permit program, EPA developed the Combined Sewer Overflow Control Policy in 1994, which is a set of national standards for controlling CSOs through the NPDES permit program. The policy provides guidelines for municipalities and regulatory permitting authorities for meeting the Clean Water Act's pollution goals. The Policy has four fundamental principles which should be met in order to ensure that CSO controls are both cost effective and meet environmental objectives (EPA, 2002). The four fundamental principles include:

1. Clear levels of control to meet health and environmental objectives
2. Flexibility to consider the site-specific nature of CSOs and find the most cost-effective way to control them
3. Phased implementation of CSO controls to accommodate a community's financial capability
4. Review and revision of water quality standards during the development of CSO control plans to reflect the site specific wet weather impacts of CSOs.

Both state regulatory agencies and EPA permitting authorities are continuing to further advance implementation of the CSO Policy. They have been working with towns across the country to incorporate CSO conditions into NPDES permits along with other enforceable measures like administrative and judicial orders. In January of 1997, EPA implemented nine minimum control measures under the CSO Control Policy (EPA, 2002). These measures were put in place to reduce the impacts of CSOs that are not expected to require significant design or construction. The nine minimum controls are listed (EPA, 2002):

1. Proper operation and regular maintenance programs for sewer systems and CSO systems
2. Maximum use of the collection system for storage
3. Review and modification of pretreatment requirements to assure CSO impacts are minimized
4. Maximization of flow to the publicly owned treatment works (POTW) for treatment
5. Prohibition of CSOs during dry weather
6. Control of solid and floatable materials in CSOs
7. Pollution prevention
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

Communities with combined sewers are also expected to develop long-term control plans for CSOs that will provide for full compliance with the Clean Water Act, which will include the attainment of all water quality standards. Currently, communities with CSOs are in different stages of developing and implementing long-term control plans. These stages include: characterizing their combined sewer systems, monitoring the impacts of CSOs on receiving waters, and discussing water quality and water quantity goals for CSOs with permitting and environmental authorities. When evaluating alternatives for CSO controls, EPA evaluates controls for a range of overflow events per year. In addition, the long-term plan evaluates controls that achieve between 75% and 100% capture for treatment (EPA, 2002). It also may consider expansion of POTW primary and secondary capacity in the CSO abatement alternative analysis.

The long-term CSO control plan should also adapt one of the following approaches for meeting their requirements: a “presumption” approach or a “demonstrative” approach. For a presumptive approach, a program that meets certain criteria are presumed to provide adequate control levels to meet water quality requirements provided that permitting authorities determine that the presumption is reasonable enough depending on data and analysis conducted in the system. A demonstrative approach involves demonstrating that if a control program doesn’t meet specific criteria that it still is adequate to meet water quality requirements set by the Clean Water Act (EPA, 2002).

For the study in Worcester, the focus for CSO management will be on using a presumptive approach. As stated for stormwater management, the long-term CSO policy set forth by EPA and MassDEP may need to be updated in Massachusetts to consider the effects of climate change. The impacts of climate change may lead to more intense and frequent storm events, which may directly lead to the increase of CSO overflows. More monitoring may need to take place in the future to determine if changes need to be made in the future to the current CSO control program.

2.2 State and Local Regulations

In the state of Massachusetts EPA authorized the NPDES permit program for stormwater discharging. In Massachusetts, it is a 5-year permit that is issued by both EPA and the state environmental regulatory agency, the Massachusetts Department of Environmental Protection (MassDEP). The permit requires towns and cities in Massachusetts to meet six minimum control measures, and towns report their progress on these control measures by sending an Annual Report by May 1st of each year to EPA and MassDEP. The six control measures are (EPA, 1994):

1. Pollution Prevention and Good Housekeeping – This measure addresses runoff from municipal operations and includes what practices towns should carry out to operate stormwater systems effectively.

2. Illicit Discharge Detection and Elimination (IDDE) Program – Illicit discharges are non-stormwater discharges to the storm drain system. They typically contain pollutants like bacteria, so the MS4 permit requires towns to develop and implement a program that prohibits illicit discharges, includes a storm sewer map that shows where all storm drain outfalls are located, and plans to locate and eliminate illicit discharges.

3. Construction Site Runoff Control – Construction site owners and operators are required to file a Notice of Intent for construction that affects more than one acre of land. Towns are allowed to implement stricter rules at the local level, but minimum requirements include legally enforcing mechanisms to control erosion and procedures for municipal site review of projects.

4. Post Construction Runoff Control - This measure requires ongoing management of stormwater prior to construction, and requirements include adapting mechanisms to control stormwater and establishing procedures for the long-term operation and management of BMPs.

5. Public Education and Outreach – Towns in Massachusetts are encouraged to distribute educational materials to local audiences within the community and implement a formal public education program.

6. Public Participation and Involvement – This measure involves giving the public opportunities to play a role in developing and implementing the MS4 program.

In 1996 MassDEP issued the Stormwater Policy that established the Stormwater Management Standards. These standards aimed to encourage recharge and stormwater discharge prevention to avoid pollution of surface water and groundwater. In 1997 MassDEP published the Massachusetts Stormwater Handbook as a guide for the Stormwater Policy (MassDEP, 1997). The stormwater standards were revised to promote increased stormwater recharge, treatment of further runoff from polluting land, the use of low impact development (LID), pollution prevention, illicit discharge removal, and improved operation and maintenance of BMPs (MassDEP, 1997). The Stormwater Management Standards address water quality and quantity by requiring the implementation of a wide variety of stormwater management strategies. The Stormwater Management Strategies are listed below (MassDEP, 1997):

1. No new standard conveyance may discharge untreated stormwater directly to or cause erosion in wetlands or waters of the Commonwealth.

2. Stormwater management standards shall be designed so post-development peak discharge rates don’t exceed pre-development peak discharge rates.

3. Loss of annual recharge to groundwater shall be eliminated or minimized through the use of infiltration measures including environmentally sensitive site design, LID techniques, best management practices, 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.

4. Stormwater management systems shall be designed to remove 80% of the average annual post-construction load of Total Suspended Solids (TSS). The standard is met when suitable practices for source control and pollution prevention are identified in a long-term pollution prevention plan and are later implemented and maintained. It is also met when structural BMPs are sized to capture the required water quality volume determined and when pretreatment is provided (all actions in accordance with the Massachusetts Stormwater Handbook).

5. For land uses with higher potential loads, source control and pollution prevention shall be implemented to eliminate or reduce the discharge of stormwater runoff from such land uses to the maximum extent practicable. If through source control and/or pollution prevention all land uses with higher potential pollutant loads cannot be completely protected from exposure to rain, snow, and stormwater runoff, the proponent shall use the specific structural stormwater BMPs determined by the Department to be suitable for such uses as provided in the Massachusetts Stormwater Handbook.

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 measure and the specific structural stormwater BMPs determined by the Department to be suitable for managing discharges to such areas.

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 BMP 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.

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.

9. A long-term operation and maintenance plan shall be developed and implemented to ensure that stormwater management systems function as designed.

10. All illicit discharges to the stormwater management system are prohibited.

These standards are enforced for projects in Massachusetts in compliance with NPDES, the Clean Water Act, the Massachusetts Wetlands Protection Act, and the Massachusetts 401 Water Quality Certification Regulations. Unless otherwise stated, stormwater runoff from all projects in Massachusetts including site preparation, construction and redevelopment, and all point source stormwater discharges shall be managed according to these ten standards (MassDEP, 1997). Single-family homes and housing development projects with detached single-family dwellings do not apply. This study focuses on stormwater and CSO discharges in Worcester, MA, which is required to meet these standards enforced by EPA and MassDEP. As stated for the federal regulations, the state stormwater management standards may need to be updated to better manage stormwater in the future under climate change scenarios. More intense storms in the future may lead to increased pollutants, so stormwater runoff volumes may be increased under these standards. In addition, longer dry periods between storms may increase pollutant loadings. Building developers and stormwater mangers will need to be able to adapt and change their approach to managing stormwater in the future under a changing climate change. The uncertainty of climate change is expected to greatly affect the magnitude and intensity of storms in the future, so it is important that both federal and state regulators be prepared to adapt to these situations and be ready to possibly make adjustments to their current standards.

2.3 Stormwater Management Solutions

Climate change has quickly become a reality that urban planners must consider when designing urban drainage systems. It is expected that the cumulative effects of gradual change in hydrology from climate change will alter both the magnitude and frequency of extreme storm events, leading to higher peak flows over the life of urban drainage infrastructure. Engineers now have to consider climate change in order to better adapt and serve the interests of the public. A great deal of evidence has shown that human activity over the last fifty years has greatly affected the warming of the Earth's system. It has become increasingly more important to properly manage stormwater to decrease the effects of climate change in the future. Specifically, it is important to better manage stormwater in urban areas. Historically, stormwater has been managed by infrastructure and best management practices that are specifically designed for a particular design storm, which is based on historical precipitation data available in that area. Over the years a group of different best management practices have been tested and determined to work the best to control flooding and improve water quality. This section gives a description of specific best management practices for stormwater management, which also includes in detail both storage best management practices and a relatively new group of practices known as low impact development (LID).

2.3.1 Best Management Practices

Both the quality and quantity of stormwater can be managed and improved through the use of best management practices (BMPs) within a watershed. BMPs are effective structural and non-structural methods of protecting both the quantity and quality of water from potential adverse effects. Structural BMPs include detention and retention basins, bioretention, infiltration trenches, dry wells, sediment traps, vegetated swales, deep sump catch basins, sediment forebays, and constructed wetlands (USEPA, 2007). Structural BMPs are used to trap and control runoff before it enters receiving waters. These types of strategies have the potential to reduce flooding within a watershed by controlling peak flows during storm events. They can also help remove pollutants through both physical and biological processes, and they can infiltrate stormwater into the ground and recharge groundwater aquifers (Mass DEP, 1997). Non-structural BMPs include practices that can directly control water quality issues at the source. They directly control pollutants from entering the source of watersheds and can preserve natural habitats in these areas with improved water quality (Guitierrez, 2006). Different types of non-structural BMPs include public outreach and education of how to avoid the growth of pollutants, street cleaning, and the use of zoning to protect open space (Mass DEP, 1997).

Stormwater is traditionally managed through storage BMPs like underground storage, detention and retention ponds, and stormwater wetlands. A retention pond is a basin that catches runoff from higher elevation areas (Kasco Marine, Inc., 2006). They are often created near developed areas and have become so popular over the years that they are now required in many areas around the country with new development. Retention ponds are developed to limit flooding and remove pollutants (Kasco Marine, Inc., 2006). Detention ponds are similar to retention ponds, but they do not require a permanent pond of water. Detention ponds are designed to detain stormwater runoff for a minimum amount of time to allow pollutants to settle (USEPA, 2009a). These ponds can also be designed with small pools of water at both the inlet and outlet of the pond. Dry detention ponds traditionally have been one of the most widely used methods of stormwater management and may be the most appropriate best management practice for different areas under different considerations (USEPA, 2009a).

Stormwater wetlands are structural best management practices that incorporate wetland vegetation into their design. As runoff from stormwater enters the wetland, pollutants are removed through settling and biological processes (USEPA, 2009a). Stormwater wetlands are one of the most effective BMPs for pollutant removal, and they also provide aesthetic value and are used effectively for the development of habitats (USEPA, 2009a). Stormwater wetlands are particularly used to treat stormwater runoff and have less biodiversity in terms of plant and animal life than natural wetlands (USEPA, 2009a). Wetlands have few restrictions in terms of their use, but they do have limited applicability in highly urbanized areas like Worcester.

For this particular study, underground storage was the primarily BMP of focus due to the high level of development and small amount of available land in the city of Worcester. There are several different types of underground storage structures, including pre-cast concrete and plastic pits, chambers, perforated pipes, and galleys. (Mass DEP, 2008). Underground storage retention and detention captures stormwater collected from surrounding impervious areas. The stored water is directly released to an outlet pipe and is directed back to natural water bodies above the surface at a rate designed to reduce peak flows during storm events (Mass DEP, 2008). Underground storage has very few water quality benefits, but they can be used as a successful technique for stormwater management in developing areas (Lake Superior Streams, 2012). They are especially successful as part of an overall stormwater management plan combined with other stormwater BMPs (Lake Superior Streams, 2012). In addition, it may be necessary to use pretreatment methods for underground storage in Worcester since there is a potential for high pollutant loadings from streets and highways. These types of structures can trap sediments and pollutants that can be cleaned to make sure the storage tanks are working properly to manage stormwater. Pretreatment options for stormwater management, specifically for underground storage, include deep sump catch basins, proprietary separators, and oil-grit separators (Mass DEP, 2008).

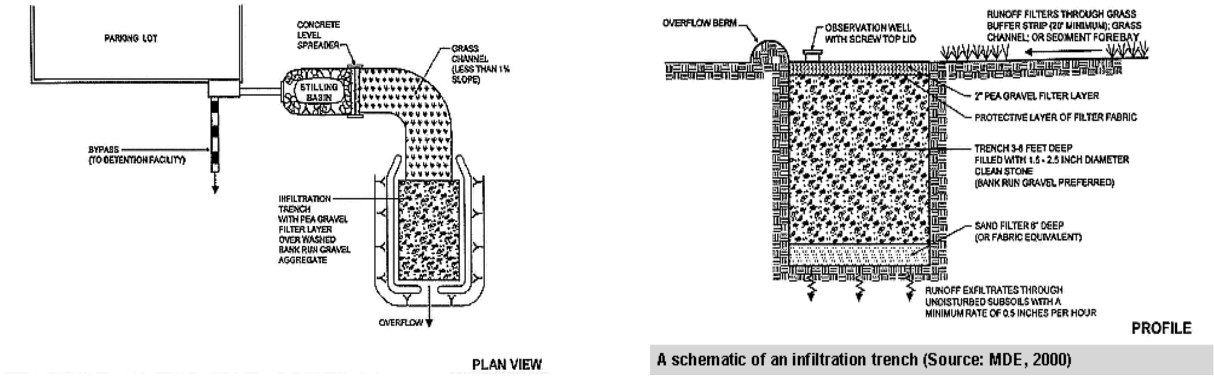
2.3.2 Low Impact Development

Low Impact Development is a sub-group of BMPs that is a relatively new approach to managing stormwater. According to Low Impact Development Inc. it is "an innovative stormwater management approach with a basic principle that is modeled after nature: manage rainfall at the source using uniformly distributed decentralized microscale controls" (Low Impact Development Center, Inc., 2007). LID technology is designed to model the hydrology of a site by using design techniques that infiltrate, filter, and store runoff. The development of LID began with the introduction of bioretention technology in the mid 1980s in Prince George's County, Maryland. LID was first used to Help Prince George's County deal with the growing limitations with conventional stormwater management practices (Low Impact Development Center, Inc., 2007). Low Impact Development works together with nature to manage stormwater at its source. It uses principles like preserving and recreating natural landscapes. It also helps minimize imperviousness to improve site drainage to better treat stormwater and use it as a resource instead of waste (Low Impact Development Center, Inc., 2007). Examples of LID include bioretention, green roofs, rain barrels, disconnected downspouts, tree box planters, and infiltration swales. LID applications can help reduce flooding and also improve the water quality of surface waters in their vicinity. By implementing LID practices and principles, water can be managed in order to reduce the impacts of developed areas, and they also promote the natural movement of water through a watershed. LID has the ability to maintain and restore the hydrology and ecological functions of a watershed (Low Impact Development Center, Inc., 2007). Some LID applications are referred over others mainly due to cost considerations, but in many cases a combination of different LID applications are used in urban areas to best manage stormwater. Maintenance is also an important factor in choosing the most effective type of low impact development, as all types of LID require proper maintenance. For this study in Worcester, and in the case study in Somerville, MA, the following types of LID were selected to be focused on for this research study: infiltration trenches and dry wells, porous pavement, rain barrels, green roofs, blue roofs, and bioretention.

Infiltration Trenches and Dry Wells

An infiltration trench is a shallow quarry that is filled with stone in order to create a reservoir for stormwater runoff. The void spaces created by the stone provide underground storage for water that enters the trench (Mass DEP, 1997). The runoff will gradually filtrate through the bottom of the trench into the subsoil and to the water table. The design of an infiltration trench can also be modified to include vegetation to create a biofiltration area (Mass DEP, 1997). In addition to reducing runoff volume and peak discharges through infiltration, this type of LID technology is used to remove pollutants from stormwater runoff. They also help reduce the size and cost of downstream stormwater control facilities and storm drain systems by infiltration stormwater. They also can be utilized in larger developed areas where space is limited

(Mass DEP, 1997). A dry well is a specific type of infiltration trench that disposes unwanted stormwater runoff from rooftops (Mass DEP, 1997). It is a common type of infiltration trench that is used in many developed urban areas, and it will specifically be used as a type of LID application for the Worcester, MA combined sewer overflow (CSO) system. Both a plan view and profile view of an infiltration trench are included in Figure 1 below.



A schematic of an infiltration trench (Source: MDE, 2000)

Figure 1: Infiltration trench plan view (left) and profile view (right)
(USEPA, 2009a)

Porous Pavement

Porous pavement is a type of manufactured paved surface that allows water to infiltrate through into the soil due to the higher void spaces of the pavement. Porous pavement consists of irregular shaped crushed rock that is pre-coated with asphalt binder (Mass DEP, 1997). Stormwater runoff is able to seep through into the lower layers of the pavement system of gravel for temporary storage. After seeping through to a temporary storage layer, the water then naturally filters into the soil. Porous pavement often appears to be the same as traditional asphalt but it does not include finer materials and incorporates coarser materials with void spaces (Greenworks, 2011). Porous pavement has been successfully used in well developed urban areas since it stores stormwater without using up extra space. This technology can pose challenges in areas with cold weather climates, and they should be avoided in areas that generate high contaminate runoff, such as gas stations and vehicle maintenance areas, because these pollutants may seep into the soil. Porous pavement may be ideal for use in parking lots, sidewalks, driveways, and patios (Greenworks, 2011). There are several different types of porous pavement, which include: porous asphalt, pervious concrete, paving stones, and grass pavers (Mass DEP, 2008). Figure 2 below includes a design for porous pavement.

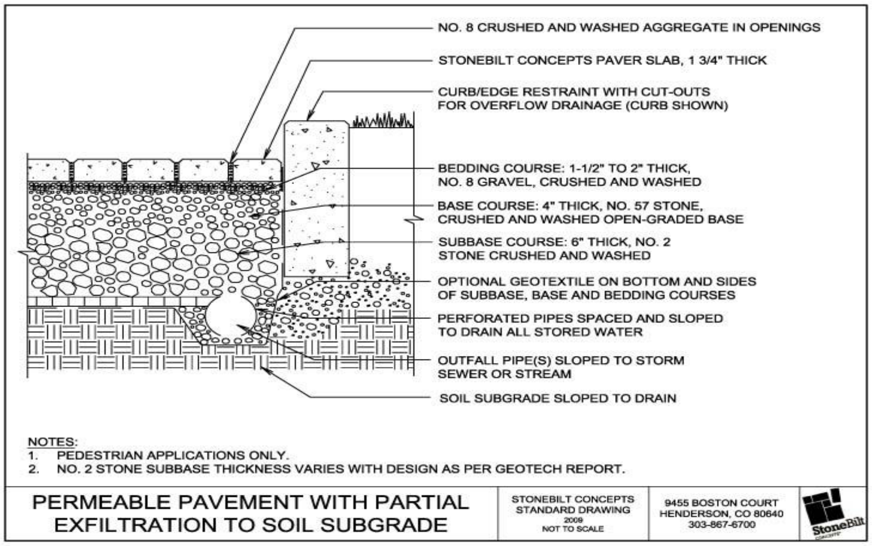


Figure 2: Porous Pavement
(StoneBilt Concepts, 2011)

Rain Barrels

A rain barrel is a system that stores stormwater runoff from rooftops that would otherwise be diverted to storm drains and streams. The runoff stored in rain barrels can be reused mainly for landscaping purposes (USEPA, 2009b). Rain barrels collect stormwater and the water can be used during periods of drought when it is needed the most. They provide an ample supply of water to homeowners for non-potable uses. Downspouts are disconnected from the sewer system and are directed to the container, which is typically a 50-55 gallon barrel that fills up during storms (USEPA, 2009b). An overflow system is included that will make sure that excessive stormwater will drain during a particularly large storm. A rain barrel can save homeowners a great deal of water during the summer months, and they can help save both money and energy by decreasing the demand for drinking water from the tap. Diverting water through the use of rain barrels will also decrease the impact of runoff to streams. Figure 3 below includes a photograph of a typical rain barrel.

Figure 3: Rain Barrel
(USEPA, 2009b)

Green Roofs

A green roof is a system of vegetative layers that grows on a rooftop of a building. Green roofs contain live vegetation in this system in lightweight engineered layers of soil (EPA, 2011c). They are designed to store stormwater in both a storage layer and soil layer within the system. Water is then taken up by the vegetation and enters the air by transpiration. In addition, overflow from the system is directed to downspouts in order to prevent possible flooding (EPA, 2011c). In addition to providing stormwater storage and preventing flooding, green roofs provide shade and cooling of the air through evapotranspiration. In addition, they help reduce the temperature of the roof surface and surrounding air. Green roofs can be installed at a wide variety of buildings, and they are becoming more popular in the United States with approximately 8.5 million square feet installed as of June 2008 (EPA, 2011c). There are two main types of green roofs: extensive and intensive. Intensive green roofs are more traditional and require a reasonable depth of soil to grow larger plants and require more labor and maintenance than extensive green roofs (EPA, 2011c). Extensive green roofs require minimal maintenance and they utilize plants that are easier to care for and are resistant to problems like drought, frost, and wind. They are usually installed on flat roofs with low slopes in order to maximum water retention (EPA, 2011c). These types of green roofs are able to accommodate a wider variety of plants, from lawn grasses to flowers, shrubs, and small tress. They also use deeper and heavier soils and can be established on a thin layer of soil. For the study conducted in Worcester, it is assumed that extensive green roofs are ideal for use as a type of LID. Please refer to Figure 4 below for a typical design of a green roof.

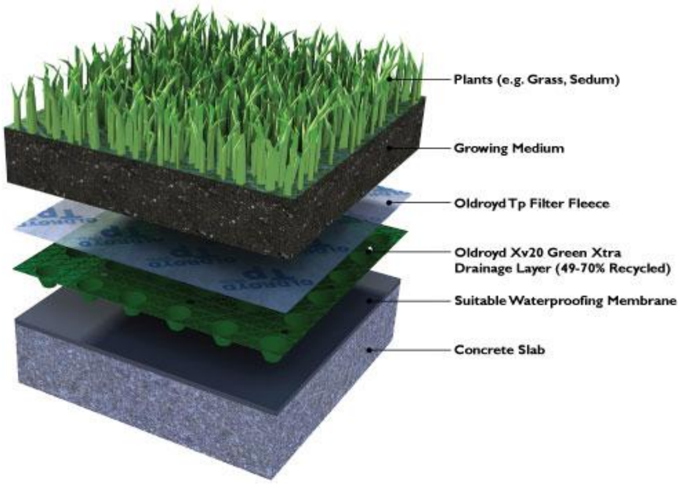


Figure 4: Green Roof
(Caine, 2012)

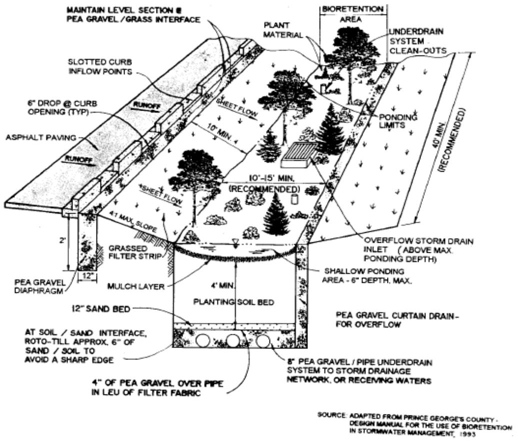
Blue Roofs

Blue roofs are non-vegetated rooftop detention systems that detain stormwater until the end of a storm surge. The detention systems involve weighted containers with stones that hold back water (City of New York, 2012). Weirs at the drain inlets of these blue roofs create temporary ponding and the gradual release of stormwater. After the completion of a storm, the stored water evaporates into the air, or excessive stormwater over two inches deep will overflow to downspouts (City of New York, 2012). Flatter roofs or roofs with low slopes are the most effective types of roofs for this installation, and the rooftops must have enough load-bearing capacity to carry the additional ponded stormwater. Blue roofs can reduce the impacts of combined sewer systems during large storms and are relatively inexpensive to install when compared to green roofs (City of New York, 2012). When coupled with light colored roofing material, blue roofs can provide sustainable and environmental benefits. Specifically, they can be used as a cooling mechanism for the rooftops (City of New York, 2012). Figure 5 below is a photograph of a blue roof on top of a building in New York City.

Figure 5: Blue Roof
(NYC Environmental Protection, 2012)

Bioretention

Bioretention is a type of low impact development technique comprised of retention or detention basins that use soils, plants, and microorganisms to both treat and store stormwater before it infiltrates into the soil or is discharged downstream. Bioretention areas serve as filtration devices that remove pollutants by physical, biological, and chemical processes (Low Impact Development Center, Inc., 2007). These basins are made up of a gravel layers used for storage, a planting soil layer, and a mulch layer at the top that is planted with dense vegetation that requires little maintenance. Stormwater is directed to the basin and then percolated through the system where it is treated. The percolated stormwater also flows through the soil and is taken up by the vegetation in the system (Low Impact Development Center, Inc., 2007). The water is then transpired into the air once treated in the soil. Microorganisms within the mulch layer consume many of the pollutants from the stormwater so the water is cleaner when it enters through the soil or downstream (Low Impact Development Center, Inc., 2007). The bioretention basin may also be designed with an underdrain system, which removes excess treated water to either the storm drain system or receiving water downstream. Please refer to Figure 6 for a typical bioretention basin.



SOURCE: ADAPTED FROM PRINCE GEORGE'S COUNTY - DESIGN MANUAL FOR THE USE OF BIORETENTION IN STORMWATER MANAGEMENT, 1993

Figure 6: Bioretention Basin
(Lake Superior Streams, 2012)

2.4 CSO Management Solutions

In 1994, EPA published the CSO Control Policy to regulate the reduction and removal of combined sewer overflow activations and the improvement of CSO water quality (EPA, 2002). Some common approaches to CSO management include the use of retention basins and sewer separation. Retention basins treat incoming stormwater runoff by allowing particles to settle so algae in the basins can take up nutrients. One main objective of retention basins is to reduce flooding during large storm events by reducing the peak flow (Kasco Marine, Inc., 2006). They can easily be designed to control hazardous floods by having storage above the permanent pool. After the storm has passed, the retention basin can store the excess sewage from the combined sewer overflows and discharge water back to the system (Kasco Marine, Inc., 2006). Off-line retention basins have to be constructed with pumping facilities to pump sewage back into the system following the storm. Operation and maintenance is an important factor to ensure the proper operation of a retention basin. Retention basins are able to significantly reduce CSOs in urban areas when designed and operated properly (Kasco Marine, Inc., 2006). However, retention basins can pose safety hazards and have limited use in arid regions where supplement pools of water are constantly in demand.

Sewer separation is a typical strategy used for managing CSOs in urban areas in the United States. It is the practice of separating a combined sewer system into separate sewers for sanitary and stormwater flows (USEPA, 1999). In a separate system, stormwater is sent directly to a stormwater outfall for discharge into the receiving waters downstream. The separate sewage flows to a wastewater treatment plant and is treated before being discharged to the receiving waters (USEPA, 1999). Sewer separation may be considered wherever there is a combined sewer system, and it is a particular consideration in cities like Worcester. Sewer separation is often the most appropriate technology in areas where most sewers are already separated and certain constraints and costs prohibit the use of other structural systems. It is also used in areas where receiving water capacities can prohibit the use of other CSO controls, additional infrastructure improvements are also required, and the combined sewer system is undersized. In many cases, sewer separation can result in the reduction or elimination of basement and street flooding and sanitary discharges to receiving waters (USEPA, 1999). It can also decrease the impacts of stormwater contaminants on aquatic life. Separating combined sewer systems can contribute to improvements in overall water quality by eliminating sanitary discharges to receiving waters. However, the increased stormwater discharges may lead to the increase of pollutants in surface water (USEPA, 1999). Without mitigation, increased loads of runoff containing heavy metals, sediments, and nutrients, may run off into water bodies in the area (USEPA, 1999).

Both existing and future impacts from stormwater pollutants into the receiving water bodies should be evaluated before sewer separation is considered and eventually implemented. Negative impacts associated with sewer separation may include extensive construction and environmental impacts related to construction like excessive noise and possible erosion (USEPA, 1999). In addition, construction of these systems can disrupt people living in and working in nearby areas and may disrupt sewer services and the need for water controls. In many cases sewer separation is not cost effective and may need to be implemented simultaneously with other techniques to improve urban areas like road paving and utility repair (USEPA, 1999).

2.5 Literature Review

2.5.1 Urban Drainage Solutions under Climate Change

Research and interest in the subject of climate change and how it related to managing urban drainage systems have continued to increase over the past few years. It has become widely accepted that new technology needs to be developed to help water systems better prepare for a changing climate around the world. However, there has not been a great deal of research done specifically on climate change in regards to its effects on management of stormwater and combined sewer systems. Some articles involving current research of urban drainage systems under climate change are summarized in this section.

Arisz et al. focus on the importance of considering climate change in urban drainage design and how to plan for new stormwater infrastructure instead of improving on existing systems. Gradual changes in weather patterns and increasing climate variability and extreme weather are expected to affect hydrologic conditions in the future. Engineers now have to consider climate change in order to adapt and better serve the public. In addition, evidence exists that human activity has affected the warming of the Earth's system over the last 50 years (Arisz et al., 2006). The effects of climate change can be quantified using General Circulation Models (GCMs) for different scenarios based on future assumptions of greenhouse gas emissions. The magnitude of storm drainage design systems is based on levels of service provided by certain types of drainage infrastructure (Arisz et al., 2006). Acceptable methods for design flow calculations involve hydrologic simulation models, empirical peak runoff methods, or statistical methods based on hydrometric record analysis. In addition, Arisz et al. describe the drainage system design process and the concept of minor and major drainage ways. Minor drainage ways are created by smaller, more frequent storms and use the more traditional storm sewer system design. However, major drainage is create by larger, less frequent storms and is served by open channels, rivers and streams, roads, and detention and retention ponds. However, the design of these systems require the public to change their views on flooding and how much can be tolerated in urban areas (Arisz et al., 2006). The minor drainage system will surcharge, and this will be addressed during design. Increases in flow due to climate change are most easily accommodated by the major drainage system. In addition, the service life of drainage infrastructure can last up to 100 years, so there are expected changes in the site's hydrology over time. The cumulative effect of these changes become significant over the entire life of the drainage system and should be taken into account during initial designs (Arisz et al., 2006).

An article by Mailhot et al. discusses the influence of climate on urban drainage infrastructure. Projections from climate models have suggested that there is an increased probability of intense rainfall from increased greenhouse gas concentrations. Urban drainage design is based on statistical analysis of past events, and an increase in the intensity and frequency of extreme storm events will lead to more flooding (Mailhot et al., 2010). As a result, current design criteria need to be changed to consider the impacts of climate change. A new procedure is in effect that integrates three different components: climate projections for extreme rainfall over a considered region, expected level of performance, and expected lifetime of the system (Mailhot et al., 2010). A new level of service needs to be defined as a global adaptation strategy which will measure the uncertainty of projected rainfall changes. Existing urban drainage capacity has been defined through statistical data analysis from previously recorded rainfall. Two statistical approaches have been used to analyze extreme storm events. The first method is based on annual maximum values for variable storm durations. The second approach uses partial duration series, and for this approach values that are above a certain threshold are kept (Mailhot et al., 2010). Urban drainage system design is based on statistical analysis of past events, and flooding in urban areas is expected to happen more frequently due to effects of climate change, which required new design criteria for urban drainage systems. It is important that the evolution of the service level of drainage systems be assessed in the context of climate change. Expected changes due to climate change need to be integrated into design criteria (Mailhot et al., 2010).

Hejazi et al. discuss how a continuous streamflow model can be used to examine how climate change and land use change affect the hydrology of urban watersheds. A case study was conducted in the Maryland Piedmont metropolitan region, and a hydrologic model was developed to examine both observed and expected streamflow and how it is affected by changes in climate and land use (Hejazi et al., 2008). Three different scenarios were analyzed for future situations: climate change, land use change, and a combination of both. The Canadian Climate Center and Hadley climate models were used for temperature and precipitation predictions (Hejazi et al., 2008). Results show that an increase in precipitation leads to an increase in peak flows during storms. More significant trends were found from a combination of land use and climate change versus only land use or climate change by themselves. This may indicate that both parameters are important factors that affect stream flow and urban drainage, but one factor is not necessarily more important than the other. McCuen and Snyder's streamflow model contains three different types of storage for runoff: surface water, unsaturated zone (sub-surface) storage, and groundwater (Hejazi et al., 2008). The model inputs include specifications from each of these three storage mechanisms. The continuous streamflow model is used for six watersheds in Montgomery County, Maryland, and between 10 and 50 years of daily streamflow data are available from six USGS stream gauges (Hejazi et al., 2008). There are evident reductions in low flows and increases in peak flows under combined land use and climate change scenarios. For an area that is already urbanized like the Maryland Piedmont region, climate change plays a greater role in influencing flow, but both of these factors play important roles for developing urban areas (Hejazi et al., 2008).

Sample et al. explain how methods have been used to evaluate stormwater and determine best management practices for managing stormwater within the context of land development. Urban development has led to the increase in stormwater flow, extreme storm events, and an overall decrease in water quality (Sample et al., 2003). With an increased knowledge of climate change and the impacts of nonpoint source pollution, a more holistic approach has been taken for urban stormwater management to include the multiple purposes of controlling both flooding and stormwater pollution (Sample et al., 2003). Several case studies were evaluated on the design of urban drainage systems for stormwater. A case study was selected from Tchobanoglous, a sewer designer who developed calculations used for the design of storm sewers. Several different cost analyses were used to develop best management practices, including parcel-level cost analysis, transportation cost, housing cost, and landscaping cost (Sample et al., 2003). There was also a significant portion attributed to stormwater quality control. After a complete analysis, results of the optimization analysis showed that the total optimal system cost is $3.9 million (Sample et al., 2003). The key issue of this analysis is the allocation of fixed cost percentages to stormwater control needs to be evaluated further. Until recently, research has not been done on best management practices for stormwater flows. The article by Sample et al. presents a methodology to analyze urban stormwater control and shows the possible effectiveness of optimization and best management practice techniques for cost analysis (Sample et al., 2003).

Finally, a report by Damodarum et al. describes their research of using modeling to incorporate low impact development (LID) in an existing hydrologic model in order to estimate the effects of different types of LID on stormwater management. This modeling approach was applied to a watershed located on the Texas A&M University campus in College Station, Texas (Damodarum et al., 2010). The hydrologic model predicts the stormwater reductions that result from fitting existing infrastructure with new LID technologies. An LID scenario was compared to both a best management practice (BMP) scenario and a combined scenario, and results from the model were compared to existing conditions before new developments were implemented. For the BMP scenario, a detention pond was implemented into the model. For the LID scenario, Damodarum et al. used a combination of retrofitted rooftops, parking lots with permeable pavement, rainwater harvesting systems, and green roofs (Damodarum et al., 2010).

The results of the model show that LID is effective for smaller storms and in many cases can be more effective than storage-based BMPs. However, as storm intensity increases, these infiltration-based improvements are not as effective in impacting peak flow. It was concluded from this research that in order to effectively manage stormwater to meet the goals of sustainability, smaller and more frequent storms need to be examined as much as larger storms since they have significant environmental impacts (Damodarum et al., 2010). It was determined that infiltration-based LID is the most effective type of low impact development for smaller storms, and storage-based BMPs are the most effective for larger storms. As a result, it will be important to use both types of stormwater management and possible combinations of methods to best achieve flood control and sustainability objectives in the future (Damodarum et al., 2010).

A review of past research in stormwater management over the past few years shows that research on stormwater and CSO management under climate change continues to grow and is expected to continue. There are not many new methods for developing robust strategies under climate change to better manage urban stormwater in the future. The methods that have been developed have plenty of room for advancement, and there is a great need to further improve current systems, specifically those in urban areas as cities in the United States and the world continue to grow at a rapid rate. The case studies previously described all applied stormwater simulation models to evaluate different alternatives for stormwater management, but none of these studies use methodologies to determine and test robust strategies to plan for the future. One of the main goals of this research is to introduce a new methodology to effectively test a variety of strategies for managing stormwater under a robust, changing climate that will be able to perform regardless of future outcomes.

2.5.2 Green Infrastructure

With the implementation of regulations like NPDES, the Clean Water Act, and the CSO Control Policy set force by EPA and state regulators, cities around the country have begun to address stormwater issues with the use of green infrastructure. Green infrastructure can be described as an approach to stormwater management that is cost-effective, sustainable, and environmentally-friendly. Green infrastructure management techniques can be used to infiltrate, capture, and restore stormwater in order to maintain and restore the natural hydrology of an area. Green infracture can include LID technology at a small scale, which will be analyzed for the Worcester CSO system. At a large scale, green infrastructure can help preserve and restore natural landscapes like forests and wetlands, and they can help improve water quality and protect natural ecosystems in the process. Many cities across the country have incorporated green infrastructure to improve stormwater management. Philadelphia and Seattle are two prime examples of cities who have continued to improve with the use of green infrastructure.

Philadelphia, Pennsylvania

The city of Philadelphia has a sewer collection system that is 40% municipal separate storm system (MS4) and 60% combined sewer overflow system (CSO). Over the past few years the city has been "working to improve stormwater management through restoration and demonstrative efforts, regulations and incentives for the private sector and a revised billing system" (USEPA, 2010). Green infrastructure has been used as its most effective approach that recognizes the connection between land use and water quality. The city is currently in the process of completing plans for each stream system and working with municipalities through watershed partnerships. Citywide policies supporting creation and preservation of green spaces in the city include Green Plan Philadelphia, the Green Roof Tax Credit, and the Green Streets program. More opportunities exist for landscape architects to be an important part of planning and design for projects in Philadelphia, from sewershed demonstrations to stormwater fee discount programs (USEPA, 2010). The Philadelphia Water Department (PWD) plans to invest in decentralized green infrastructure that will minimize runoff and manage it at the source. A green infrastructure approach allows Philadelphia to integrate land, water, community and infrastructure goals to make it a smarter investment with more benefits (USEPA, 2010).

In addition, the stormwater billing system in Philadelphia revised stormwater management and the use of impervious surfaces. Rates were set by determining the amount of a property's imperviousness and the amount of runoff generated. Philadelphia has created financial incentives for developers to reduce imperviousness of sites, and the city is getting the community to build green infrastructure projects that will improve watersheds and help mitigate flooding. With new stormwater regulations implemented in Philadelphia, the city now encourages urban infill through exemptions for redevelopment projects. Focusing development in vacant or infill areas has helped reduce the total imperviousness of the region. New regulations were applied in January 2006 for developments to be built on infill lots instead of undeveloped, natural areas (USEPA, 2010). During the first year of Philadelphia’s new stormwater regulations, over one square mile of the city was built with LID features. These techniques are expected to manage most one-inch storms when fully built and reduce CSOs by 25 billion gallons to save the city approximately $170 million. However, stormwater regulations only result in 20% of the total land served by land-based controls, and 20% is only reached after the regulation has been in place for 20 years (USEPA, 2010). Philadelphia’s program includes projects that also address public land, streets, vacant property, and waterfront separation.

Seattle, Washington

The city of Seattle is located on the Puget Sound in the state of Washington and contains many successful green infrastructure projects and policies. Seattle Public Utilities (SPU) is the local agency that meets NPDES permit requirements and it coordinates with Seattle’s Natural Drainage System (NDS) approach that supports green infrastructure in terms of larger development and planning (USEPA, 2010). With many Seattle communities near the Puget Sound, the primary motivation for stormwater management is to protect aquatic biota and creek channels as well as improving water quality. The future of coho salmon in the Pacific Northwest is at risk and has become a priority for residents and regulators in the state of Washington. SPU has used practices to infiltrate stormwater runoff into soils, which treats water for pollutants and recharged water bodies though groundwater recharge.

The Seattle Green Factor was developed to require property owners to achieve 30% parcel vegetation using a set of practices like green roofs and porous pavement. In the past few years, SPU revised Seattle’s Comprehensive Drainage to help control flooding and improve water quality through the use of green infrastructure. In addition, it was revised to establish a long-term plan for capital improvement and operating programs.

Seattle is currently in the process of updating the Stormwater Codes and Manuals that have been developed to address new developments in the city. The new codes will require green infrastructure analysis to evaluate in-site design for all new development or redevelopment plans. A fee-in-lieu policy is also incorporated that will allow developers to pay a fee inside of using detention vaults for flood control. SPU plans to use incomes from these fees for basic restoration and for salmon-bearing creeks, and they will also use them for incorporating green infrastructure practices in major improvement programs (USEPA, 2010).

In addition, the city has recognized the contribution of streets to overall imperviousness, as the central goals of NDS are to protect aquatic life and creek channels and to improve water quality by controlling stormwater runoff. The city plans to redevelop public right-of-ways to mimic predevelopment hydrologic processes to store and treat runoff through vegetative systems. SPU has also developed the Rainwise Incentive Program to encourage private property owners to manager stormwater flows. Through educational materials and low cost incentives, SPU hopes to protect both public infrastructure and the environment (USEPA, 2010).

Finally, the city of Seattle has used Capital Improvement Program (CIP) projects to connect green infrastructure and stormwater management with overall assets and demand management for SPU sewers and drain systems. LID has been used as a major part of these projects, with an example being the Alaska Way Viaduct Project. The Viaduct is an elevated highway retrofit along the waterfront in Seattle. The Seattle Department of Planning and Development (DPD) plans to work with the Washington Department of Transportation (WDOT) to include LID features as part of a major capital improvement project (USEPA, 2010).

2.6 Existing Conditions

Worcester, MA is located in Worcester County of Massachusetts and is the second largest city in the New England region with a population of 181,045 as of the 2010 Census (Monahan, 2009). It is located approximately 40 miles west of Boston and 38 miles East of Springfield. Worcester's climate is typical of the New England region, with typical warm and humid summers and cold, windy, and snowy winters. The city averages 49.1 inches of precipitation per year and an average of 67.2 inches of snowfall each year (National Weather Service, 2007).

Figure 7: Map of Worcester, MA
(Massachusetts Living, 2012)

The Blackstone River passes through the city of Worcester with its headwaters found at Institute Park. The river flows underground through the center of the city and emerges at the foot of College Hill flowing through Quinsigamond Avenue near Water Street. Water Street was originally the Blackstone Canal and has emerged as the center of Worcester's "Canal District" (Public Works and Parks, 2007). The city is well known for its seven main hills: Airport Hill, Bancroft Hill, Belmont Hill, Grafton Hill, Green Hill, Pakachoag Hill, and Vernon Hill, although there are actually a total of more than seven hills in the city. Worcester's main water bodies include Lake Quinsigamond, Indian Lake, Bell Pond, and Coes Pond (Public Works and Parks, 2007). Worcester has developed several parks over the years with a total of 1,200 acres of publicly owned property. Elm Park was the first publicly owned park in the city, which was purchased in 1854 and was one of the first public parks in the United States (Public Works and Parks, 2007). In 1903, the Green family of Worcester donated 549 acres of Green Hill area land for Green Hill Park, which became the largest park in the city (Public Works and Parks, 2007). Other parks in Worcester include: Newton Hill, East Park, Crompton Park, University Park, and Institute Park. While Worcester is a heavy urban area with a great deal of developed, impervious land, the city does have a rich tradition of publicly owned parks which have been preserved for decades (Figure 8).

Figure 8: Aerial view of Worcester
(Hansen, 2006)

2.6.1 Combined Sewer System

A combined sewer overflow (CSO) system is a type of sewer system that collects both sanitary wastewater and stormwater runoff in a single pipe system. Most of the time CSOs transport all of their sewage to a wastewater treatment plant downstream, where it is treated and discharged to receiving water bodies. However, during periods of heavy rainfall or snowmelt, the wastewater volume in a CSO can exceeds its capacity. As a result, combined systems are designed to overflow in these situations and discharge excess wastewater directly to nearby waters. CSOs not only contain stormwater but also contain untreated industrial and municipal waste along with hazardous waste. Combined sewer overflow systems have been designed in urban areas all over the country since the late 1800s as an effective way to distribute, treat, and manage stormwater (King County, 2012). From the late 1800s up until the 1940s, environmental engineers designed combed sewers to transfer sewage and stormwater runoff directly to the nearest receiving water bodies. Around the 1950s, most sewer systems were built as separate systems with separate lines for wastewater and stormwater. Treating wastewater became a standard operating procedure in the late 1950s, and interceptor pipes were built to transport wastewater to a treatment plant (King County, 2012). The standards for wastewater treatment led to the modern-day design for a combined sewer system, which includes interceptor pipes that treat combined sewage from wastewater and stormwater lines before the water is discharged to downstream waters. There are approximately 772 cities in the United States who currently use combined sewer systems (King County 2012).

Figure 9: Separated sewer system
(King County, 2012)

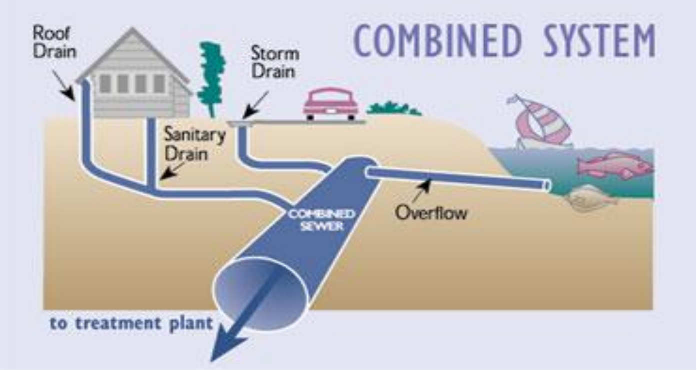


Figure 10: Combined sewer system
(King County, 2012)

Worcester CSO system covers a total of approximately four square miles of the city, which includes most of downtown, Shrewsbury Street, Green Island, and sections of Main South. Decades ago when heavy rainfall events would lead to combined sewer overflows, the mixture of stormwater and wastewater would flow untreated to the Blackstone River (City of Worcester, MA, 2012). In the 1980’s, Worcester became one of the first cities in New England to construct a combined CSO facility that provides wastewater treatment to the incoming water flow from storm events before it is discharged to the Blackstone River. This facility was named the Quinsigamond Avenue Combined Sewer Overflow Treatment Facility (QCSOTF) (City of Worcester, MA, 2012). The QCSOTF is located near Crompton Park in Worcester, and the facility functions as a sewage pumping station during dry weather events. The sewage is pumped from the facility to the Upper Blackstone Wastewater Treatment Facility (UBWWTF) where it is fully treated before being discharged to the Blackstone River. When heavy rain events occur, the facility switches to treatment mode. When in treatment mode, the QCSOTF treatment includes bar racks, disinfection, storage and settling, and de-chlorination. In this system, the bar rocks remove large objects at the first stage of treatment, which includes large branches and pieces of garbage that may damage equipment that is located downstream. After disinfecting the wastewater with sodium chloride, the flow moves slowly down through 2.5-gallon contact tanks where the solids settle down below the water. This treatment phase allows for maximum disinfection while retaining a large volume of flow for release to the Blackstone River or further pumping at the UBWWTF (City of Worcester, MA, 2012). Finally, de-chlorination is used to remove chlorine used in the disinfection process, and the treated flow is discharged to the Mill Brook and eventually to the Blackstone River.

Since the QCSOTF discharges flows into the Blackstone River, it is regulated under the Clean Water Act by USEPA and MassDEP. The discharged flows are regulated by these agencies under the National Pollutant Discharge Elimination System (NPDES) permitting program that was set up under the Clean Water to control the pollution of water bodies created by facility discharges. The most recent permit released by these government agencies sets limits on the amount of certain contaminants a facility can discharge, and in particularly MassDEP and USEPA expressed the desire for the city of Worcester to limit the amount of flow being discharged from the QCSOTF. However, since the amount of flow discharged from the facility depends on the amount of rainfall events in the city, it is very difficult to control what can be discharged. In addition, with the growing knowledge of climate change and its impacts on the frequency of extreme storm events, it is expected that the number of rainfall events in the city will continue to increase annually. However, some measures have been taken by the city of Worcester to meet the requirements set by USEPA and MassDEP. The most cost effective stormwater reduction options have been described in the 2004 CSO Long-term Control Plan and are currently being implemented (City of Worcester, MA, 2012). Included in this plan are changes to Green Hill Pond, which previously entered the CSO system from Belmont Street. These changes have been done to the pond’s overflow structure so most of the flow from Green

Hill Pond is sent to the Coal Mine Brook and eventually to Lake Quinsigamond (City of Worcester, MA, 2012).

Modifications are also being made to the Mill Brook conduit upstream from the Quinsigamond plant so greater volumes of combined sewer flow can be stored underground and their release to the QCSOTF can be more controlled. There are also ongoing discussions between regulatory agencies and the city of Worcester to install larger pumps at the QCSOTF in order to allow more combined sewage to be pumped from the treatment facility to the UBWWTF. A variety of cost-effective solutions have been examined in order to help separate combined sewage in a more efficient way. However, it is beyond the financial capabilities of the city to be able to remove the combined sewer overflow system entirely.

The combined sewer makes up approximately 15% of the city, and it carries sanitary flows during dry weather periods directly to the Upper Blackstone Wastewater Treatment Facility. During periods of heavy rainfall, which usually occurs approximately two times per month, the flow that exceeds storage capacity is pumped to the Upper Blackstone WWTF and is discharged downstream to the Mill Brook after complete treatment. The Mill Brook is located at the headwaters of the Blackstone River. The Worcester CSO system contains approximately 60 miles of combined sewers with five main combined sewer overflow collectors designed to store combined sewage and later send it to the UBWWTF while conveying excess flow to the QCSOSTF (City of Worcester, MA, 2012). The five combined sewer overflow collectors are listed below along with their respective dimensions:

1. Lincoln Square Overflow Collector (72” pipe and 2,000 feet long)
2. Harding Street Overflow Collector (10’x12’ box culvert and 2,000 feet long)
3. Canton Street Overflow Collector (36” pipe and 1,100 feet long)

4. Quinsigamond Avenue Overflow Collector (48" pipe and 1,520 feet long)

5. Southbridge Street Overflow Collector (60" pipe and 1,400 feet long)

During dry weather periods, the combined sewer system carries flow from one of four major interceptors: the Eastern Interceptor, Western Interceptor, Main Street Interceptor, and Cambridge Street Interceptor. This flow is eventually directed to the Upper Blackstone treatment facility, with the majority of flow (76%) directed from the Eastern Interceptor. A total of 18% of flow in the system is carried through the Western Interceptor. Flow from the Southgate Place area in the southwestern section of the CSO service area discharges to the Cambridge Street Interceptor (CDM, 2004). Finally, a smaller area of the system that is located in the Southgate Street vicinity is discharged from the Main Street Interceptor directly to the QCSOSTF. The flow from this area is pumped from the QCSOSTF to the Upper Blackstone facility (CDM, 2004).

During wet weather, as flow rates increase during heavier storm periods low flows continue as described and higher flows are directed at regulators to the overflow collectors and to the QCSOSTF, where the flow is screened and enters a wet well. The flow is then pumped from the wet well to the Blackstone treatment facility (CDM, 2004). Flow that exceeds the wet well and pumps capacity during large storms is chlorinated by two 1.25 million gallon contact chambers (CDM, 2004). When the pumps are all turned on about 19 MGD of flow is directed to the Upper Blackstone treatment facility. During very heavy rain events, the pumping is significantly reduced to allow for full capacity of the UBWWTF to be able to treat flows more effectively at different service areas (CDM, 2004). The QCSOSTF also stores flow in excess of the pumping capacity and can fill up to 2.5 MG into the contact chambers. If insufficient storage is available to store stormwater runoff, it will pass through a dechlorination facility to be discharged to the outfall (CDM, 2004). Figure 11 includes a schematic of the Worcester CSO system, which includes the two treatment facility, major flow meters, and overflow collectors.

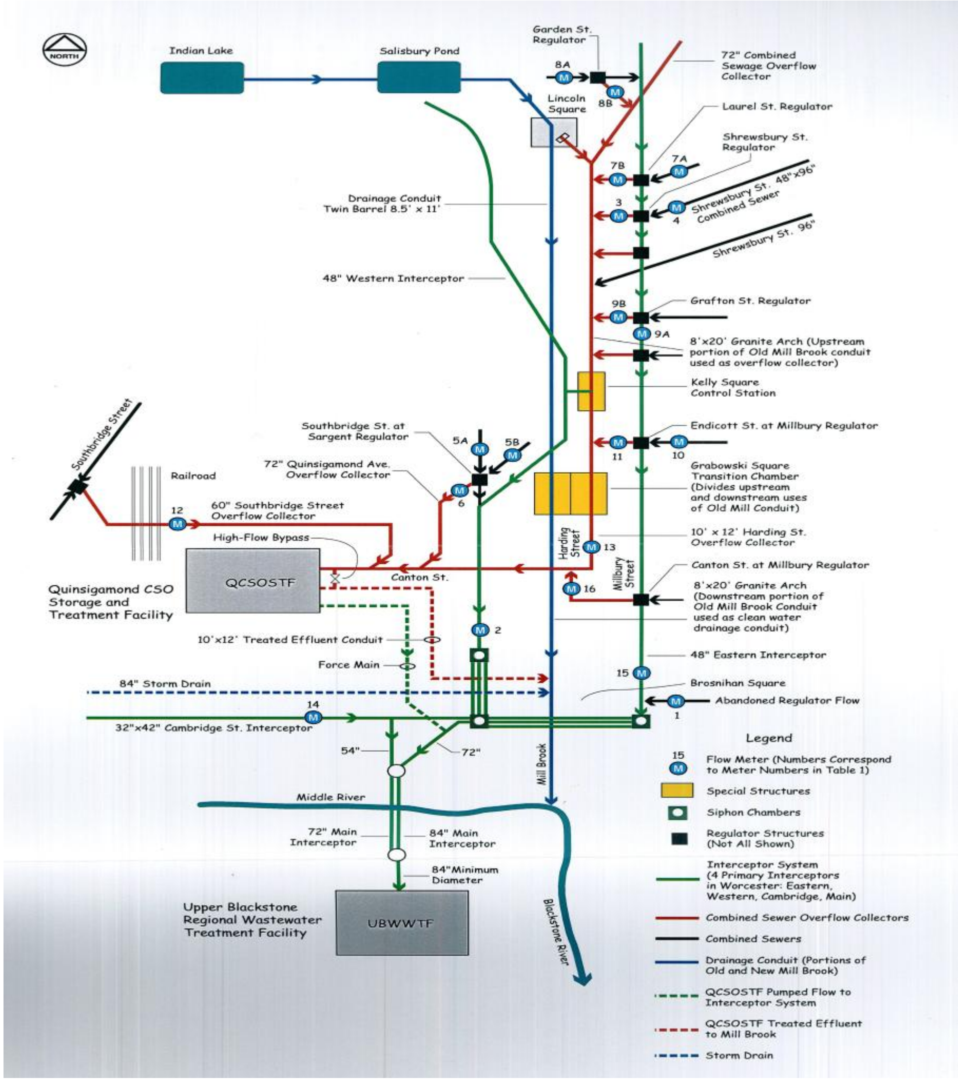


Figure 11: Worcester CSO System Schematic
(CDM, 2004)

2.6.2 Quinsigamond Avenue Combined Sewer Overflow Storage and Treatment Facility (QCSOSTF)

The Quinsigamond Avenue CSO facility is located near Crompton Park on Quinsigamond Avenue in Worcester (Figure 12). Its primary functions are to serve as a pumping station during dry weather periods or periods of small rain storms when only wastewater or wastewater mixed with small amounts of runoff flows through the combined sewers. During periods of heavy rain events, the facility switches to treatment mode, which includes screening, settling, and disinfection of all flow up to a 5-year storm before discharging to the Mill Brook (CDM, 2004). The QCSOSTF discharges are regulated by EPA and Mass DEP under the NPDES permit program under the Clean Water Act. The most recent permit has required the city to take steps to reduce the frequency of stormwater discharges to the Blackstone River. However, since stormwater discharges are controlled by the number of storms, reducing the number of discharges from the facility has become a difficult task. Options to reduce the amount of stormwater entering the CSO system have been explored and identified in Worcester's 2004 CSO Long-term Control Plan (CDM, 2004). Cost-effective combined sewer projects have been considered, but it is beyond the financial capabilities of the city to completely eliminate the current combined sewer system.

In addition to the Quinsigamond Avenue facility, a large drainage conduit carries stormwater through the combined sewer area from the upstream separate stormwater system to the Mill Brook and Blackstone River downstream. The conduit contains two 8.5'x11' twin boxes that transition into an 8'x20' granite arch (CDM, 2004). All of the flow that enters through the conduit is completely separated from the combined sewer system.

Figure 12: Quinsigamond Avenue Combined Sewer Overflow Storage and Treatment Facility (QCSOSTF)
(Google, 2012)

2.6.3 Upper Blackstone Wastewater Treatment Facility (UBWWTF)

The Upper Blackstone Wastewater Treatment Facility is located off Route 20 in Millbury, MA downstream of the Worcester CSO system (Figure 13). It was first put into use in 1976 originally as a secondary treatment facility designed for an average flow of 56 MGD (UBWPAD, 2012). Since the startup of the facility, it has been asked by EPA and Mass DEP to continue to develop and achieve stricter water quality effluent standards to improve the quality of the Blackstone River. The facility is owned by the Upper Blackstone Water Pollution Abatement District (UBWPAD), which has spent over $170 million in plant improvements to achieve higher environmental standards (UBWPAD, 2012). These improvements have included improved air pollution controls, modernized landfill construction, improved laboratory facilities and security, and higher effluent standards. Effluent discharges from the Upper Blackstone facility are directed to the Blackstone River, which originates at the confluence of the Middle River and Mill

Brook in Worcester (UBWPAD, 2012). The Blackstone River flows southeast from Worcester for 46 miles into Rhode Island where it joins with the Seekonk and Providence Rivers, and these rivers eventually discharge to the Narragansett Bay (UBWPAD, 2012).

Figure 13: Photograph of Upper Blackstone Wastewater Treatment Facility (UBWWTF)
(UBWPAD, 2012)

2.6.4 Flow Metering Program

As part of the Worcester CSO model analysis, flow data was collected for the June 2-4, 2001 storm. This data was collected as part of a flow metering program for the Worcester Long Term CSO Control Plan (CDM, 2004). Results were used to develop a better understanding of how the Worcester CSO system functions under dry and wet weather conditions. A map of the Worcester CSO system is shown in Figure 14, including the major sewer segments outlined in black.

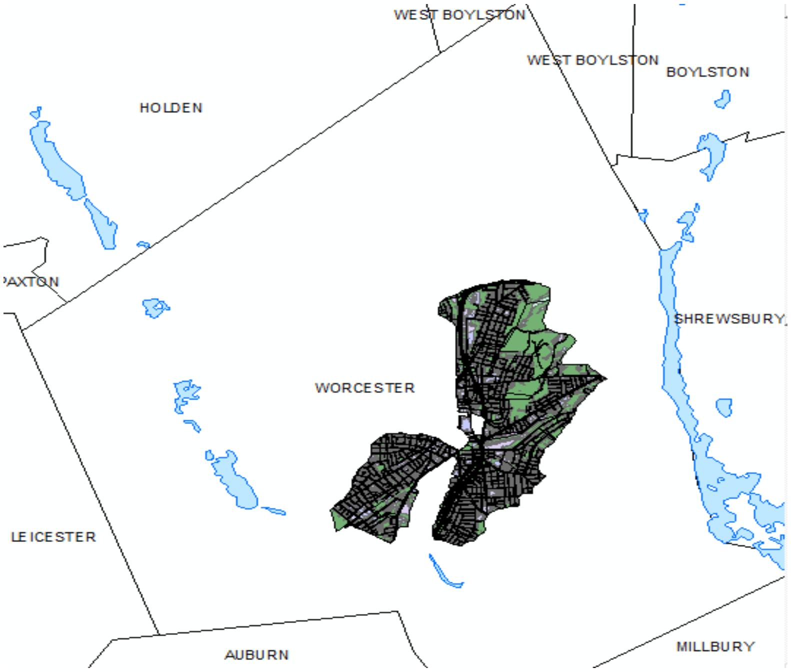


Figure 14: Map of Worcester CSO System watershed area

For this study, results were used to calibrate the model developed for the Worcester sewer system. The metering program was conducted under the direction of Camp, Dresser & McKee (CDM) by Severn Trent Pipeline Services, and the program extended from April 9, 2001 to June 14, 2001. It included the installation of 16 different continuously recording flow meters at 20 sites in Worcester (CDM, 2004). Flow metering began at each meter location as soon as they were installed with the first installation completed April 9 of that year (CDM, 2004). Tipping bucket rain gages were used to record rainfall during the monitoring period and were installed at the Worcester Department of Public Works (DPW) and the Worcester Fire Station Headquarters. The meters measure depth and velocity of runoff during each storm, with the water depth being measured by a pressure transducer and the velocity measured by an ultrasonic Doppler transducer. The transducer measures velocity by determining the time for the Doppler signal to reflect off the water and return to the measuring device. Depth and velocity were measured at 5-minute intervals, and discharge was computed by multiplying the cross-sectional area at the recorded depth by the water velocity (CDM, 2004). The meters are shown in the schematic in Figure 11, and a description of each flow meter and its location is included in Table 1. Meters that are denoted by A and B are at locations where there are multiple sensors that collected flow data at more than one location.

Table 1: Flow meter information for June 2001 storm analysis

Meter	CSO Area	Location	Pipe Size	Metered Flow	Date of Installation	Date of Removal
1	Eastern Interceptor overflow connection	Brosnihan Square	36-in diameter	Influent	4/9/2001	6/14/2001
2	Western Interceptor	Quinsig. Ave. near Ashmont St.	48-in diameter	Influent	4/9/2001	6/14/2001
3	Shrewsbury St. @ Washington Sq. Regulator	Washington Sq.	70.6-in height, 49.74 in width	Overflow	4/10/2001	6/14/2001
4	Shrewsbury St. @ Washington Sq. Regulator	Shrewsbury St. near I-290	70-in height, 51-in width	Influent	4/10/2001	6/14/2001
5A/5B	Southbridge St. @ Sargent St. Regulator	Southbridge St. @ Sargent St.	60-in diam./60-in height, 48-in width	Influent / Influent	4/11/2001	6/14/2001

Table 1: Flow meter information for June 2001 storm analysis

Meter	CSO Area	Location	Pipe Size	Metered Flow	Date of Installation	Date of Removal
6	Southbridge St. @ Sargent St. Regulator	Southbridge St. @ Sargent St.	72-inch diameter	Overflow	4/13/2001	6/14/2001
7A/7B	Laurel St. Regulator	R.O.W off Summer St. near Laurel	56.5-inch height, 41.2-inch width / 49-inch height, 40-inch width with curved bottom	Influent / Overflow	4/11/2001	6/15/2001
8A/8B	Garden St. Regulator	Garden St.	72-inch diameter / 72-inch diameter	Influent / Overflow	4/12/2001	6/15/2001
9A/9B	Grafton St. @ Posner Sq. Regulator	Grafton St. under I-290	15-inch / 41.75-inch height, 31-inch width	Effluent / Overflow	4/12/2001	6/14/2001
10	Endicott St.@ Millbury St. Regulator	Endicott St. near Millbury St.	31-inch height, 25.75 inch width	Influent	4/13/2001	6/14/2001
11	Endicott St.@ Millbury St. Regulator	Endicott St. near Millbury St.	36-inch height, 25.24-inch width	Overflow	4/13/2001	6/14/2001

Table 1: Flow meter information for June 2001 storm analysis

Meter	CSO Area	Location	Pipe Size	Metered Flow	Date of Installation	Date of Removal
12	Southbridge St. Overflow Collector	Northwest corner of QCSOSTF	60-inch diameter cement-coated iron pipe	Influent	4/16/2001	6/15/2001
13	Harding St. Overflow Collector	Seymour St. at Harding St.	144-inch width, 120-inch height with curved bottom	Influent	4/16/2001	6/14/2001
14	Cambridge St. Interceptor	Cambridge St. @ Pitt St.	42-inch height, 32-inch width	Influent	4/17/2001	6/14/2001
15	Eastern Interceptor	Millbury St. near Brosnihan Sq. and I-290 ramp	48-inch diameter	Influent	4/17/2001	6/14/2001
16	Canton St @ Millbury St. Regulator	Canton St. near Millbury St.	36-inch diameter RCP	Overflow	4/17/2001	6/14/2001

Three of the 16 meters were installed in interceptors, and three were installed in overflow collectors. The rest of the flow meters were installed in combined sewer regulators. These particular sites were selected for the program to represent the main sections of the CSO system. Main goals of the program include understanding how much flow is generated during wet weather to be directed to the UBWWTF, how much flow from the CSO area is delivered through the interceptor system to the QCSOSTF, and how much flow from the QCSOSTF is delivered to the UBWWTF or discharged to the Blackstone River. Data were collected from 6 of 17 regulators in the Worcester system, with regulators selected based on geographic location, land use, and tributary area (CDM, 2004). Hourly influent data from the Quinsigamond Avenue and Upper Blackstone treatment facilities, including pumping and effluent discharge data, were obtained to evaluate the responses of wet weather in these facilities. Data was also obtained to determine if additional flow would be able to be discharged to the UBWWTF.

3.0 METHODOLOGY

This section provides details for the model formulation, calibration, and analysis for model results of the Worcester CSO system. This section describes the EPA SWMM model and how the model is developed for 2001 and 2008 Worcester storms. After developing the model using past storms, the model was calibrated to better match the observed data. Stormwater and CSO management strategies were identified for Worcester and incorporated into the existing model for high, low, and moderate climate change scenarios in 2010, 2040, and 2070. These simulations were conducted for 3-month, 10-year, and 100-year storms, and results of these storms were compared for different strategies using a list of different performance metrics for comparison. Simulation results using these performance metrics were analyzed using a design-cost approach and net-benefit approach to determine which stormwater management strategy is the most feasible option in the future under climate change uncertainty.

3.1 EPA Stormwater Management Model (SWMM)

The Worcester, MA Combined Sewer Overflow System was modeled using the Stormwater Management Model. This model was developed by EPA and is a dynamic rainfall-runoff simulation model used for both single-event and long-term continuous simulations of stormwater runoff quantity and quality in mostly urban areas (EPA, 2012b). The model was first developed in 1971 and has been upgraded several times since that time (EPA, 2012b). It has been widely used throughout the world as a tool for planning, analysis, and design for stormwater runoff, combined sewer systems, sanitary sewers, and other drainage systems in both urban and non-urban areas. Figure 15 includes an example of a SWMM model interface for a specific storm for the Worcester CSO system.

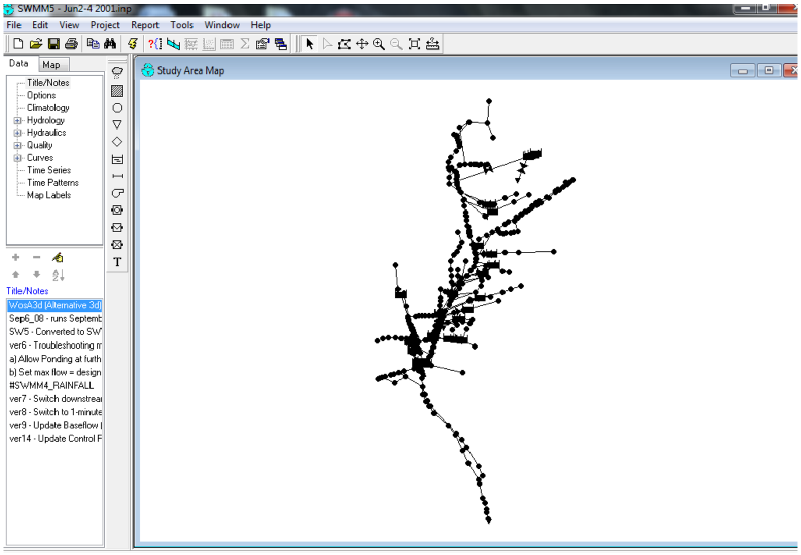


Figure 15: Stormwater management model (SWMM) interface

There are two main components of the SWMM model, which includes a runoff component and a routing component. The runoff component operates on subcatchment areas that receive the precipitation and generate runoff and pollutant loads. The routing component of SWMM transfers the runoff through a system of pipes, channels, storage tanks, pumps, and regulators. SWMM measures the quantity and quality of runoff in each subcatchment and determines the flow rate, flow depth, and water quality of each pipe and channel during a certain period of time (Rossman, 2010). EPA's most recent version of the model, SWMM 5.0, now includes the ability to model the performance of specific types of LID controls. The updated model allows engineers and planners to represent a combination of LID controls in order to determine the effectiveness of different control options on managing stormwater and combined sewer overflows. SWMM includes a variety of hydrologic processes that produce runoff from urban areas. The hydrologic processes include (Rossman, 2010):

1. Time-varying rainfall
2. Evaporation of standing surface water
3. Snow accumulation and snow-melt

4. Rainfall interception from depression storage
5. Infiltration of rainfall into unsaturated soil layers
6. Percolation of infiltrated water into groundwater layers
7. Interflow between groundwater and the drainage system
8. Nonlinear reservoir routing of overland flow
9. Runoff reduction via LID controls

The most recent version of SWMM was released in August 2010 to include the use of LID controls, which are designed to capture stormwater runoff within a subcatchment and provide a combination of hydrologic processes, including detention, evapotranspiration, and filtration (Rossman, 2010). A mass balance approach is used for each LID control in SWMM, and the model keeps track of the amount of water that travels through the system and is brought into storage.

There are two different approaches used in SWMM for placing LID controls within a subcatchment. The first approach involves putting one or more LID controls in an existing subcatchment that displays an equal amount of area that doesn’t have LID. This approach allows a mix of different LID techniques to be used in a single subcatchment, with each one treating a different portion of runoff from the non-LID portion of the subcatchment (Rossman, 2010). Under this option the low impact development techniques act in parallel, where the outflow from one becomes the inflow to another. After placement of the LID the percent impervious and width properties of the subcatchment may need to be adjusted to compensate for original subcatchment area that is now replaced by LID (Rossman, 2010). The other approach used in SWMM involves creating a new subcatchment that is entirely devoted to one particular type of LID. The first approach described above will be used for this study.

Each type of LID contains a combination of unique layers. Depending on the type of LID, water is able to exit an LID control through various types of processes. They can leave through evaporation, infiltration, an underdrain system, or overflow once storage capacity is exceeded (Rossman, 2010). Water flows through the underdrain system to corresponding nodes downstream. Overflow can also be sent from an LID control to pervious areas in the subcatchment before entering the drainage system. This option was used for this system for rain barrels so the stored water can be used for irrigation.

3.2 Model Development

The Worcester CSO model was developed using EPA's SWMM 5.0 by CDM Smith, who provided input files of stormwater flow data for 2001 and 2008. SWMM is made up of different modules that are used to simulate hydrologic processes. The RUNOFF, TRANSPORT, and EXTRAN modules were used for modeling the Worcester CSO system (CDM, 2004). The RUNOFF module was used to simulate rainfall and runoff characteristics of flow into the CSO system, infiltration and inflow into the system, and pipe flow in outlying portions of the sewer system. The TRANSPORT module was used to transport sanitary wastewater flows throughout the system, and these flows were then transferred through the system using the EXTRAN module (CDM, 2004). Metered data at 20 locations within the city's CSO system were used to calibrate the modules in SWMM. The main features of the SWMM model for Worcester's CSO system are listed below (CDM, 2004):

1. Detailed representation of 31 combined sewer catchments

2. Infiltration / inflow simulation response from 20 sanitary sewer catchments

3. Flow contributions from the surrounding towns of Holden, West Boylston, Rutland, and Auburn

4. Dry weather flows with hourly, daily, and monthly time steps

5. Detailed hydraulic and operation representation of the QCSOSTF

6. Detailed representation of major pipes in the system including four interceptors and all overflow collectors

7. Representation of the Grabowski Square and Kelly Square structures

8. Siphon simulations in Brosnihan Square

9. Representation of 16 combined sewer regulators

10. Model calibration based on monitoring from April, May, and June 2001 at 20 locations within the sewer system and at two rain gages.

The calibrated model was used to evaluate how the Quinsigamond Avenue plant interacts with the Upper Blackstone treatment facility. The model was also used to predict the duration, frequency, and volume of treated overflows from the QCSOSTF for various control options. Most of the data obtained for the model was provided by the City of Worcester, and the data included plans for the interceptor and overflow collectors, QCSOSTF construction plans, and land use data. Additional data was obtained by MassGIS and the National Resource Conservation Service (NRCS) (CDM, 2004).

The June 2-4, 2001 storm was modeled in SWMM 5.0 using observed data collected by the City of Worcester Department of Public Works (DPW). The depth, velocity, and flow of water discharged though each flow meter was provided. The flow depths were provided in units of inches along with the total precipitation amount at every 5-minute interval over the duration of the storm. Velocity was provided in units of fps (feet per second) and flowrate was provided in units of MGD. Complete observed flow and rainfall data were provided for 16 flow meter locations along with the QCSOSTF and UBWWTF.

Data was also provided for three storms in 2008. These storms included the following time periods: July 19-25, August 10-11, and September 25-29. For these three storms, sewage pump and drain pump flows were provided every 5 minutes over the duration of each storm, which represent the total wet weather and dry weather flows entering the QCSOSTF, respectively. It is also indicated in the observed data when the sewage and drain pumps are turned on. The effluent discharge flow from the plant is also provided, with all flows indicated in units of gpm (gallons per minute). Flow data was also provided for the UBWWTF. The data provided included total inflow (in MGD) for each hour during the storm. In addition to hourly flow data, a summary of the maximum, minimum, and average flow was provided for each day. Table 2 displays a summary of the key boundary conditions throughout their system and their location in the SWMM model.

Table 2: Key boundary conditions of Worcester CSO System

Boundary Condition	**Location in Worcester**	**SWMM Model Location**
Flow Meter 1	Brosnihan Square	Junction EI012911
Flow Meter 2	Quinsigamond Ave. near Ashmont St.	Junction WI00431
Flow Meter 3	Washington Square	Junction SC00850
Flow Meter 4	Shrewsbury St. under I-290	Junction SS00662
Flow Meters 5A /5B	Southbridge St. @ Sargent St.	Junction SI00380 / SI00000
Flow Meter 6	Southbridge St. @ Sargent St.	Junction QC00065
Flow Meters 7A / 7B	Off Summer St. near Laurel St.	Junction EI08916 / EI09095
Flow Meters 8A / 8B	Garden St.	Junction EI12543A / EI12543B
Flow Meters 9A / 9B	Grafton St. under I-290	Junction EI06038A / EI06038B
Flow Meter 10	Endicott St. near Millbury St.	Junction EI03220R
Flow Meter 11	Endicott St. near Millbury St.	Junction WI05525R
Flow Meter 12	Northwest corner of QCSOSTF	Junction SI01093
Flow Meter 13	Seymour St. @ Harding St.	Junction HC00245
Flow Meter 14	Cambridge St. @ Pitt St.	Junction CI02828

Table 2: Key boundary conditions of Worcester CSO System

Boundary Condition	Location in Worcester	SWMM Model Location
Flow Meter 15	Millbury St. near Brosnihan Square and I-290 ramp	Junction EI00514
Flow Meter 16	Canton St. near Millbury St.	Junction EI01137X
QCSOSTF	Quinsigamond Avenue	Storage Unit QCSOTF1
QCSOSTF Effluent Discharge	Downstream of QCSOSTF	Conduit OTF00002
Dry Weather Flow	Drain Pump at QCSOSTF	Pump1 at QCSOTF1-WI00830
Wet Weather Flow	Sewage Pump at QCSOSTF	Pump1 at OT00011B-MI00040

3.3 Calibration and Validation

Although the Worcester CSO system had been previously calibrated in SWMM by CDM in December of 2001, further adjustments were made to the current model to make sure that it performed well for the purposes of this study (CDM, 2004). After initial runs of the current model before calibration, it was determined that the overall shape of the model flows was similar to the observed data. However, the total inflow for both 2001 and 2008 was significantly less for the model flow. It was noticed that the 2001 model performed much better than the 2008 data, especially for flows entering the Quinsigamond Avenue facility.

Before making further adjustments to the current model, the total inflow and outflow of the QCSOSTF were determined to check if there is flow continuity in the system. The total outflow was determined by adding the inflow to nodes from pipes exiting the Quinsigamond Avenue facility storage tanks and the flow from combined sewage that is pumped from the QCSOSTF downstream. This flow is directed from two pumps (Pump1 at QCSOTF1-WI00830 and Pump1 at OT00011B-MI00040) that direct flow to the QCSOTF downstream and eventually towards the Upper Blackstone facility to the Mill Brook. Although the flows were fairly balanced in the system for the June 2001 and August 2008 storms, there was a great deal of error found in the total flow for the July 2008 and September 2008 storms.

It was determined that the presence of dry weather at the QCSOSTF system will lead to an imbalance between inflow and outflow to the facility. After turning off the dry weather flows in the CSO system (Pump1 at QCSOTF1-WI000830) in the model, the total inflow and outflow to the QCSOSTF were calculated, and the flows were relatively balanced in and out the facility for all four storm events. After completing this analysis, it was appropriate to move forward and continue further calibrations and updates of the current SWMM model to better represent the Worcester CSO system flows compared to the observed flows. Table 3 shows the results of inflow and outflow calculations at the QCSOSTF with no dry weather flow included in the model.

Table 3: Total QCSOSTF stormwater flow volumes	
June 2-4, 2001 Storm	Total Flow (MG)
Total QCSOSTF Inflow	27.6
Total QCSOSTF Outflow	27.9
July 19-25, 2008 Storm	Total Flow (MG)
Total QCSOSTF Inflow	33.3
Total QCSOSTF Outflow	33.0
August 10-11, 2008 Storm	Total Flow (MG)
Total QCSOSTF Inflow	2.48
Total QCSOSTF Outflow	2.47
September 25-29, 2008 Storm	Total Flow (MG)
Total QCSOSTF Inflow	12.1
Total QCSOSTF Outflow	10.6

After running the original developed model in SWMM, the observed flow was compared to the modeled flow for various boundary conditions in the Worcester CSO system. For the June 2001 storm, flows and water depths were modeled and compared to the observed data at each of sixteen flow meters. The June 2001 storm lasted for a total of three days, from June 2nd to June 4th with a total rainfall volume of 661.6 MG during the entire duration of the storm. The total rainfall was estimated by adding the total rainfall from meters 6, 12, and 13. Meter 6 in the Worcester CSO system is located on Southbridge Street at the Sargent Street Regulator Overflow. It is located in the southwestern portion of the combined sewer area of Worcester. Meter 12 is also located at the Southbridge Street Overflow Collector and is located in a manhole that is at the northwestern corner of the QCSOSTF, which measures flow just prior to entering the facility. Meter 13 is located at the Harding Street Overflow Collector at the intersection of Harding Street and Seymour Street. Flow that is measured from these three meters is all transported to the QCSOSTF for treatment and storage.

The model was also calibrated to match with data from three storms in 2008: July 19-25, August 10-11, and September 25-29. For these three storms, observed flows and rainfall amounts were provided from the operators at the Quinsigamond Avenue facility. The flow data from the QCSOSTF included total dry weather, wet weather, and effluent discharge flows that were measured every 5 minutes over the duration of each storm event. Figure 17 shows a plot comparing observed and model drain pump flow for the July 2008 storm, which measures the dry weather flow for the Worcester CSO system. This plot clearly shows that the model underestimates the dry weather flows, as the total dry weather flow for the system is greater for the observed data than the model. Similarly, the wet weather flow was plotted for the July 2008 storm comparing the model to the observed data (Figure 18). These flows are measured from the sewage pump flows, and the plot shows that the model underestimates flows compared to the observed data. Finally, the effluent discharge from the QCSOSTF was modeled, and a plot of modeled flow at the discharge was compared to the observed flows (Figure 19). While the shape of the model is very similar to that of the observed flows, the total effluent discharge from the model for the entire storm is much less than that of the observed data.

A similar analysis was performed for both the August and September 2008 storms, which both yielded similar results. The August storm has much smaller values for the model than the observed data, which is probably due to the fact that this is such a small storm comprised mainly of dry weather flows. As a result, the effluent discharge for the model is close to zero for the August storm. The September 2008 storm yields similar results to the July 2008 storm, where the model flows are much less than the observed flows for both dry weather and wet weather. In addition, while the shape of the curve for the model is similar to the observed flows for the September storm, the total model discharge is much less and has flows close to zero most of the time with only a few sharp peaks at points with the highest amounts of rainfall. Results for July 19-25 are provided in Figures 16-18, which show results for dry weather flow, wet weather flow, and effluent discharge, respectively. Figures 19-21 show a comparison of model and actual results for wet weather flow, dry weather flow, and effluent discharge for the August 10-11 storm. Similar results are provided (Figures 22-24) for the September 25-29 storm in 2008.

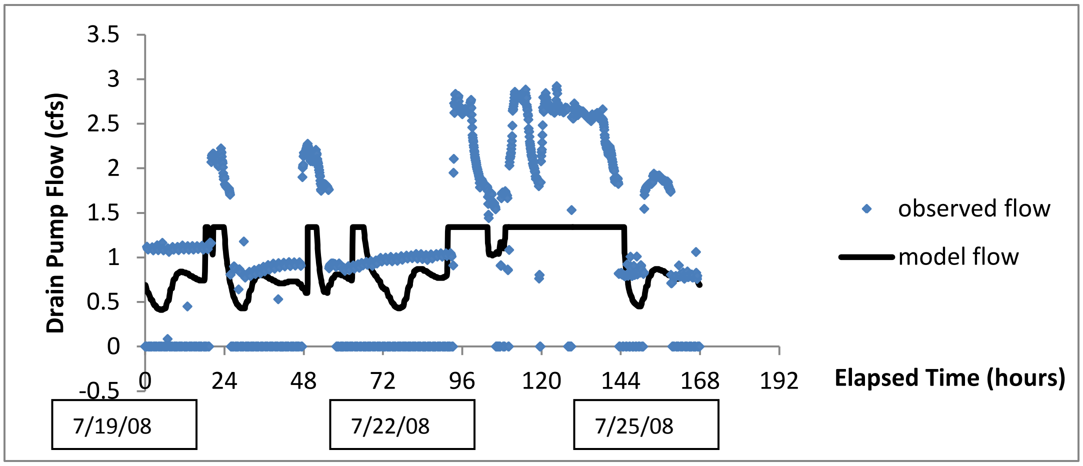


Figure 16: Dry Weather Flows July 19-25, 2008

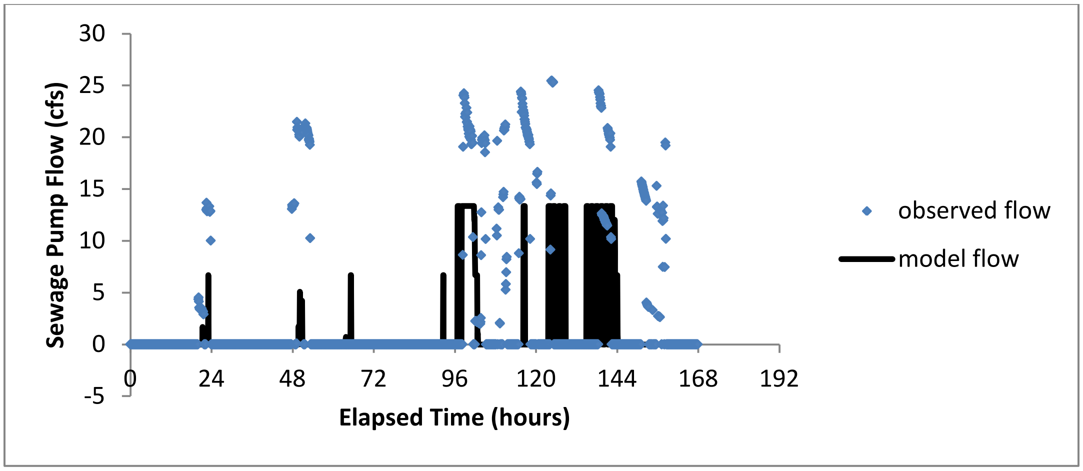


Figure 17: Wet Weather Flows July 19-25, 2008

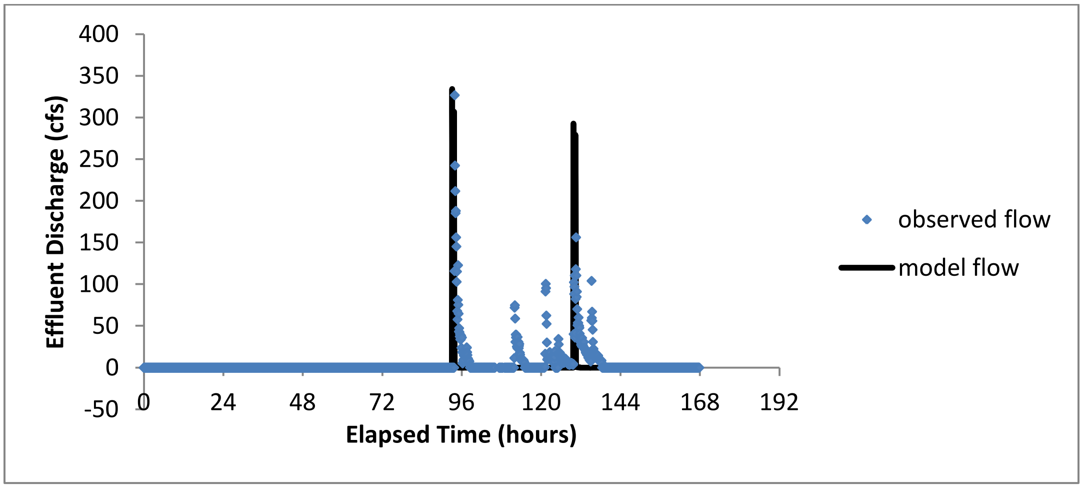


Figure 18: Effluent Discharge July 19-25, 2008 (Old Control Rules)

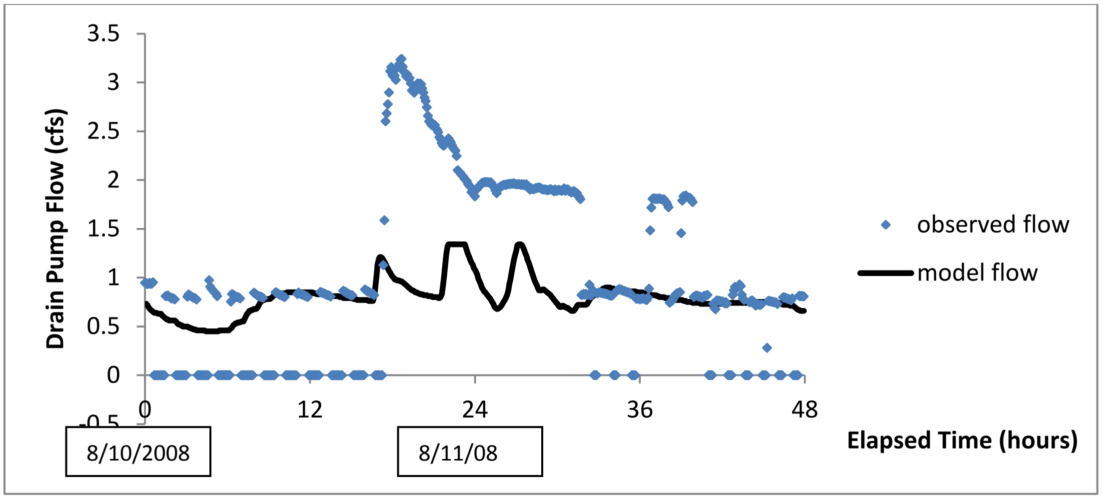


Figure 19: Dry Weather Flows August 10-11, 2008

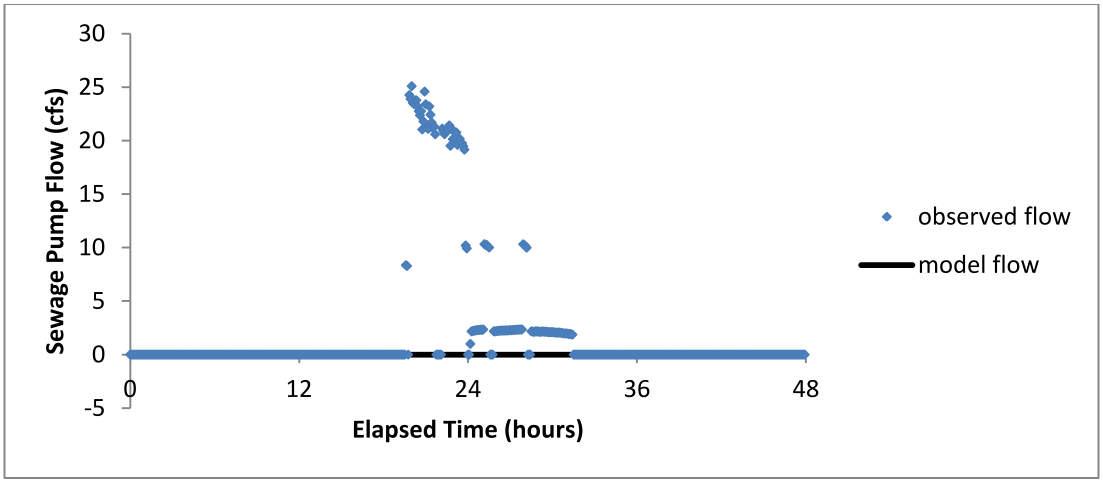


Figure 20: Wet Weather Flows August 10-11, 2008

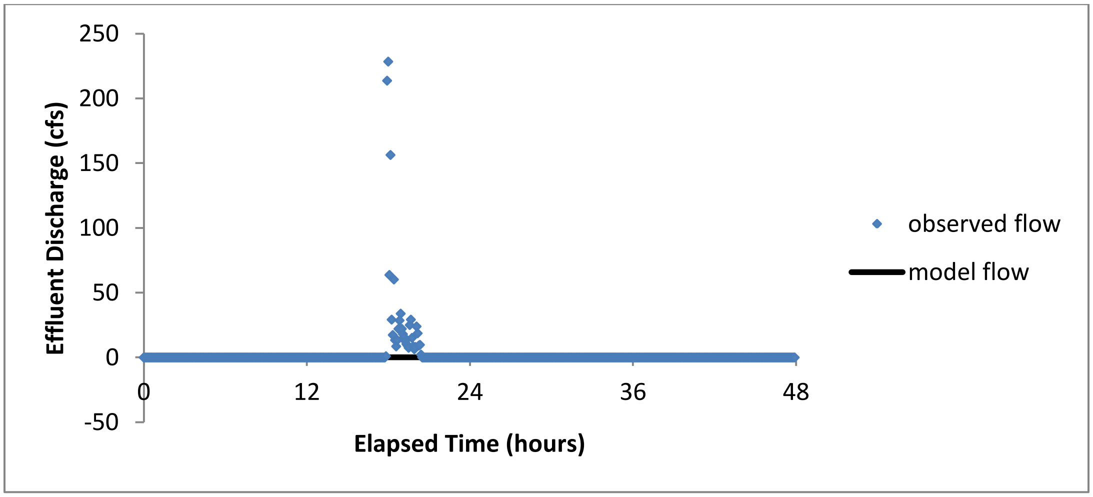


Figure 21: Effluent Discharge August 10-11, 2008

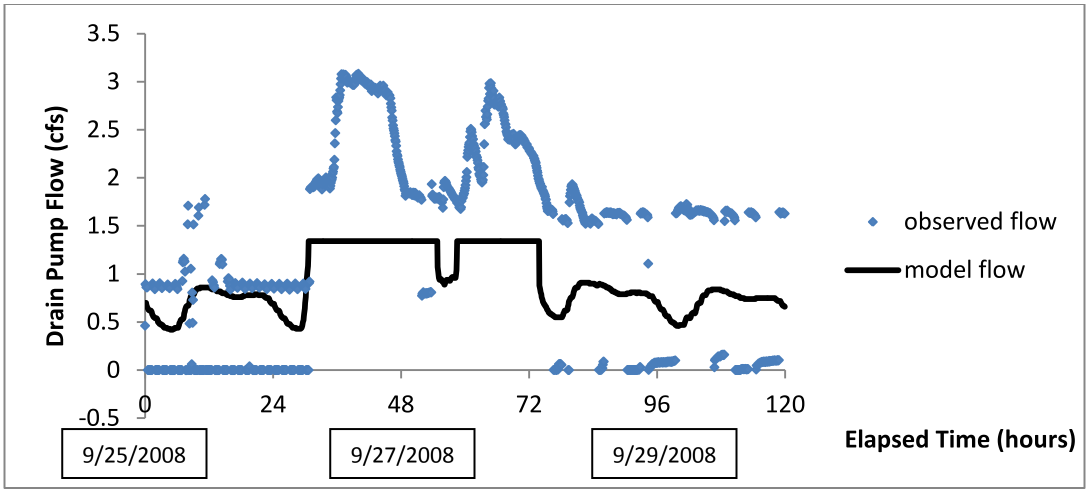


Figure 22: Dry Weather Flows September 25-29, 2008

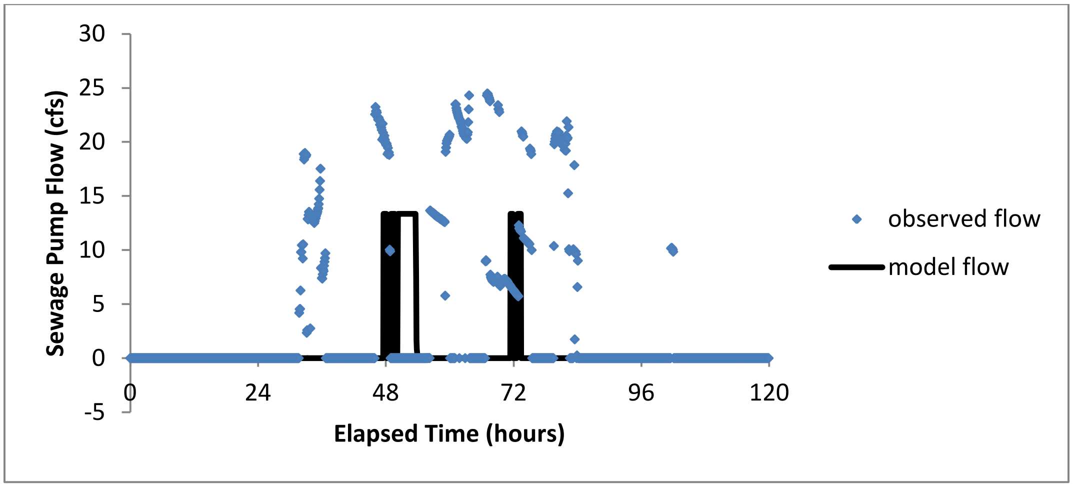


Figure 23: Wet Weather Flows September 25-29, 2008

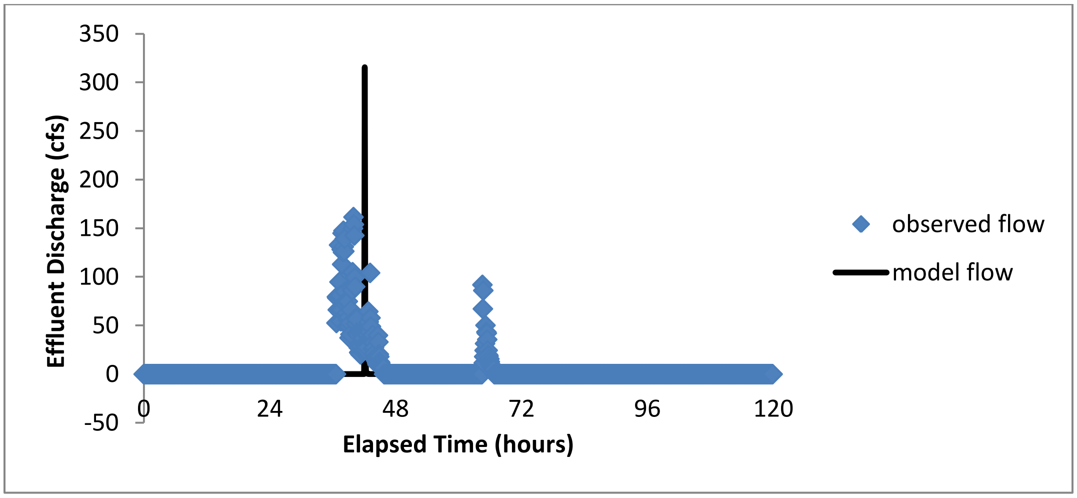


Figure 24: Effluent Discharge September 25-29, 2008

After initial calibration of the model, it was determined that more adjustments needed to be made specifically to improve the performance of the SWMM model for the 2008 storms. Since the operating procedures and pump control rules were updated for the QCSOSTF in September 2007, the current SWMM model did not factor in these adjustments since it was last updated in 2001. As a result, it was necessary to make adjustments to the control rules in the model to better represent the 2008 storms. Arbitrary control depths were updated in the model to test if it would lead to model improvements. The model was initially set up with the following control inputs, described below in Table 4. In addition, the QCSOSTF controls are set up in the model by control curves that are referred to in the control rules. Table 5 provides information for each of eight control curves used in the model.

Table 4: QCSOSTF control rules (updated in 2001)

Rule Pre 1	If QCSOTF1 depth <15, orifice OR1atQCSOTF1-QCSOTF2 = 0
Rule Pre 2	If QCSOTF1 depth <15, orifice OR2atQCSOTF1-QCSOTF2 = 0
Rule Pre 3	If QCSOTF1 depth <15, orifice OR1atQCSOTF1-OT00001 = 0
Rule Pre 4	If QCSOTF1 depth <15, orifice OR2atQCSOTF1-OT00001 = 0
Rule 1	If QCSOTF1 depth >=15, OR1atQCSOTF1-QCSOTF2 = 1 (Priority 1)
Rule 1B	If QCSOTF1 depth <=13, OR1atQCSOTF1-QCSOTF2=0 (Priority 2)
Rule 2	If QCSOTF1 depth >=15, OR2atQCSOTF1-QCSOTF2 =1 (Priority 3)
Rule 2B	If QCSOTF1 depth <=13, OR2atQCSOTF1-QCSOTF2 =0 (Priority 4)
Rule 3	If QCSOTF1 depth >=17, OR1atQCSOTF2-OT00001 =1 (Priority 5)
Rule 3B	If QCSOTF1 depth <=15, OR1atQCSOTF2-OT00001 =0 (Priority 6)
Rule 4	If QCSOTF1 depth >=17, OR2atQCSOTF2-OT00001 =1 (Priority 7)
Rule 4B	If QCSOTF1 depth <=15, OR2atQCSOTF2-OT00001 =0 (Priority 8)
Rule 5	If QCSOTF1 depth >=0, OR1atQCSOTF1-OT00011A = CURVE C3
Rule 6	If link MN114582 flow >=0, OR1atOT00011A-OT00011B = CURVE C8
Rule 7	If HC02652 depth >=0, OR1atHC02652y-HC02652x = CURVE C5
Rule 8	If QCSOTF1 depth >=0, OR1atHC02652-HC02652y = CURVE C6
Rule 9	If HC02652 depth >=0, OR1atHC02652-HC02652x = CURVE C7

Table 5: Control curve information (updated in 2001)

Control Curve	Controller Valve	Control Setting
Curve C1	13	0
Curve C1	13.5	0.25
Curve C1	14	0.5
Curve C1	14.5	0.75
Curve C1	15	1
Curve C2	15	0
Curve C2	15.5	0.25
Curve C2	15	0.5
Curve C2	16.5	0.75
Curve C2	17	1
Curve C3	1.25	0
Curve C3	2.75	1
Curve C4	2.6371	1
Curve C4	2.6380	0
Curve C5	8.4	1
Curve C5	8.5	0
Curve C6	4.05	1
Curve C6	7.05	0.17
Curve C7	7.8	0
Curve C7	8.4	1
Curve C8	82	1
Curve C8	83	0

Curves C1 and C2 describe the storage depths used at the Quinsigamond Avenue facility when the orifices at the storage tanks are turned on and off, and Curve C3 is used to describe when the orifice connecting the QCSOSTF and downstream discharge node is turned on and off. Curve C4 provides a description of the control flows downstream of the Quinsigamond Avenue facility based on the treatment capacity of the Upper Blackstone treatment facility. Curves C5, C6, and C7 provide information for opening and closing the gate at the Kelly Square controls, and Curve C8 provides downstream controls based on flow (in cfs).

These control rules and curves were updated in an attempt to improve the model results for the three 2008 storms. The 2001 control rules base their controls on three storage tank depths: 13 feet, 15 feet, and 17 feet. These depths were decreased to 10 feet, 13 feet, and 15 feet in an attempt to allow more flow to pass through the gates at the QCSOSTF and increase the total flow discharged from the plant. These new controls were compared to the old control rules using a number of different parameters. The key parameters for comparison included effluent discharge, drain pump (dry weather) flow, sewage pump (wet weather) flow, total discharge volume, and total runoff in the system. The total discharge volume was defined as the total sum of the wet weather flow and effluent discharge from the QCSOSTF. The total runoff was determined by adding the effluent discharge from the QCSOSTF with the UBWWTP interceptor flow and inflow to the QCSOSTF. It was also important that the total runoff was less than the rainfall, and the relationship between those two parameters was displayed using a coefficient (Cvol), which is equal to the ratio of runoff volume to rainfall volume. Tables 6-8 shows a summary of these parameters for the four storms analyzed in SWMM. Table 6 provides a summary for the current controls that were updated in 2001, while Table 7 shows the new controls that were implemented as a test to determine if the model would improve for the 2008 storms. While the new controls seemed to improve the model, more improvements were made to further calibrate the model and decrease discrepancies between the model and observed data. Data that is not listed was not available for the particular storm and parameter.

Table 6: Comparison of model results and observed data for various parameters (old control depths: 13', 15', and 17')

	June 2-4, 2001 Storm			July 19-25, 2008 Storm	
	Observed	Model		Observed	Model
Total Discharge Volume (MG)				30.78	11.64
Total Rainfall Volume (MG)	661.6	661.6		258.4	258.4
Volume of Runoff (MG)		524.3		214.9	201.3
Cvol		0.7924		0.8319	0.779
Sewage Pump Volume (MG)		2.013		11.52	5.610
Drain Pump Volume (MG)		1.561		4.976	4.293
Effluent Discharge Volume (MG)	59.80	23.35		19.26	6.031
QCSOSTF Inflow Volume (MG)	29.6	41.2			67.68
QCSOSTF Outflow Volume (MG)		26.93			15.94
Interceptor Flow to UBWWTF (MG)					128.0

	August 10-11, 2008 Storm			September 25-29, 2008 Storm	
	Observed	Model		Observed	Model
Total Discharge Volume (MG)	5.288	0.000		25.44	3.441
Total Rainfall Volume (MG)	18.65	18.65		158.9	158.9
Volume of Runoff (MG)	34.99	32.43		134.3	121.6
Cvolume	1.876	1.739		0.8454	0.7655
Sewage Pump Volume (MG)	2.727	0.000		10.53	2.209
Drain Pump Volume (MG)	1.399	1.034		4.158	2.991
Effluent Discharge Volume (MG)	2.561	0		14.91	1.232
QCSOSTF Inflow Volume (MG)		1.039			24.28
QCSOSTF Outflow Volume (MG)		1.034			6.432
Interceptor Flow to UBWWTF (MG)		31.39			95.14

Table 7: Comparison of model results and observed data for various parameters (new control depths: 10', 13', and 15')

	June 2-4, 2001 Storm			July 19-25, 2008 Storm	
	Observed	Model		Observed	Model
Total Discharge Volume (MG)				30.78	13.66
Total Rainfall Volume (MG)	661.6	661.6		258.4	258.4
Volume of Runoff (MG)		524.3		214.9	242.7
Cvol		0.7924		0.8319	0.939
Sewage Pump Volume (MG)		2.013		11.52	4.086
Drain Pump Volume (MG)		1.561		4.976	4.317
Effluent Discharge Volume (MG)	59.80	23.35		19.26	9.574
QCSOSTF Inflow Volume (MG)	29.6	41.2			47.23
QCSOSTF Outflow Volume (MG)		26.93			
Interceptor Flow to UBWWTF (MG)					185.9

	August 10-11, 2008 Storm			September 25-29, 2008 Storm	
	Observed	Model		Observed	Model
Total Discharge Volume (MG)	5.288	0.000		25.44	5.534
Total Rainfall Volume (MG)	18.65	18.65		158.9	158.9
Volume of Runoff (MG)	34.99	43.48		134.3	157.8
Cvol	1.876	2.33		0.8454	0.99
Sewage Pump Volume (MG)	2.727	0.000		10.53	3.234
Drain Pump Volume (MG)	1.399	0.003		4.158	0.01
Effluent Discharge Volume (MG)	2.561	0		14.91	2.30
QCSOSTF Inflow Volume (MG)		1.039			19.94
QCSOSTF Outflow Volume (MG)					
Interceptor Flow to UBWWTF (MG)		42.44			135.56

While these new control rules improved the model results, further adjustments were made to the control rules so they better represent the actual control rules that were implemented by the Quinsigamond Avenue facility operators in 2007. In the QCSOSTF facility control operations manual for 2007, it was explained that in the dry weather mode, "the level in the wet well will be maintained below elevation 424…by the operation of the 2-600 gpm sludge pumps" (Gately et al. 2007). This elevation of 424 represents the 0-foot level described in the current SWMM model for low flow conditions. QCSOSTF water levels of 432 feet, 434 feet, and 441 feet were implemented in the updated control rules as determinations for opening the influent gates (Gately et al. 2007). As a result, it was determined that depths of 8 feet, 10 feet, and 17 feet would be used as a the final control rules implemented for the SWMM model for the Worcester CSO system. Table 8 shows a summary of a comparison between the observed and model using the final updated control rules. In addition to using these new depths, the peak flow for the QCSOSTF system was updated to 50 MGD or 77.5 cfs, and this information was updated in the control curve inputs for the model along with the control rules. By increasing the maximum flow allowed through the gates, it was expected that more flow will be allowed to discharge from the QCSOSTF, which increased the total effluent discharge for the model.

Table 8: Comparison of model results and observed data for various parameters (final control depths: 8’, 10’, and 17’)

	June 2-4, 2001 Storm			July 19-25, 2008 Storm	
	Observed	Model		Observed	Model
Total Discharge Volume (MG)				30.78	12.91
Total Rainfall Volume (MG)	661.6	661.6		258.4	258.4
Volume of Runoff (MG)		524.3		214.9	250.06
Cvol		0.7924		0.8319	0.968
Sewage Pump Volume (MG)		2.013		11.52	3.346
Drain Pump Volume (MG)		1.561		4.976	4.27
Effluent Discharge Volume (MG)	59.80	23.35		19.26	9.567
QCSOSTF Inflow Volume (MG)	29.6	41.2			54.79
QCSOSTF Outflow Volume (MG)					
Interceptor Flow to UBWWTF (MG)					185.7

	August 10-11, 2008 Storm			September 25-29, 2008 Storm	
	Observed	Model		Observed	Model
Total Discharge Volume (MG)	5.288	0.000		25.44	5.394
Total Rainfall Volume (MG)	18.65	18.65		158.9	158.9
Volume of Runoff (MG)	34.99	43.48		134.3	158.87
Cvol	1.876	2.33		0.8454	1.00
Sewage Pump Volume (MG)	2.727	0.000		10.53	3.234
Drain Pump Volume (MG)	1.399	0.003		4.158	0.010
Effluent Discharge Volume (MG)	2.561	0		14.91	2.16
QCSOSTF Inflow Volume (MG)		1.039			20.90
QCSOSTF Outflow Volume (MG)					
Interceptor Flow to UBWWTF (MG)					

3.4 Climate Change Scenarios

A variety of CSO/stormwater management strategies were identified and modeled in SWMM under three different climate change scenarios: high, low, and moderate. Each strategy was simulated under these climate change scenarios for the 3-month, 10-year, and 100-year 24 hour storms design storms. The simulations were performed for three different periods of time: 2010 (present-day), 2040, and 2070. A total of seven different strategies were simulated at three different climate change scenarios for three different points of time and three different design storms for a total of 147 simulations.

The simulation results were analyzed using three performance metrics and two different decision-making approaches to quantify the results. These decision-making approaches include a net cost and benefits approach and an expected net benefits approach. Both of these approaches use risk analysis strategies to determine the best approach to use in the future to best manage future storms under climate change. Costs to meet each design scenario were compared to determine the most cost-effective robust strategy. In addition, net benefits were determined for each strategy to determine the most effective robust strategy to better manage stormwater in the Worcester CSO with climate change uncertainty.

Climate change scenarios were developed and simulated in SWMM in order to best develop design storms in the future and predict future storm scenarios. However, one of the challenges of designing for climate change is determining the probabilities of future climate conditions. This particular study for Worcester does not use scenarios with assigned probabilities but analyzes data from General Circulation Models (GCMs). GCMs are mathematical models of the Earth’s atmosphere and are used for weather forecasting. In this case, they were used to understand climate and predict climate change in the future. GCMs take a variety of factors into account when determining future climate change projections like precipitation and temperature, which include atmospheric, chemical, and biological factors as well as ocean movement (Climap, 2012). The Intergovernmental Panel on Climate Change (IPCC) recommends different measures to mitigate global warming based on different scenarios, and they can predict what results a specific reduction in greenhouse gases may have (Climap, 2012). For this study in Worcester, three points in time were used to analyze climate change scenarios: 2010, 2040, and 2070. The years 2040 and 2070 were chosen to allow a 60-year planning timeframe as a plausible period for stormwater management. In addition, data was available from GCMs for the years 2050 and 2100, which allows for interpolation of GCM data for the Worcester system.

Global weather performance is extremely complex, which makes climate change uncertain and difficult to predict in the future. In addition, “downscaling” techniques are used to interpolate data further into the future, which creates more uncertainty. These techniques are used in GCMs in order to make predictions for specific locations. For this study, downscaling techniques used by Anthony Powell of the University of Colorado uses twenty GCMs for the Special Report on Emission Scenarios (SRES) for greenhouse gases (Powell, 2008). These design storms techniques were used for a similar study in Somerville, MA (Caputo, 2011) and have been used for the Worcester system to provide a comparison of the two Massachusetts CSO systems. This system includes SRES scenarios B, A1b, and A2, which estimate percent changes in annual precipitation. Scenario B represents a low climate change scenario, which represents the use of maximum sustainability in the future. Scenario A1b represents a moderate climate change scenario, and A2 is a high scenario with the maximum change in precipitation possible (IPCC, 2001).

For each climate change scenario (B, A1b, and A2), a total of twenty GCM sets of data for daily precipitation were fit to a distribution model known as the Log Pearson Type III distribution. Results of the precipitation data were displayed as box and whisker plots to show how variable relative percent changes are for annual precipitation, and the data are displayed in Figures 26, 27, and 28. Figure 25 shows the box and whisker plots for the 2-year 24-hour design storm, Figure 26 shows results for the 10-year 24-hour design storm, and Figure 27 shows results for the 100-year 24-hour design storm. These plots were developed by Powell for 2050 and 2011 (Powell, 2008). For each plot, Q1 represents the 25th percentile of precipitation data, the median is the 50th percentile, and Q3 is the 75th percentile (Caputo, 2011).

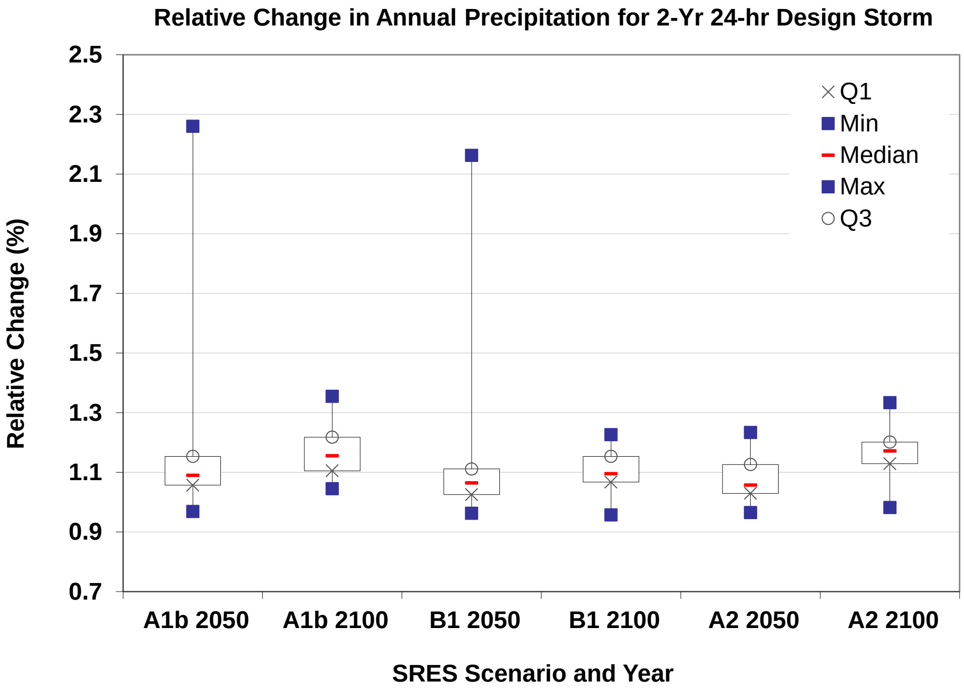


Figure 25: Relative change in annual precipitation for 2-year 24-hour design storm
(Caputo, 2011)

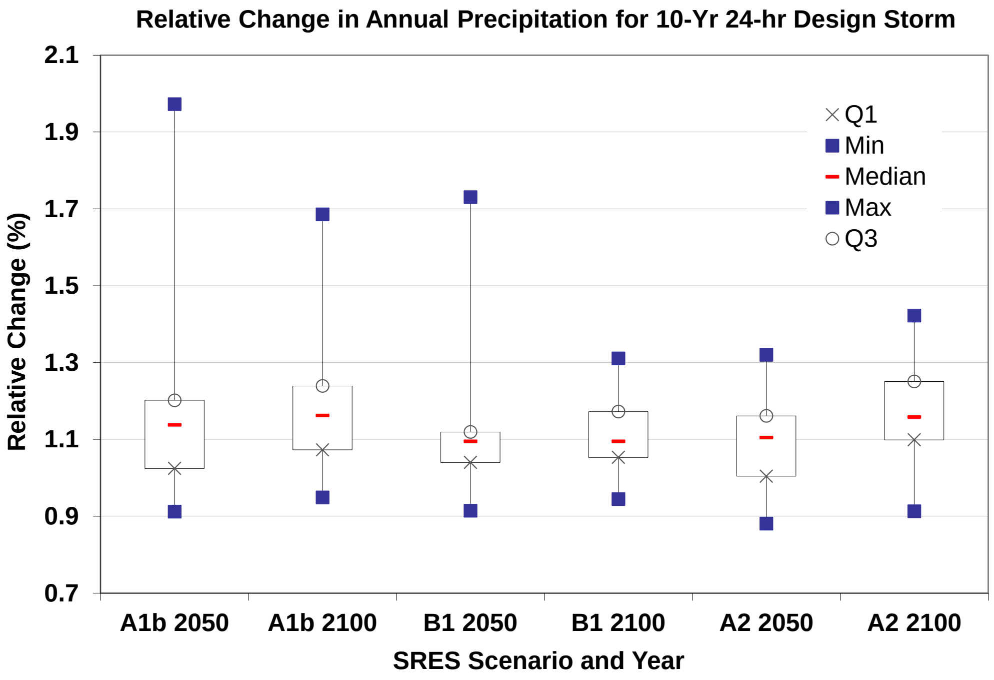


Figure 26: Relative change in annual precipitation for 10-year 24-hour design storm (Caputo 2011)

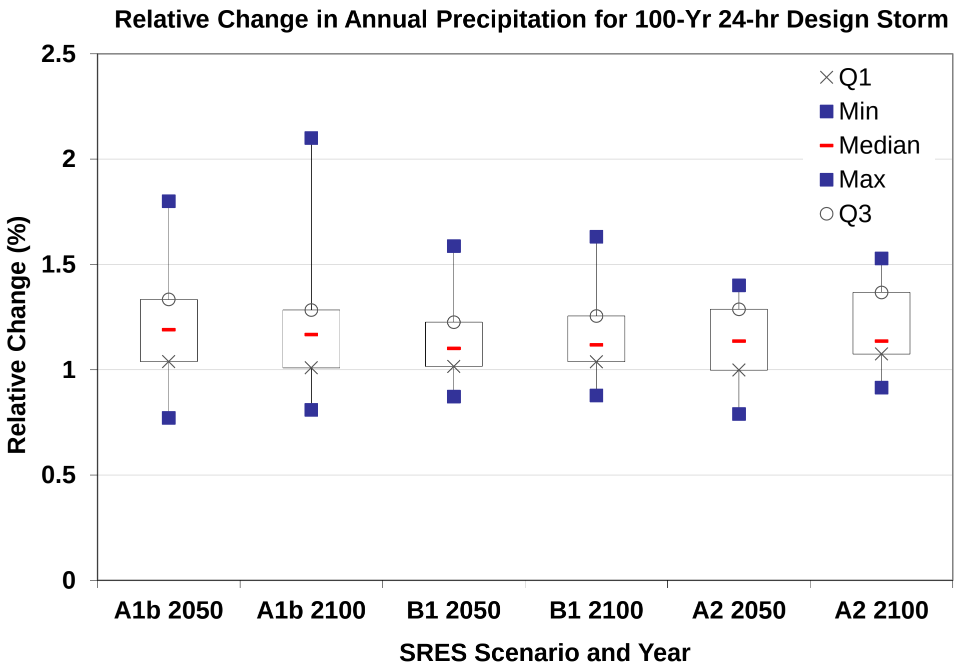


Figure 27: Relative change in annual precipitation for 100-year 24-hour design storm (Caputo 2011)

Based on the data from the downscaled SRES scenarios, three different climate change scenarios were defined as high, low, and median scenarios for 2050 and 2100. The high climate change scenario is represented by Q3 of the SRES data or the maximum of the 75% values. The moderate scenario is the median of the 50th values of the SRES. In some cases the SRES scenario defined for a climate change scenario was different for 2050 versus 2100. For the 10-year storm, the SRES scenario that had a minimum value for the 25th percentile in 2100 (B1) was different than the SRES scenario that had the minimum value for the 25th percentile in 2050 (A2). As a result, the SRES climate change scenario chosen for 2100 was also chosen for 2050 to make sure that interpolation between values was accurate enough to be used for 2040 and 2070. For the low climate change scenario for the 10-year design storm, SRES scenario B1 was chosen for 2050 and 2100. For the study of the Worcester CSO system, the 3-month design storm was used as the smallest storm. This storm was used for future design storms along with 10-year and 100-year storms. However, Powell used the 2-year storm as the smallest design storm for the SRES climate change scenario analysis. Since no data were available for the 3-month storm, the 2-year storm percentages were used to represent 3-month storm percentages for this study. A table of all relative percent changes for each climate change scenario in 2050 and 2100 are shown below and the SRES climate change scenario used is shown in parentheses (Table 9).

Table 10: Relative percent changes for each climate change scenario in 2050 and 2100

24-hour Design Storm	Annual Relative Percent Change for each Climate Change Scenario (%)					
	2050			2100		
	Low	Median	High	Low	Median	High
3-month	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)

After obtaining data from these climate change scenarios, values for the high, median, and low scenarios were linearly interpolated to find climate change scenarios for 2040 and 2070 to be used in the Worcester study. Linear interpolation was performed between data from 2010 and 2050 in order to obtain high, median, and low scenarios for 2040. For relative percent changes in 2070 linear interpolation was performed between data from 2050 and 2100. This procedure is based on previous work completed by Lauren Caputo and final calculated relative percent changes for 2040 and 2070 are shown in Table 10 for each climate change scenarios for the 3-month, 10-year, and 100-year design storms (Caputo, 2011).

Table 10: Relative percent changes for each climate change scenario in 2040 and 2070

24-hour Design Storm	Annual Relative Percent Change for each Climate Change Scenario (%)					
	2040			2070		
	Low	Median	High	Low	Median	High
3-month	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

These percent changes were used for each climate scenario and multiplied by existing design storm totals for Worcester to obtain future design storm precipitation totals. The 3-month 24-hour design storm total was determined based on data computed from CDM's Rainmaster program from the 4-year Worcester hourly record (CDM, 2002). A 3-month 24-hour design storm total of 1.8 inches was used for the Worcester study to represent a present storm in 2010. Design storm totals for the 10-year and 100-year storms in 2010 were obtained from the Cornell University interactive web tool that is used for analysis of extreme precipitation scenarios (Cornell University, 2011). The 10-year design storm was defined as 4.35 inches, and the 100-

year storm was defined as 7.84 inches for Worcester. Table 11 provides a summary of storm totals for each climate change scenario in 2040 and 2070.

Table 11: Summary of storm totals for each climate change scenario in 2040 and 2070

Storm Totals for Each Climate Change Scenario (inches)							
24-hour Design Storm	2010	2040 High	2040 Median	2040 Low	2070 High	2070 Median	2070 Low
3-Month	1.80	2.05	1.94	1.89	2.12	2.02	1.94
10-year	4.35	4.96	4.74	4.52	5.22	4.92	4.57
100-year	7.84	9.96	8.94	8.15	10.35	8.94	8.08

3.5 Design Storms

For design storm simulations, the 3-month, 10-year, and 100-year storms were chosen in order to fully test the variability of responses to different types of storms. These three storms represent a low, median, and high frequency storm that were simulated in SWMM under different climate change scenarios. All three design storms were input as 15-minute precipitation data for a total of 72 hours. The 72-hour storms include the 24-hour design storm during the middle 24-hour time period. As a result, the design storms are simulated using one day of dry weather, 24 hours of rainfall, and a final day of dry weather. Input data for each design storm was determined using the Soil Conservation Service (SCS) Type III distribution, which represents the typical distribution for a storm in the Northeast region of the United States (Chow et al., 1998).

The 3-month storm was chosen to represent a small, frequent storm for evaluation that is usually exceeded by a larger storm four times each year or once every three months. The EPA CSO Policy states that there should be no more than an average of four combined sewer overflow events per year, which is well represented by a 3-month storm. On average, the

Worcester CSO system typically overflows more than four times per year. During periods of significant rainfall, both stormwater and sanitary sewage enter the Quinsigamond CSO facility (QCSOSTF). Depending on the amount of flow entering the facility, the incoming flows are either pumped to the Upper Blackstone facility (UBWWTF) or treated at the QCSOSTF if flows become more significant. Once treated, the flow is discharged downstream to the Mill Brook and eventually into the Blackstone River.

The 10-year and 100-year storms were chosen as larger, more infrequent storms because they must be evaluated under Standard 2 under the Massachusetts Stormwater Rules for the design of stormwater management systems. In a single year, a 10-year design storm has a 10% chance of being exceeded, and a 100-year storm has a 1% chance of being exceeded. These particular storms also provide data that were used to determine the expected value of costs and benefits during the decision making process for best management practice options for stormwater management in the future.

3.6 Performance Metrics

Three performance metrics were chosen for this study in order to compare different strategies for stormwater management. These performance metrics include volume of hazardous flooding into the streets, total volume of flow through the Quinsigamond Avenue CSO facility (QCSOSTF), and total volume of flow through the Upper Blackstone Wastewater Treatment Facility (UBWWTF). Similar performance metrics were chosen by Lauren Caputo for the study in Somerville, as these performance metrics for Worcester were chosen to provide a direct comparison between the two case studies.

3.6.1 Hazardous Flooding

Hazardous flooding was chosen as a metric of interest because flooding has been a problem in many major cities in New England like Worcester. It is expected that flooding will only get worse in future years due to the expected increase of intense rainfall events without the use of more effective stormwater strategies. Worcester one particular city that is especially prone to flooding specifically in low lying areas between its several hills. There have also been many instances where heavy rain storms have led to backups in the Blackstone Canal that have caused flooding in surrounding areas. Heavy rain from Tropical Storm Lee brought major flooding to Worcester in September 2011. There were actual reports on Cambridge Street of cars being fully submerged under water under a nearby bridge during this storm event (Curran, 2011).

Hazardous flooding is defined as total flooding in the streets minus “nuisance flooding”. Nuisance flooding is the total volume of water that can flow through the streets without overtopping the curve, so it causes a nuisance but no harm or damage. Nuisance flooding was calculated for each junction in the Worcester CSO system using the following equation:

Nuisance flooding = pipe length x average road width x average curb height

However, it was found that nuisance flooding was very small compared to the total street flooding for each junction in the system, so it was neglected when determining the total hazardous flooding. Hazardous flooding was determined to be equal to the total street flooding at each junction in the system.

3.6.2 Volume of Flow through QCSOSTF

The volume of flow through the QCSOSTF was defined as the total inflow at Conduit OTF0002 throughout the length of a storm in million gallons (MG). Conduit OTF0002 is the pipe where flow leaves the Quinsigamond CSO facility. This flow discharges from the storage tanks at the Quinsigamond Avenue to outfall MB0002, which is one of three outfalls in the Worcester CSO system that carries flow to the Mill Brook. CSO volumes at outfall MB0002 were not used since stormwater enters the system from the Western Interceptor downstream of the CSO facility. As a result, evaluating flow at this outfall would not accurately represent the total combined sewage discharged from the QCSOSTF since additional stormwater would be included in the total amount of flow volume entering the outfall.

3.6.3 Volume of Flow through UBWWTF

In addition to hazardous flooding and volume of flow through the QCSOSTF, the volume of flow through the UBWWTF was also used as a metric to evaluate the performance of stormwater management strategies. The volume of flow through the Upper Blackstone facility was defined as the total inflow at outfall MI16082. The volume of flow through the UBWWTF includes all flow upstream of the Mill Brook that is pumped from node OT00011B to MI00040. It also includes flow discharged from the QCSOSTF facility during high-intensity storms when the QCSOSTF acts as a treatment facility for combined sewage. Similar to flow through the QCSOSTF, flow volumes through the Upper Blackstone facility were totaled for each stormwater management strategy in units of MG. These three performance metrics were chosen to compare the effectiveness of each adaptation option to better management stormwater under future climate change scenarios.

3.7 Stormwater Management Options

Options for stormwater management in Worcester were chosen based on their feasibility and expected performance in the future. These strategies were chosen with the long-term goal of significantly decreasing hazardous flooding in the streets of Worcester. It was also expected that if implemented the most effective option will control the increase of flow through the QCSOSTF and UBWWTF in the future. These goals for stormwater management need to be met under all climate change scenarios. As a result, each option was designed to successfully meet the stormwater management goals under the worst case scenario, which is represented by the 100-year storm under a high climate change scenario. Each option was developed to accommodate rainfall amounts from the 100-year storm for the high climate change scenario in 2010, 2040, and 2070. After performing analyses for the 100-years storm, a similar analysis was conducted for the 3-month and 10-year design storms in 2010, 2040, and 2007. With three climate change scenarios in 2040 and 2070 and a total of three different design storm totals (3-month, 10-year, 100-year), a grand total of 21 different model simulations were run for each of 7 stormwater management options. While there were many other options that were discussed and may be suitable for use in Worcester, they were ultimately deemed too intensive and unfeasible for this particular study. The seven options chosen for this study of the Worcester CSO system include: no action, underground storage throughout the watershed, underground storage upstream of the QCSOSTF, underground storage upstream of the QCSOSTF combined with additional QCSOSTF pumping, sewer separation, low impact development (LID) throughout the watershed, and a combination of LID and sewer separation. Each stormwater management option is described in detail in the following sections.

3.7.1 Option 1 – No Action

Option 1 is included to represent no action to improve stormwater management in Worcester, which is used as a baseline scenario to compare with options 2 through 7.

3.7.2 Option 2 – Underground storage throughout the watershed

Option 2 involves the approach of constructing underground storage basins throughout the Worcester CSO system area in order to help control flooding. Retention basins are the most common type of underground storage used in urban areas. While there are other types of storage that can be used for urban areas, retention and detention basins have been proposed for the Worcester system and have been used for this study.

This strategy involves providing storage in specific areas that have been deemed to have a significant amount of hazardous flooding. Hazardous flooding was previously defined as the total amount of street flooding minus nuisance flooding, but nuisance flooding has been neglected for this study. It was determined that it was reasonable to obtain a long-term goal of decreasing hazardous flooding to 0.5 MG or less for each node in the system. Hazardous flooding in 2010, 2040, and 2070 was simulated under the high climate change scenario and 100-year storm to determine the necessary storage to keep hazardous flooding below 0.5 MG. Simulation results at these storms determined that roughly the same nodes in the system experienced the most flooding.

The top 25 nodes in the system with the most flooding experienced greater than 0.5 MG of flooding during the 100-year storm in 2070. As a result, these nodes were chosen for the study and corresponding storage basins were added to the model at these nodes. 25 retention basins were designed in SWMM to control hazardous flooding at these areas of interest. Each basin was designed as an off-line storage tank that was designed to store the total amount of flooding at the node. The storage tanks were connected to the nodes by an orifice located 10 feet below the ground surface. Each orifice was designed as a closed rectangular shape orifice with dimensions of 10 feet x 10 feet at nodes with greater than 1 MG of flooding and 5 feet x 5 feet at nodes with 1 MG or less of flooding. For 2010 storms enough storage was included in order to accommodate hazardous flooding in the present 100-year storm. Additional storage was installed in 2040 to accommodate flooding in the 2040 100-year storm with a high climate change scenario. Similarly, additional storage was installed in 2070 to accommodate additional expected flooding in 2007. Storage in 2007 was designed to control flooding in the 100-year 2070 design storm under a high climate change scenario. Table 12 provides a summary of the 25 nodes used for storage along with their location in the SWMM model and in Worcester and tank dimensions to accommodate all flooding in 2070. Tank volumes are in units of acre-feet, assuming a 10-foot depth of each storage tank.

Table 12: Worcester CSO underground storage tank locations and design for 2070 (option 2)

Node	Location	Length (ft)	Width (ft)	Volume (acre-ft)
OT00015	Canton St/Quinsig Ave	690	690	109
QC00347	Canton St/Quinsig Ave	620	620	88
HC06354	Summer/E. Central St	510	510	60
EI08916U	Summer/Laurel St	410	410	39
HC07484	Summer/Prospect St	370	370	31
EI12543B	Garden St.	320	320	24
EI06038B	Grafton St/I-290	280	280	18
QC1988UA	Quinsig/Southbridge St	250	250	14
EI08696U	Summer/Laurel St	240	240	13
SS03826	Shrewsbury St/I-290	225	225	12
WI01256	WI/Quinsig Ave	225	225	12
SS05081	Shrewsbury St/I-290	205	205	10
SC05364	Shrewsbury St/I-290	205	205	10
EI0322OU	Endicott/Millbury St	195	195	9
EI02137U	Harding/Endicott St	165	165	6
WI04808	Endicott/Millbury St	165	165	6
WI05525A	Endicott/Millbury St	145	145	5
EI02745U	Endicott/Millbury St	135	135	4
EI04274B	Endicott/Millbury St	105	105	3
EI01137A	EI/Canton/Millbury St	105	105	3
HC07834	Summer/Laurel St	100	100	2
EI04274A	Endicott/Millbury St	100	100	2
EI012910	Brosnihan Square	95	95	2
SC04725	Shrewsbury St/I-290	90	90	2
SC01218	Shrewsbury St/I-290	85	85	2

3.7.3 Option 3 – Underground storage upstream of QCSOSTF

After performing an analysis for the underground storage option throughout the watershed, it was deemed appropriate to provide a more realistic storage option for Worcester. For the 2040 and 2070 storms under a high climate change scenario, flooding in some areas downstream of the QCSOSTF was as high as 35 MG for a particular node. The nodes with major flooding of over 10 MG are all located near the QCSOSTF in and around Crompton Park. These nodes with major flooding are located in the model at nodes EI08916U, HC06354, HC07484, OT00015, and QC00347. These nodes are located in the areas of Summer Street and Canton

Street near Quinsigamond Avenue. In order to accommodate flooding at these 5 locations for the 2070 100-year storm, storage basins of up to 10 acres in area are required.

After meeting with representatives of the Worcester Department of Public Works, it was determined that a more reasonable storage option was necessary due to the limited amount of available storage space in the city. However, there is a great deal of space available near the QCSOSTF in Crompton Park. Crompton Park takes up 14.6 acres of public land in Worcester and is located at Harding Street and Endicott Street (City of Worcester, MA, 2012). In order to better use available land to provide more reasonable storage options, the 5 storage tanks corresponding to the five nodes with the most flooding were replaced by one larger detention basin in Crompton Park. A storage tank was installed in the model with a total area of 8.0 acres in 2010 to accommodate flooding in the 100-year storm. Additional storage was installed in 2040 for a total storage tank area of 12.4 acres. This additional storage accommodates flooding in both 2040 and 2070 to control flooding during the 100-year storm under a high climate change scenario. All other nodes with storage are located upstream of the QCSOSTF and were not updated for this option. Table 13 provides a summary table of the 21 nodes used for storage for this adaptation option (option 3). The model and geographic location within Worcester are included for each node. In addition, the dimensions of each storage tank are indicated for design to accommodate all flooding in 2070.

Table 13: Worcester CSO underground storage tank locations and design for 2070 (option 3)

Node	Location	Length (ft)	Width (ft)	Volume (acre-ft)
OT00015	Canton St/Quinsig Ave	735	735	124
EI12543B	Garden St.	320	320	24
EI06038B	Grafton St/I-290	280	280	18
QC1988UA	Quinsig/Southbridge St	250	250	14
EI08696U	Summer/Laurel St	240	240	13
SS03826	Shrewsbury St/I-290	225	225	12
WI01256	WI/Quinsig Ave	225	225	12
SS05081	Shrewsbury St/I-290	205	205	10
SC05364	Shrewsbury St/I-290	205	205	10
EI0322OU	Endicott/Millbury St	195	195	9
EI02137U	Harding/Endicott St	165	165	6
WI04808	Endicott/Millbury St	165	165	6
WI05525A	Endicott/Millbury St	145	145	5
EI02745U	Endicott/Millbury St	135	135	4
EI04274B	Endicott/Millbury St	105	105	3
EI01137A	EI/Canton/Millbury St	105	105	3
HC07834	Summer/Laurel St	100	100	2
EI04274A	Endicott/Millbury St	100	100	2
EI012910	Brosnihan Square	95	95	2
SC04725	Shrewsbury St/I-290	90	90	2
SC01218	Shrewsbury St/I-290	85	85	2

3.7.4 Option 4 – Underground storage upstream of QCSOSTF and increased QCSOSTF pumping

Option 4 involves including underground storage at the 21 nodes located upstream and around the Quinsigamond Avenue storage and treatment facility. In addition, additional pump capacity is provided at the QCSOSTF to better control flooding along with flows into the QCSOSTF and UBWWTF. This option employs a combination of increased storage at the QCSOSTF and upstream storage tanks throughout the watershed (Option 2). Expansion of the CSO facility would reduce the frequency and volume of untreated CSO discharges upstream of the plant.

Updates to the current Quinsigamond Avenue facility have recently been proposed by the city of Worcester and CDM Smith as part of a long-term plan to control CSOs in the future. The city of Worcester has recently proposed expansions to both preliminary and primary peak treatment capacity from 119 MGD to 160 MGD. There are also proposed upgrades to the advanced treatment capacity of the plant from 80 MGD to 120 MGD (CDM, 2004). Wet weather flows exceeding the advanced treatment capacity would receive preliminary and primary treatment and disinfection. However, the flow would be routed around the advanced treatment in order to minimize upsets of the biological system during peak flow events. Wet weather flows not receiving advanced treatment would be mixed together with effluent flow from advanced treatment. Two primary clarifiers will also be used as in-line storage of flow during intense rainfall events with high flow.

In order to update QCSOSTF pumping in the SWMM model, the pump curve flows were increased to accommodate a higher capacity at the plant. Flow capacity was increased to pump more flow from node OT00011B to MI00040, which bring further flow out of the QCSOSTF to the Mill Brook to control flooding around the Quinsigamond Avenue area. At Pump1atOT00011B-MI00040, flow capacity was increased from 13.37 cfs to 19.8 cfs at a flow depth of 3.5 feet. At Pump2atOT00011B-MI00011b, flow capacity was increased from 6.68 cfs to 9.9 cfs at a flow depth of 3.75 feet and from 13.37 cfs to 19.8 cfs at a depth of 4.0 feet. These updated were all implemented to accommodate the 100-year storm in 2010. For the purposes of this study, there were no further updates installed in 2040 and 2070. However, it is expected that the city of Worcester will continue to explore options in the future to improve the QCSOSTF and accommodate increased flooding and flows in 2040 and 2070.

3.7.5 Option 5 – Sewer separation

Option 5 employs sewer separation in sections throughout the Worcester CSO system area. Sewer separation involves reconstructing the existing combined sewer system into sanitary and storm sewer systems that are not interconnected. Either a new drainage system is constructed or new sewer pipelines are installed, and the existing combined sewer is used as a sanitary or separate storm drain. If portions of the Worcester system become susceptible to structural failure, they may require complete replacement and two new pipes may be needed for separate sewer and drain systems. Sewer separation can also help eliminate CSOs by diverting all sanitary flow to the UBWWTF. System-wide sewer separation has been considered by the city of Worcester as a potential long-term control plan. For this study, a number of areas were selected to serve as possible sections of the Worcester CSO system that could be separated.

After meeting with representatives from Worcester Department of Public Works, three main sections of the CSO system were selected to be separated in the future under this adaptation strategy. Possible separated subcatchments for each project are included below:

1.) Separating Green Hill Pond and Bell Pond flows

    * North Shrewsbury St.
    * South Shrewsbury St.

2.) Separate areas to 96-inch Shrewsbury St. drain to Lake Ave.

    * Southbridge St. N
    * Southbridge St. S
    * Southbridge St. W
    * Southbridge St. Of
    * Southgate St. (Southgate St. 1, Southgate St. 2)
    *S-Southbridge St. S

3.) Separate portions of Southbridge St. catchments, including Sargent St. and Southgate Pl.

* N. Laurel St. (N. Laurel St. 1, N. Laurel St. 2, N. Laurel St. 3)

* S. Laurel St.

* Thomas St.

* Worcester Center Bl.

* N. Franklin St.

* S. Franklin St.

In order to represent complete disconnection from the CSO system in SWMM, these subcatchments were completely removed from the model. In 2010, sewer separation was performed for all subcatchments listed above, and no further action was completed in terms of sewer separation in 2040 and 2070. Figure 28 shows a map of the Worcester CSO system indicating areas for sewer separation in yellow. The CSO system was modeled with sewer separation under 2010 conditions and all climate change scenarios for 2040 and 2070 conditions.

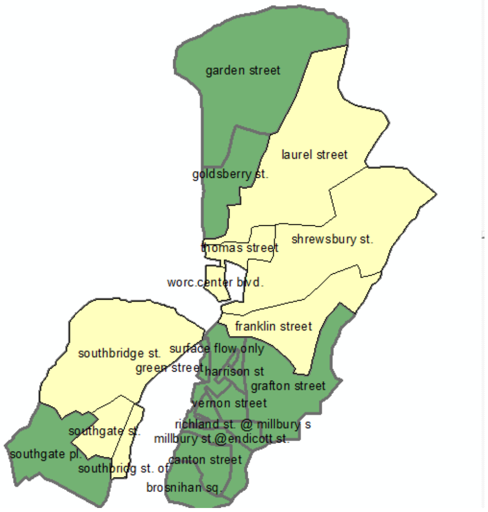


Figure 28: Map of Worcester CSO System showing proposed areas for sewer separation

3.7.6 Option 6 – Low impact development (LID) throughout the watershed

Option 6 employs low impact development (LID) technology throughout the Worcester CSO area. A GIS analysis was performed on the system, which shows that the Worcester CSO area is 44% impervious and 85% of property in the watershed is privately owned. This information presents several challenges for implementing LID. Since the majority of property in the city is owned by homeowners, employing LID will be more difficult since a majority of LID installation will need to be approved by the public. The high percentage of impervious land in the watershed makes it much more difficult to employ certain low impact development technology, including bioretention, vegetated swales, and wetland construction that needs to be implemented in pervious areas.

LID technology is continuing to grow in use in areas all over the country, but it is still a relatively new concept that has not been used to a great extent in Worcester, especially for managing the Worcester CSO system. LID has been proposed for the CSO system in Somerville, MA, and techniques used for Somerville have also been proposed for the Worcester system to provide a comparison of the two case studies. For both systems, the following LID techniques were considered:

* Infiltration trenches / dry wells
* Porous pavement
* Rain barrels
* Green roofs
* Blue roofs
* Bioretention

These LID techniques utilize stormwater drained from building rooftops and impervious areas. As a result, a zoning analysis was conducted on the watershed using GIS software to determine the rooftop area in each subcatchment. In addition, the driveway, parking lot, roadway/pathway, and other impervious land areas as well as pervious land areas were determined for each subcatchment.

Zoning data layers were downloaded from Mass GIS (MassGIS, 2012) and intersected with Worcester CSO subcatchment areas. Each subcatchment was clipped with driveways, roadways, and public and residential buildings in order to determine the total number of impervious units and impervious area in each subcatchment. The total amount of impervious, pervious, and building areas were calculated in each subcatchment and used to determine the maximum area that could drain to each type of LID.

In residential areas, impervious area was divided into buildings and driveways. Each building was designed to include the installation of on-site drywells, rain barrels, green roofs, and blue roofs. The installation of porous pavement is a reasonable LID technique to be used for driveways. A summary of maximum reasonable area to be converted to LID is included in Table 14 as well as values used for SWMM inputs. Percentages of certain LID techniques are determined based on what will be a reasonable percentage for this system and were based on LID inputs used by Lauren Caputo in Somerville to provide a direct comparison of LID impacts for the two case studies.

Table 14: LID inputs for residential areas

Buildings

60% on-site drywells	Modeled as infiltration trenches (volume = 50.3 cubic feet)
10% rain barrels	Modeled as rain barrels (volume = 9.4 cubic feet)
10% green roofs	Modeled as bioretention cells (surface storage depth = 1 inch, soil thickness = 4 inches, storage height = 1 inch, area = 2000 square feet)
10% blue roofs	Modeled as rain barrels (height = 2 inches, area = 2000 square feet)
10% no change to drainage of rooftops	No additional modeling

Driveways

25% porous pavement	Modeled as porous pavement cells (pavement thickness = 4 inches, storage thickness = 23 inches, area = 1000 square feet)
75% no change to driveway area	No additional modeling

For public, commercial, and industrial areas, impervious areas were divided into buildings, parking lots, and roadways for LID analysis. Each building in the subcatchments includes the installation of on-site drywells, green roofs, and blue roofs. The installation of porous pavement was used for parking lots and roadways. In addition, LID can be installed in each subcatchment to store stormwater in grasslands and shrubs. A summary of maximum reasonable areas to be converted to LID is included in Table 15 as well as values used for SWMM inputs. Percentages of certain LID techniques are determined based on what will be a reasonable percentage for this system.

Table 15: LID inputs for public, commercial, and industrial areas

Buildings

50% on-site drywells	Modeled as infiltration trenches (volume = 50.3 cubic feet)
20% green roofs	Modeled as bioretention cells (surface storage depth = 1 inch, soil thickness = 4 inches, storage height = 1 inch, area = 2000 square feet)
20% blue roofs	Modeled as rain barrels (height = 2 inches, area = 2000 square feet)
10% no change to drainage of rooftops	No additional modeling

Parking Lots and Roadways

75% porous pavement	Modeled as porous pavement cells (pavement thickness = 4 inches, storage thickness = 23 inches, area = 1000 square feet)
25% no change to parking lots and roadway area	No additional modeling

Grass/Shrubs/Parks

15% bioretention	Modeled as bioretention cells (underdrain coefficient, C = 0.20 in/hr, surface depth = 6 inches, soil thickness = 18 inches, storage thickness = 12 inches, area = 1000 square feet)
85% no change to pervious area	No additional modeling

LID was implemented as a time-varying process under Option 6, meaning that LID was implemented in stages throughout the watershed in 2010, 2040, and 2070. For 2010, 30% of the maximum amount of LID was installed in the SWMM model. In 2040, 50% of the maximum amount of LID was installed, and the remaining 20% of LID was installed to accommodate flows in 2070 design storms. The model was simulated under Option 6 under 2010 design storms along with 2040 and 2070 design storms for all climate change scenarios.

3.7.7 Option 7 – Combination of LID and sewer separation

Option 7 employs a combination of LID throughout the watershed and sewer separation (Options 5 and 6). The maximum amount of feasible area to incorporate LID from Option 6 was also used for this option to better determine the effects of sewer separation versus LID. Similar to Option 5, all sewer separation was conducted in 2010 to accommodate flooding and increased flow to the treatment facilities in 2040 and 2070. In 2010, 30% of the maximum amount of LID was installed in SWMM to the remaining subcatchments in the system. In 2040, 50% of the maximum amount of LID was installed and the remaining 20% of LID was installed for the 2070 storms. The model with the combination of two strategies was simulated under 2010 design storms along with 2040 and 2070 design storms for all climate change scenarios.

The following options were each analyzed specifically for their performance of meeting the design goals for this study, which include decreasing hazardous flooding and no increases in flow through the QCSOSTF and UBWWTF. Both costs and benefits of each option were compared using a design cost and net benefits approach. These results are all displayed and discussed in detail in Chapter 4.

4.0 RESULTS

This section presents results from model calibration and model simulations, which include total flooding and flow volumes through the QCSOSTF and UBWWTF for all seven adaptation options under all climate change scenarios and storm intensities for 2012, 2040, and 2070. The performance of each option was compared using two different cost analysis approaches: a design cost approach and a net benefits approach. Each approach uses risk analysis and an expected value approach to determine the most effective robust strategy to manage stormwater under future climate change scenarios. In the design costs approach, costs of strategies that met design goals were compared for each climate change scenario to determine the most cost-effective adaptation option. Similarly, a net benefits approach was used to identify the most beneficial strategy. Results for each cost analysis method are included in this section, including all constant and variable costs and benefits.

4.1 Calibration Results

Results for the June 2001 storm for meters 2, 12, and 15 are shown in Figures 29-37 with plots of total inflow, depth, and rainfall over the duration of the June 2-4, 2001 storm. Meter 2 is located near Brosnihan Square on the Western Interceptor of the sewer system along Quinsigamond Avenue. Figure 29 shows that model results are very consistent with the observed flows at this particular location. The water depths displayed by the model also closely match the observed data (Figure 30). The plot of total flow shows two areas of peak flow that is consistent with areas of peak rainfall during the storm. The plot of meter 12 flows and depths also shows consistency between the model and observed data (Figures 32 and 33). Finally, Figures 56 and 36 display the model results for inflow and depth at flow meter 15 compared with the observed data. Figure 37 shows the rainfall distribution for the storm for meter 15. Similar to the other two meters, the model matches very well with the observed data for both flowrate and depth at this location. Similar analyses were completed for all flow meters in the system, and these plots are provided in the Appendix. Figures 38-40 show observed results compared to model results for QCSOSTF discharge for the June 2-4, 2001 storm. Similar to results of the metered flows in 2001, model inflow to the QCSOSTF matches the observed flow.

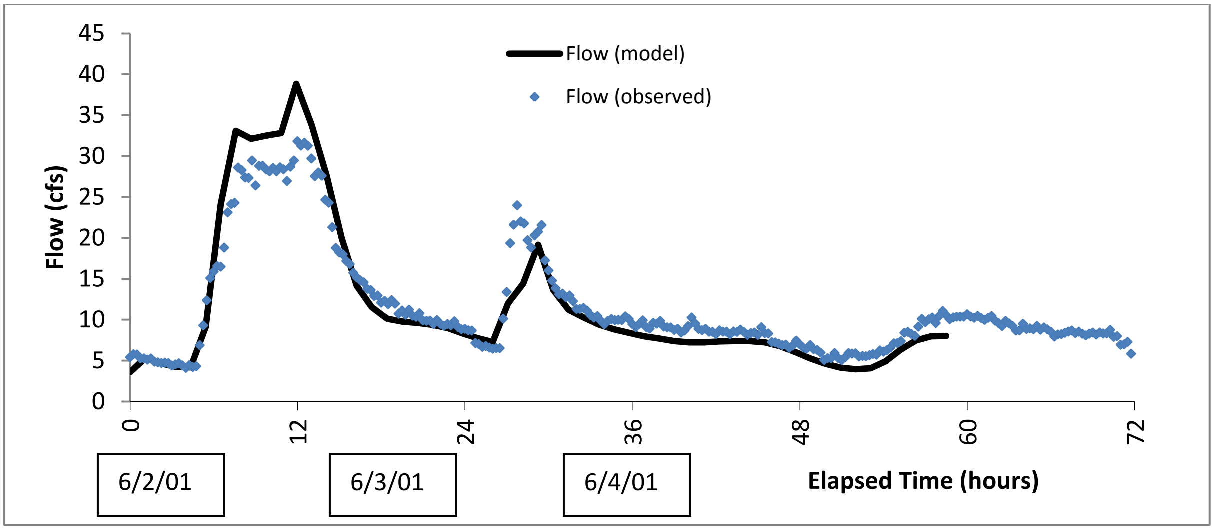


Figure 29: Meter 2 Flows June 2-4, 2001

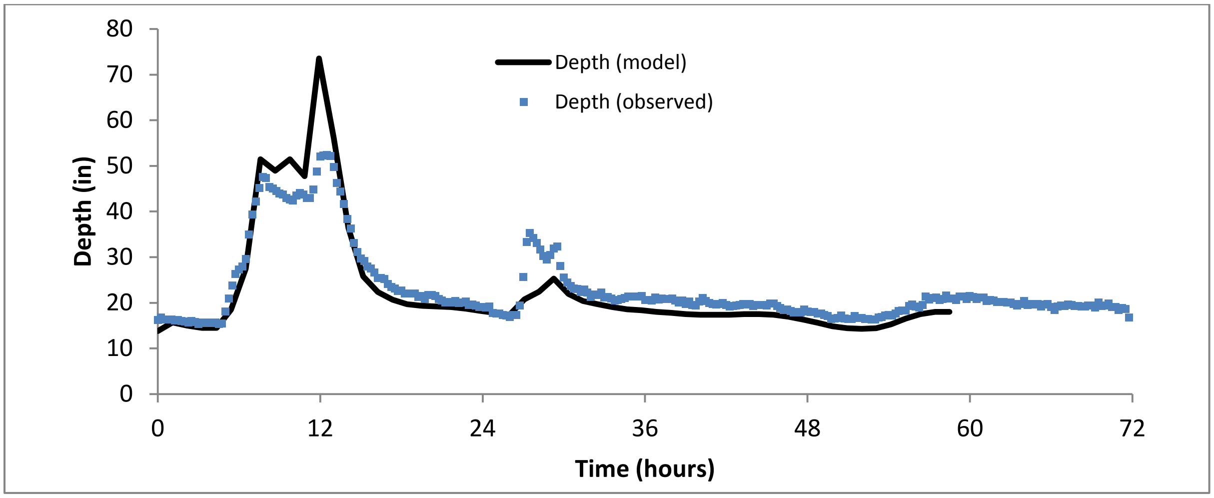


Figure 30: Meter 2 Water Depths June 2-4, 2001

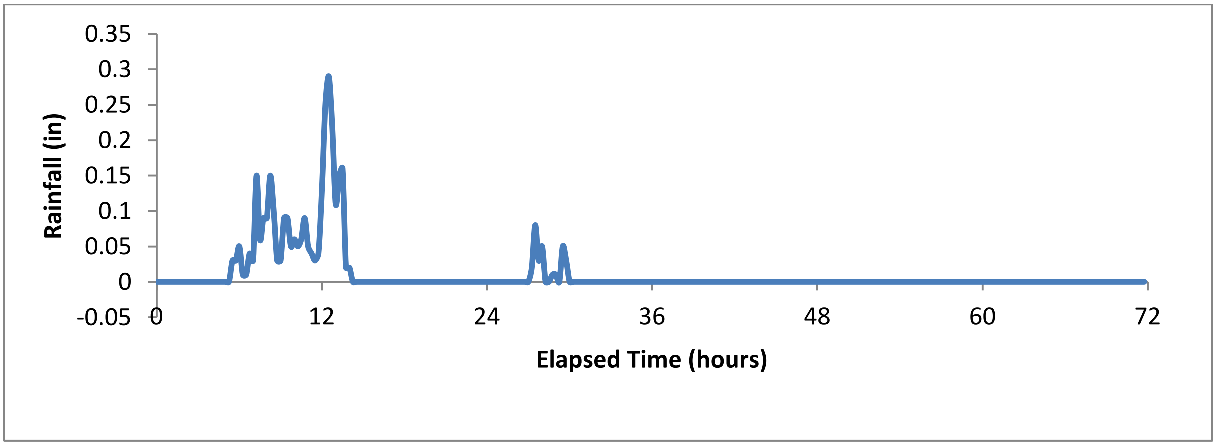


Figure 31: Meter 2 Rainfall June 2-4, 2001

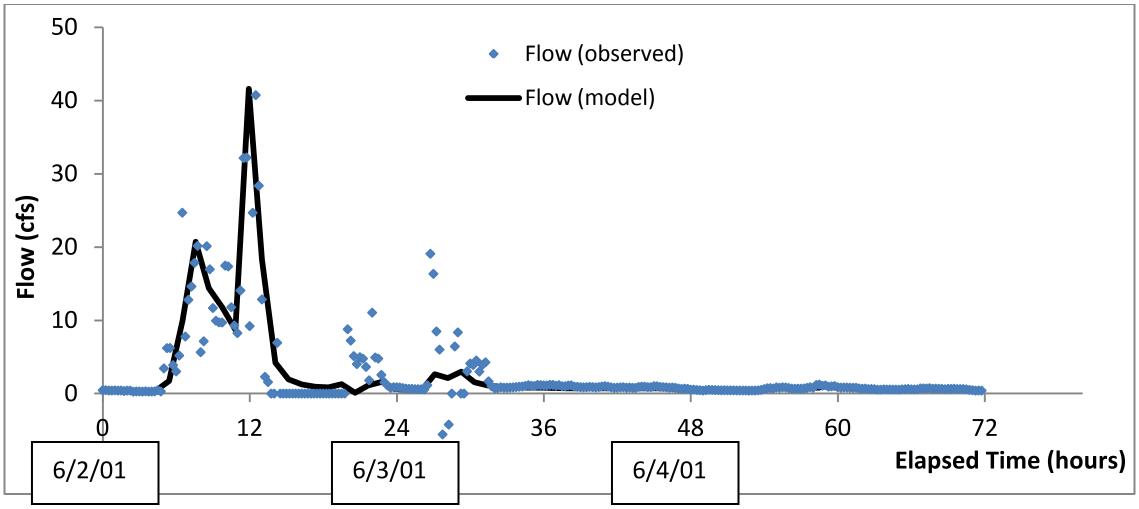


Figure 32: Meter 12 Flows June 2-4, 2001

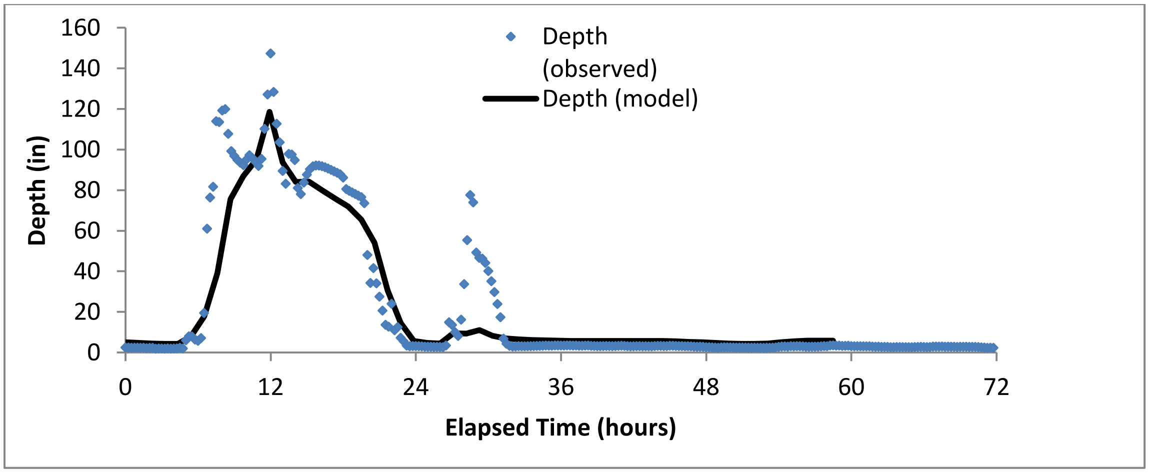


Figure 33: Meter 12 Water Depths June 2-4, 2001

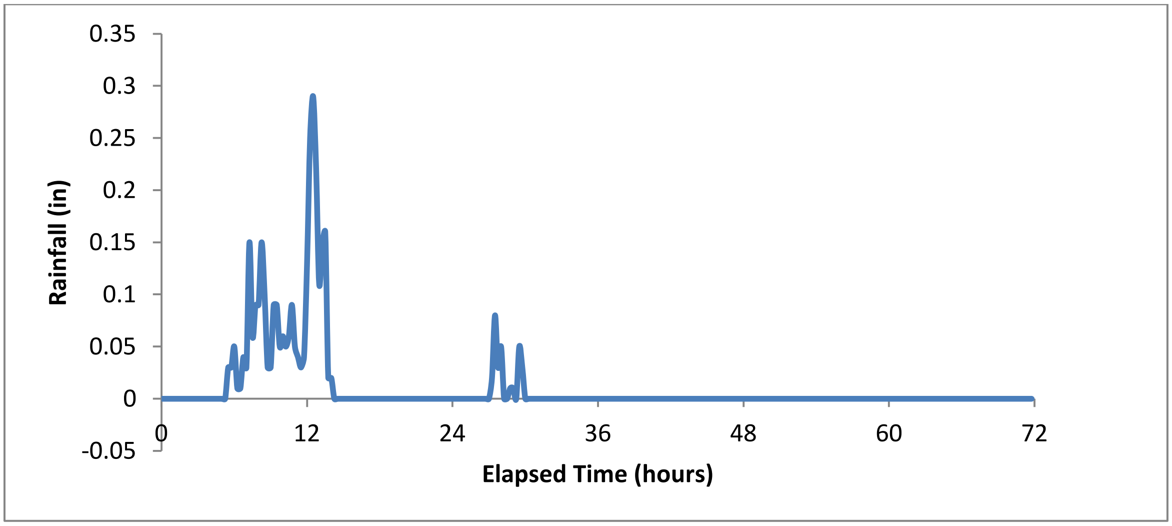


Figure 34: Meter 12 Rainfall June 2-4, 2001

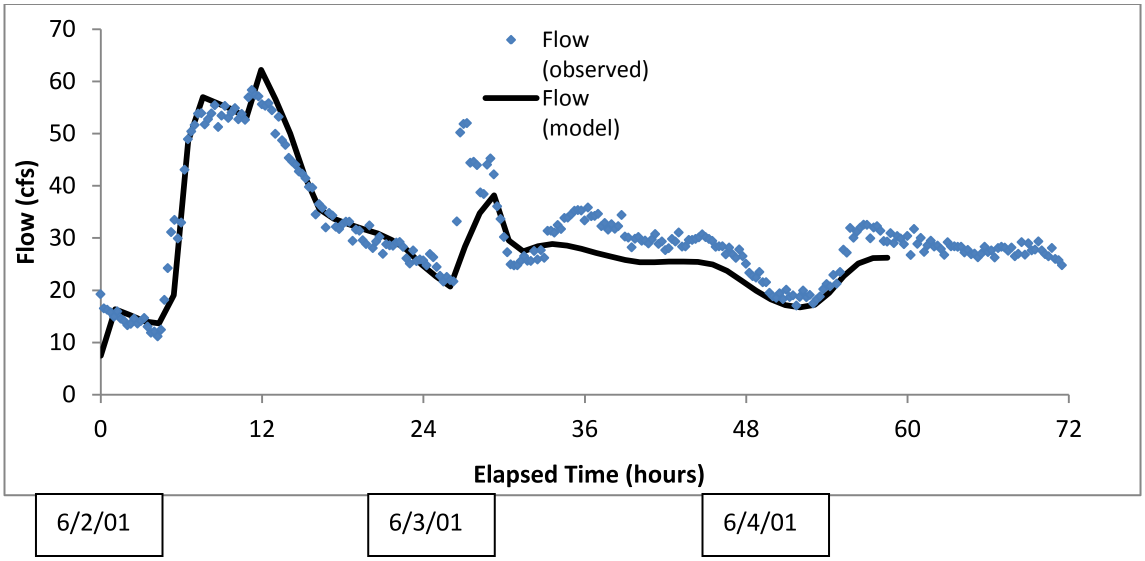


Figure 35: Meter 15 Flows June 2-4, 2001

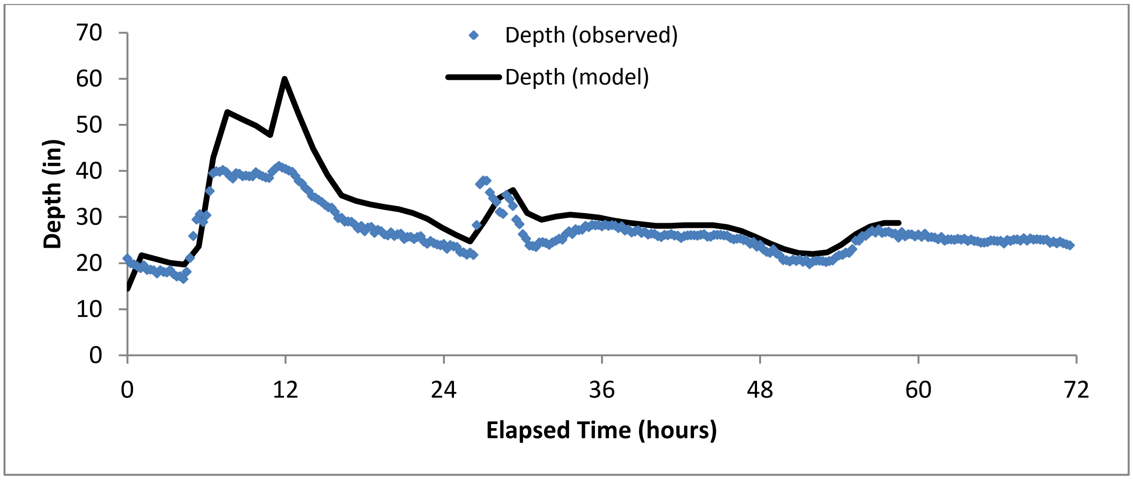


Figure 36: Meter 15 Water Depths June 2-4, 2001

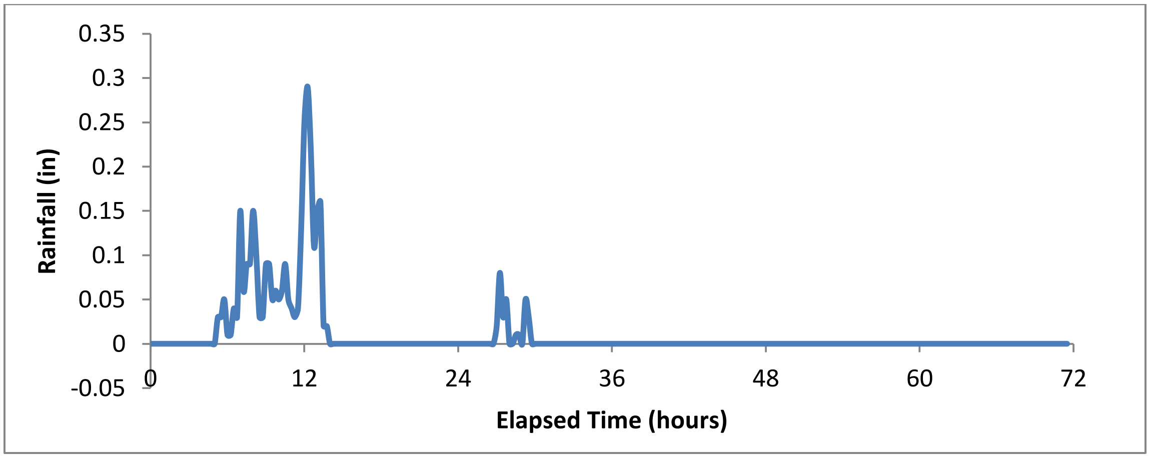


Figure 37: Meter 15 Rainfall June 2-4, 2001

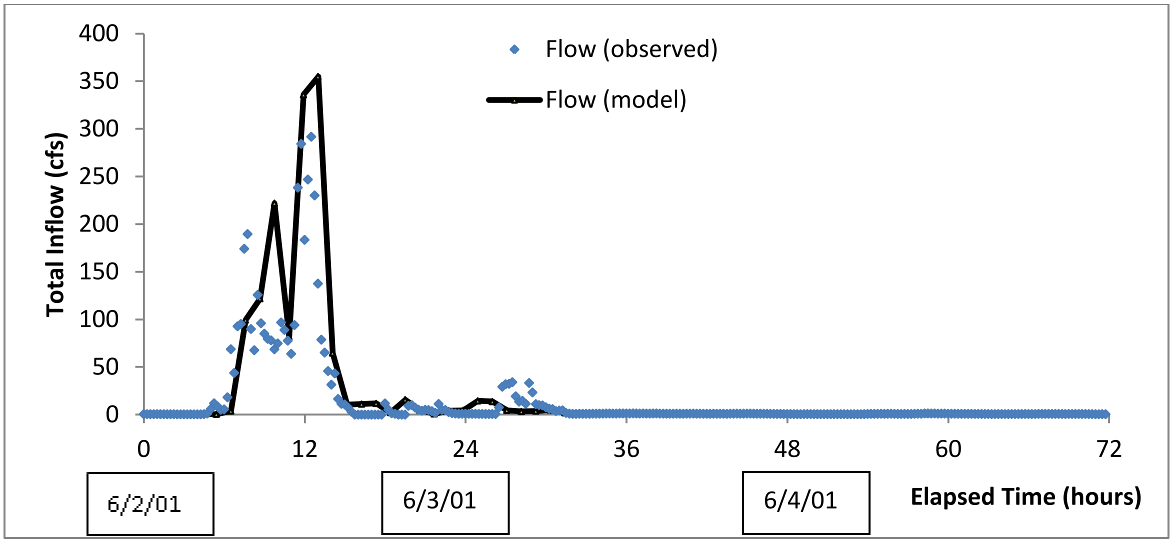


Figure 38: QCSOSTF Flows June 2-4, 2001

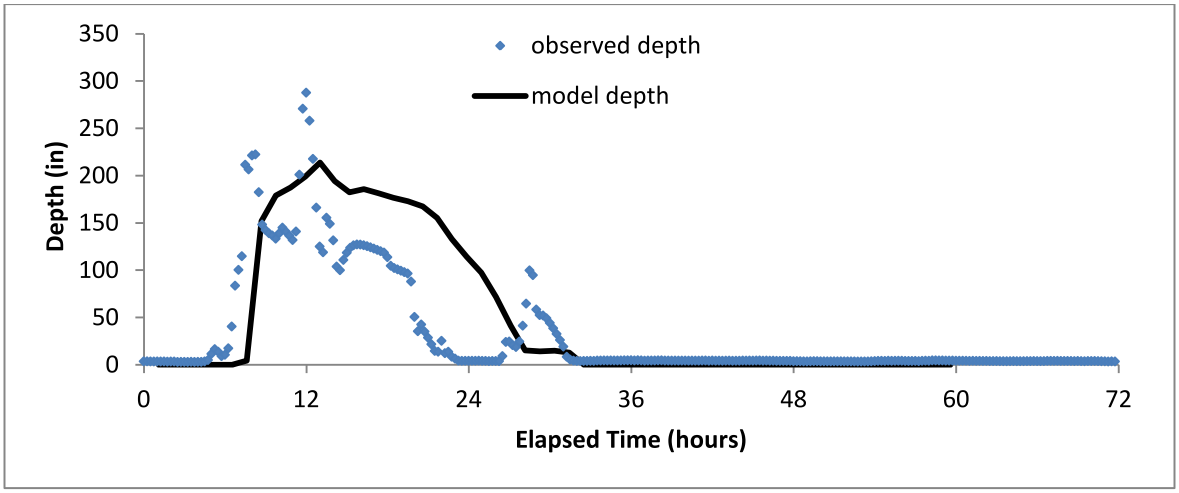


Figure 39: QCSOSTF Water Depths June 2-4, 2001

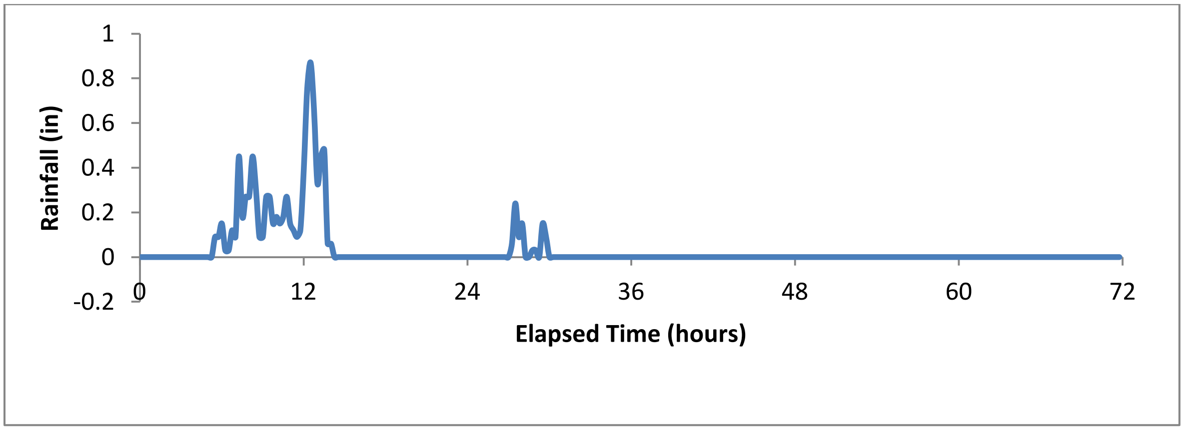


Figure 40: QCSOSTF Rainfall June 2-4, 2001

For the July 2008 storms, the model predicts the runoff volume and dry weather flows relatively well. The effluent discharge is still low compared to the observed data, but the model does make improvements with new control rules compared to the current 2001 model. New control rules for the system include lowering the depths at the QCSOSTF storage tanks at which flow is allowed to discharge. Control depths were decreased from 12’, 15, and 17’ to 8’, 10’, and 17’ (See Chapter 3). The model performs similarly for the August and September storms, with the effluent discharge still low, but improvements have been made. It was decided that these final control rules would be implemented into the model, and results were plotted for each of the three storms in 2008. Figures 41, 42, and 43 display plots that compare the model and observed effluent discharges for the July, August, and September storms, respectively. These plots show that improvements have been made to the model after calibration for the July 2008 storm. While the shape of the curve is still similar for both the observed and modeled flows, there are more points in the model where flow is much higher with the new control rules. As a result, the total discharge from the QCSOSTF increased from 6.031 MG to 9.567 MG for the July 2008 model flows for the old and new control rules, respectively (See Tables 6-8). The results do not show that there are significant improvements in the August and September storms, although the total volumes in the summary tables above do show that there are some improvements in the model for the overall total flows of these storms. Plots of dry weather and wet weather flows for the new control rules are attached in the Appendix.

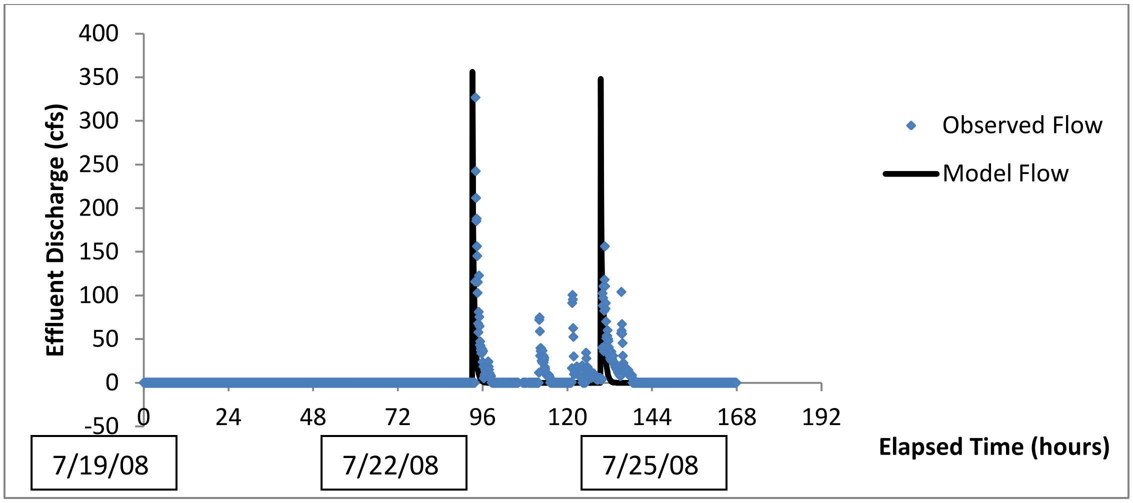


Figure 41: Effluent Discharge July 19-25, 2008 (New Control Rules)

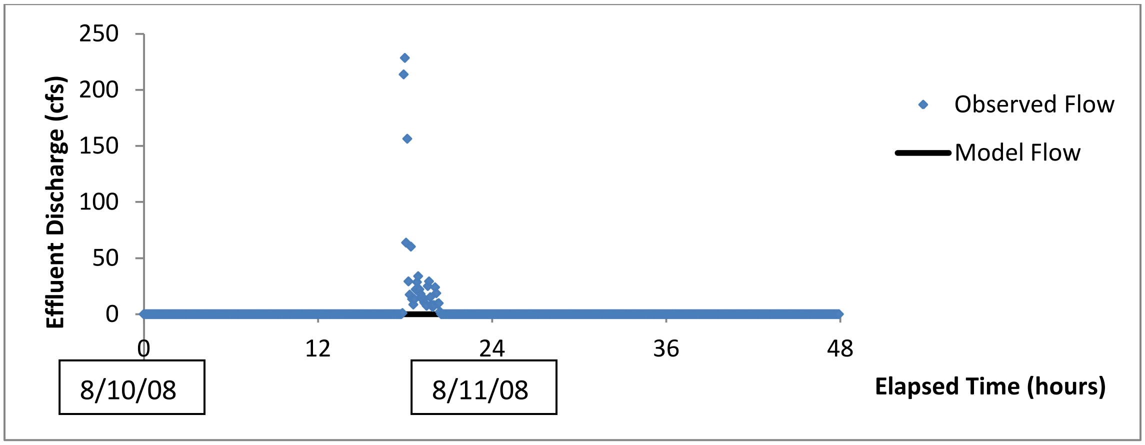


Figure 42: Effluent Discharge August 10-11, 2008 (New Control Rules)

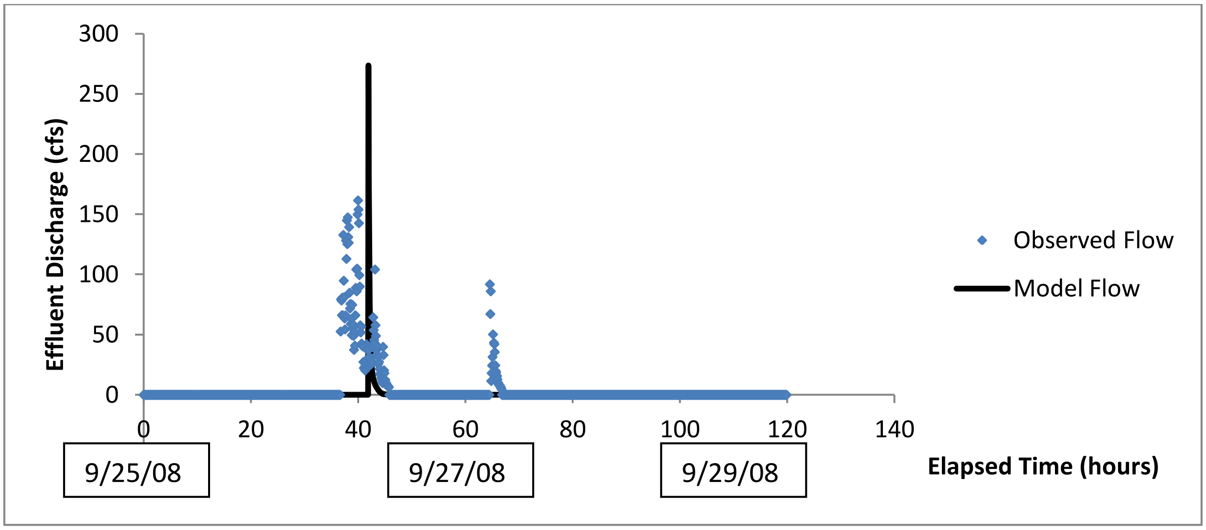


Figure 43: Effluent Discharge September 25-29, 2008 (New Control Rules)

4.2 Model Simulation Results

The total hazardous flooding, QCSOSTF flow volume, and UBWWTF flow volume were determined for each adaptation option, and these results are presented in Figures 44-64. One bar chart is presented for each of three performance metrics. Under the no action alternative, hazardous flooding totals are as high as around 180 MG during the 100-year storm in 2040. Discharge flow volume from the QCSOSTF is as high as around 130 MG for the 100-year storm in 2040, and UBWWTF flow volume totals are as high as over 300 MG. It was observed from the model results that the 10-year 2040 storm under a high climate scenario yielded the highest values for hazardous flooding and flows out of both the QCSOSTF and UBWWTF. As expected, flows and flooding values are also very high for the 100-year storm in 2070 under a high climate change scenario. Hazardous flooding is negligible for all 3-month storms, and there are negligible outflows from the QCSOSTF for storms in 2012 and 2040.

Under Option 2 (underground storage) hazardous flooding is significantly reduced throughout the watershed for all 10-year storms, and flooding is also decreased for 100-year storms under all three climate change scenarios. Flows to the UBWWTF are approximately the same as no action but flows do not significantly increase. Similarly, for the option of isolated upstream storage hazardous flooding and QCSOSTF discharge flows are significantly decreased compared to the baseline scenario but UPWWTF flows do not decrease and are about the same as the option of no action. Option 2, option 4 (upstream storage and QCSOSTF pumping), and option 5 (sewer separation) all meet the design goals of decreasing hazardous flooding and avoiding the increase of UBWWTF outflows. However, the other adaptation options do not meet all these design goals. Option 3 involves storage upstream of the QCSOSTF where hazardous flooding volumes are greater than 0.5 MG. While hazardous flooding and QCSOSTF flows are decreased under this option, flows through the Upper Blackstone facility are increased, so this option does not meet the design goal of avoiding the increase of UBWWTF flows. Option 6 involves installing LID throughout the Worcester CSO system, and both QCSOSTF and UBWWTF effluent flow volumes are increased for this option. Finally, UBWWTF outflows are increased for option 7 compared to the baseline scenario, which involves combining sewer separation and the installation of LID throughout the watershed. Table 16 provides a summary table of each adaptation option that indicates whether each design goal is met in reducing hazardous flooding and avoiding increased QCSOSTF discharge flows and UBWWTF discharge flows.

It can also be noted from the simulation results that for the 10-year 2040 storms, the effluent discharge flows from the Quinsigamond facility are not the highest for the high climate scenario compared to the moderate and low scenarios. For each option the 10-year 2040 QCSOSTF flows are approximately the same for the three climate change scenarios, and in some cases the flows for the low scenario are actually greater than the high scenario. These results may be explained by the nature of this storm, which is of high intensity but not high enough to cause additional treatment at the QCSOSTF. In addition there is less variability expected between the three climate scenarios in 2040 since high flows can be expected for all scenarios. However, a more intense storm like the 100-year storm will lead to a greater need for treatment at the QCSOSTF and more variability in outflows for high, low, and moderate climate change. Results for all options are presented in Figures 44-64 for each design storm and climate scenario (H = high scenario, M = moderate scenario, L = low scenario). Summary tables are provided in the Appendix that display totals for hazardous flooding, QCSOSTF outflows, and UBWWTF outflows for all design storms under all seven adaptation options.

Table 16: Summary of BMP options and design goal performance

	Performance Metric		
Option	Hazardous Flooding	Flow out of QCSOSTF	Flow out of UBWWTF
Option 1 - No Action	No	No	No
Option 2 - Storage throughout watershed	Yes	Yes	Yes
Option 3 - Upstream storage	Yes	Yes	No
Option 4 - Upstream storage and QCSOSTF pumping	Yes	Yes	Yes
Option 5 - Sewer Separation	Yes	Yes	Yes
Option 6 - LID	Yes	No	No
Option 7 - LID and Sewer Separation	Yes	Yes	No

Option 1 – No Action

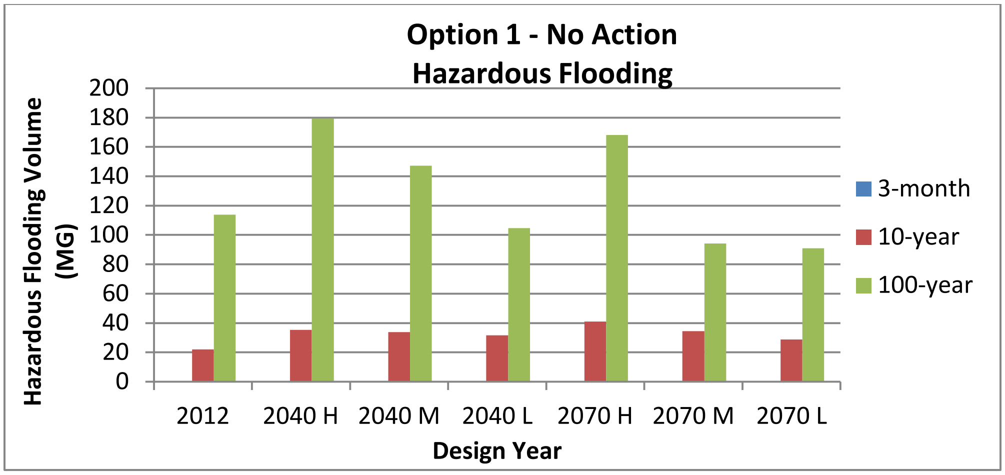


Figure 44: Hazardous flooding for option 1

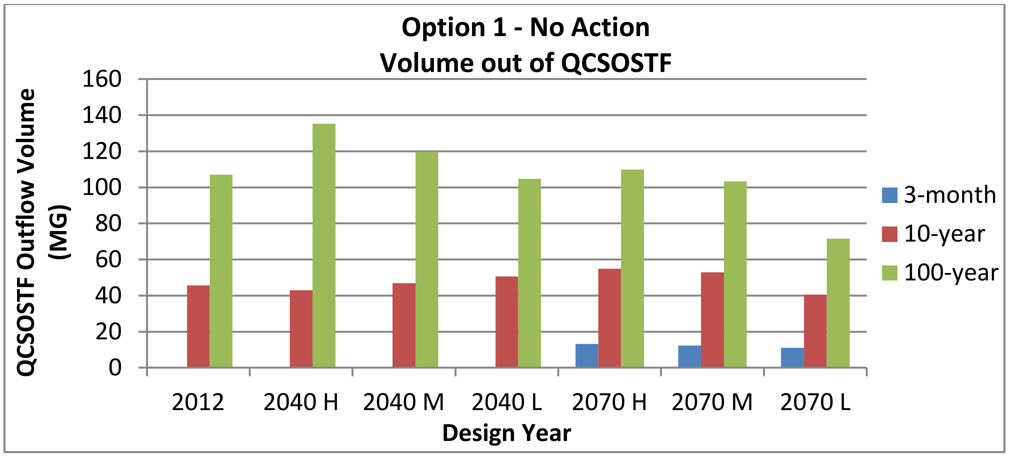


Figure 45: Volume out of QCSOSTF for option 1

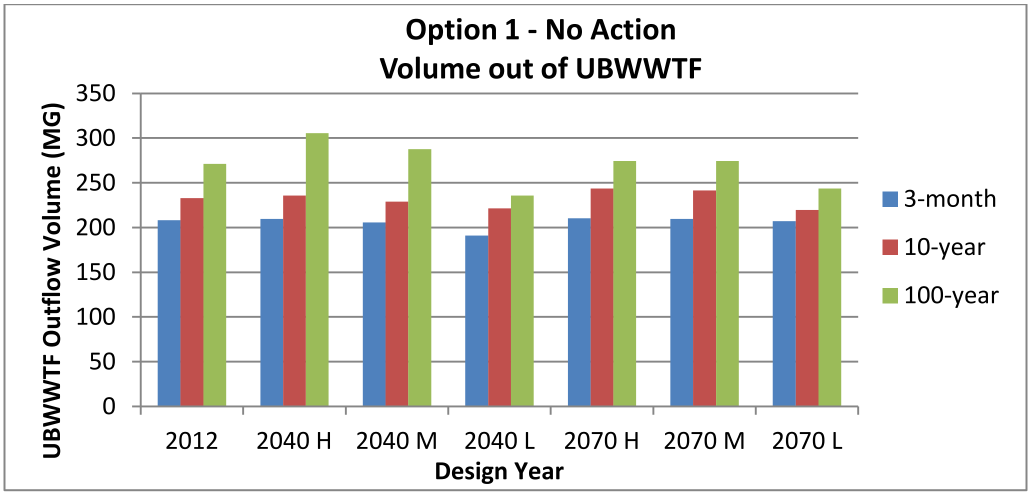


Figure 46: Volume out of UBWWTF for option 1

Option 2 – Underground storage throughout the watershed

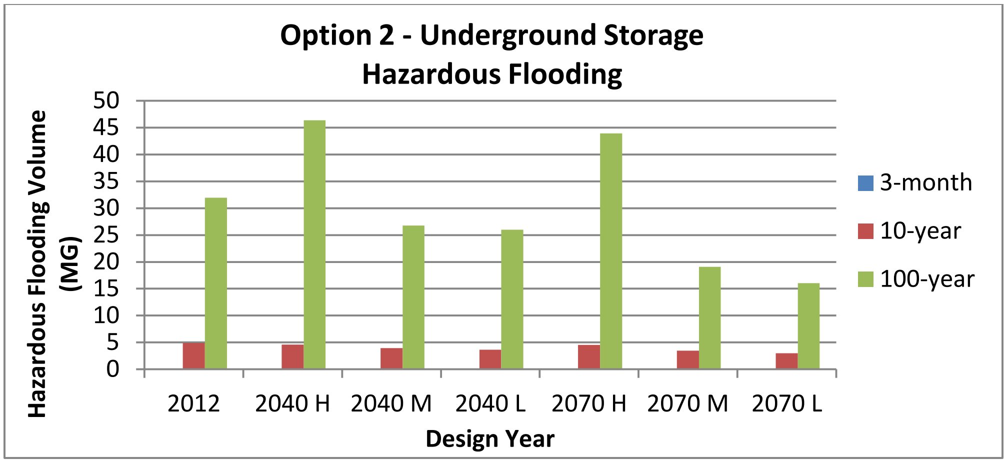


Figure 47: Hazardous flooding for option 2

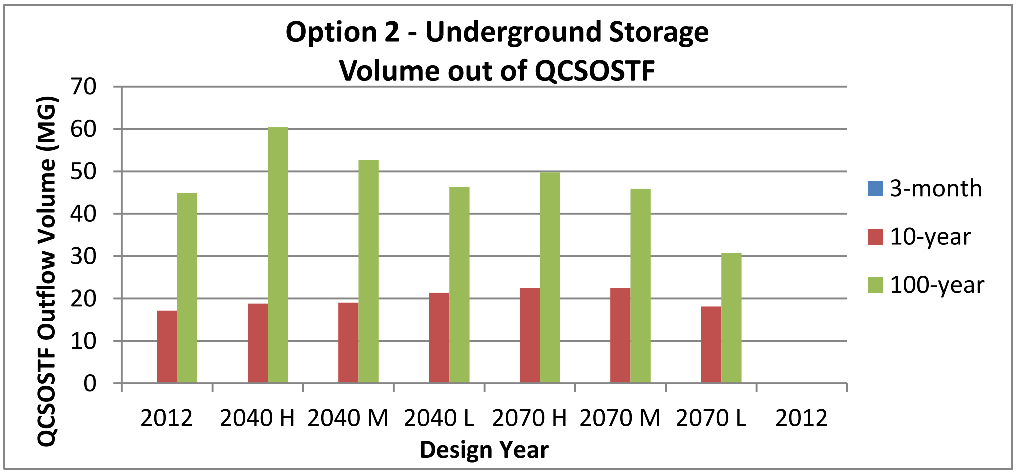


Figure 48: Volume out of QCSOSTF for option 2

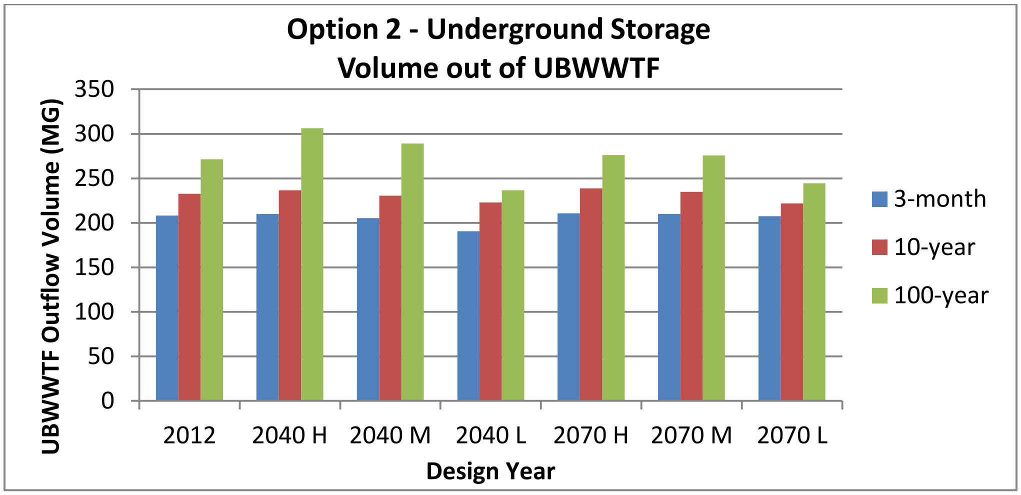


Figure 49: Volume out of UBWWTF for option 2

Option 3 – Underground storage upstream of QCSOSTF

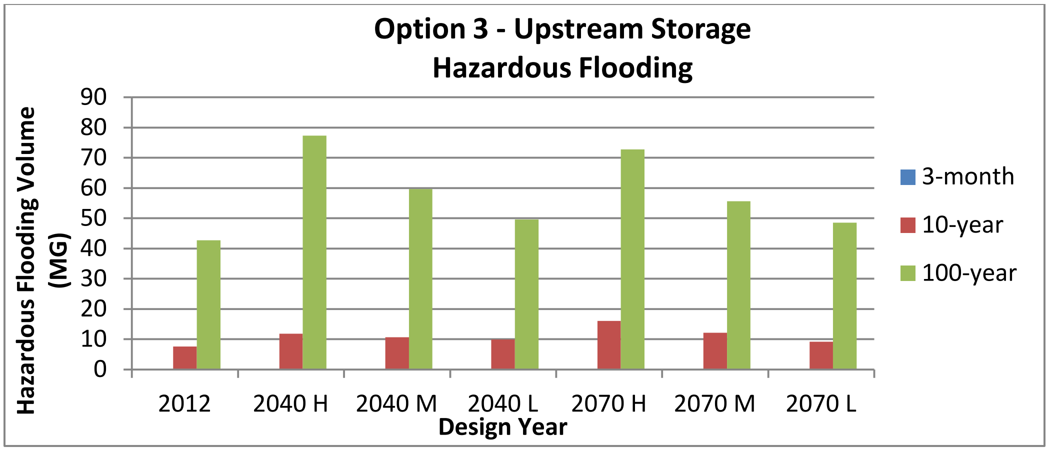


Figure 50: Hazardous flooding for option 3

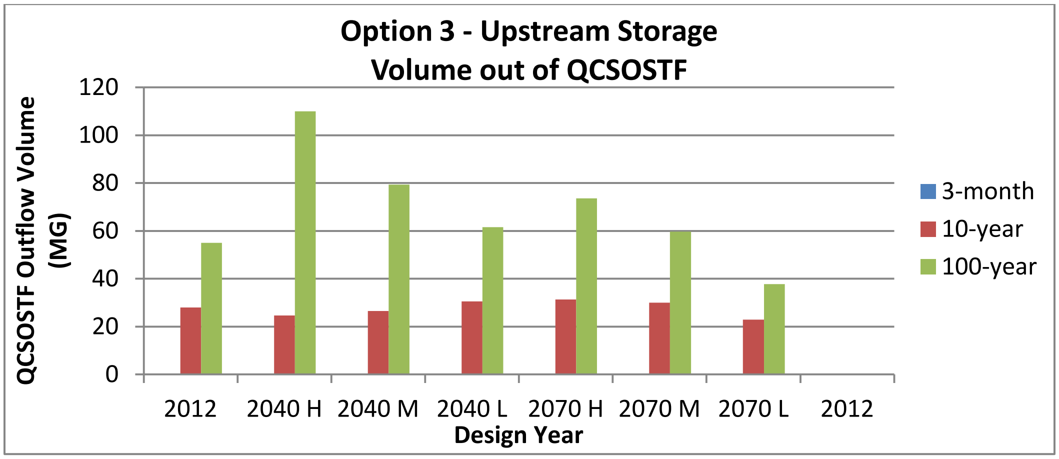


Figure 51: Volume out of QCSOSTF for option 3

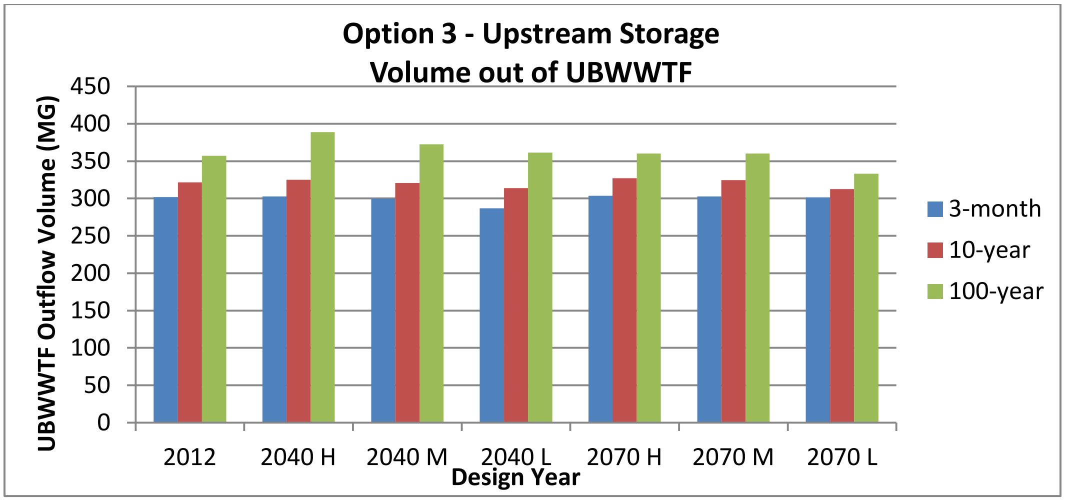


Figure 52: Volume out of UBWWTF for option 3

Option 4 – Underground storage upstream of QCSOSTF and increased QCSOSTF pumping

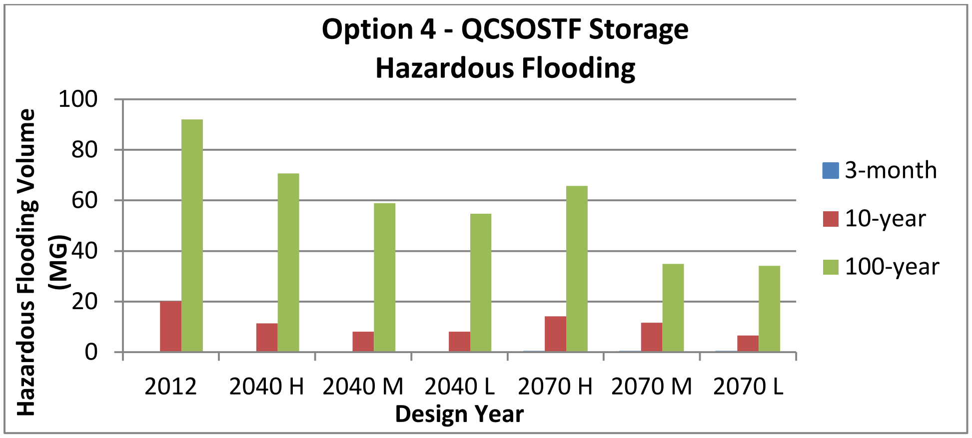


Figure 53: Hazardous flooding for option 4

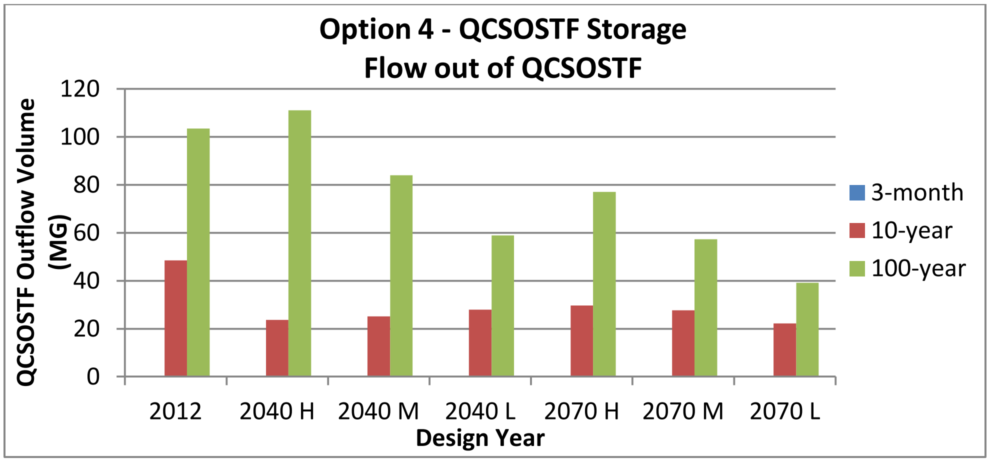


Figure 54: Volume out of QCSOSTF for option 5

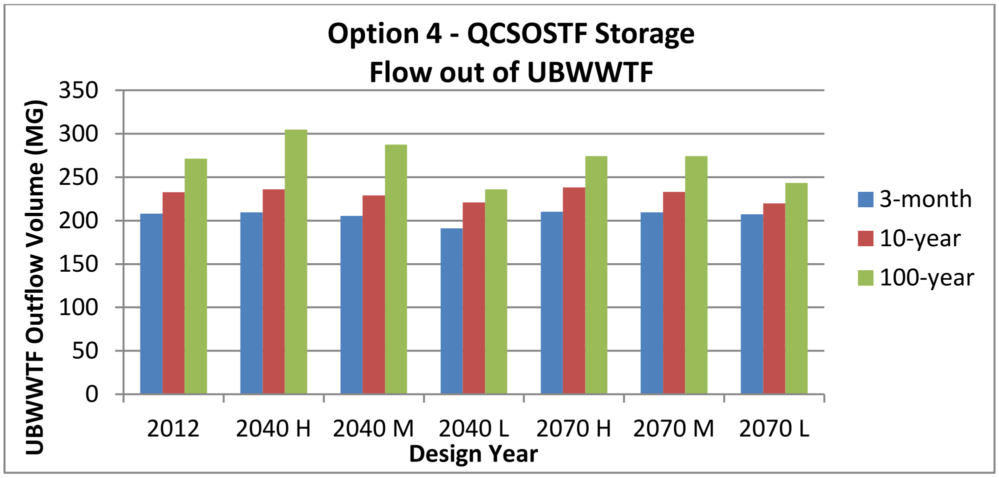


Figure 55: Volume out of UBWWTF for option 4

Option 5 – Sewer Separation

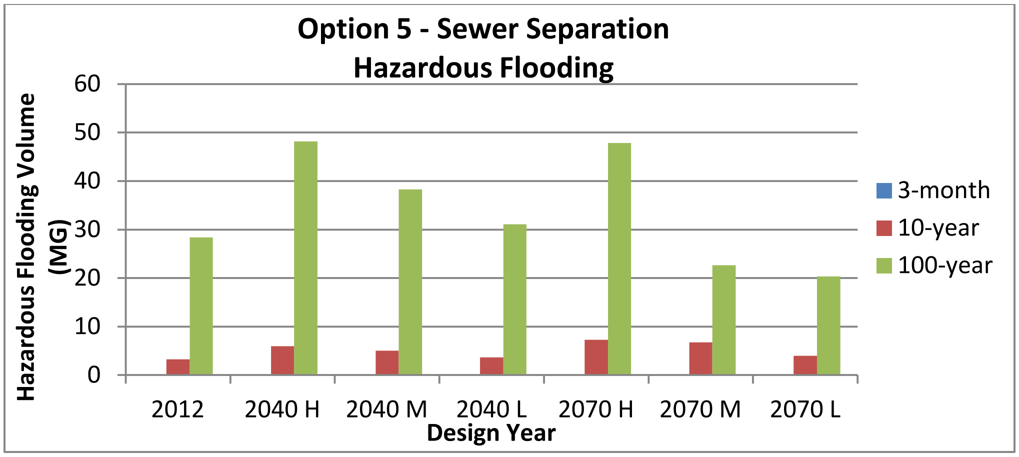


Figure 56: Hazardous flooding for option 5

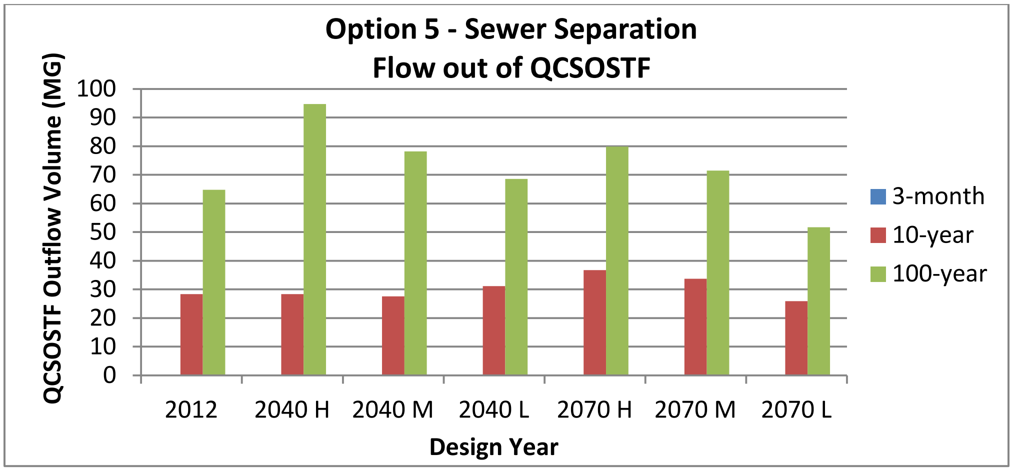


Figure 57: Volume out of QCSOSTF for option 5

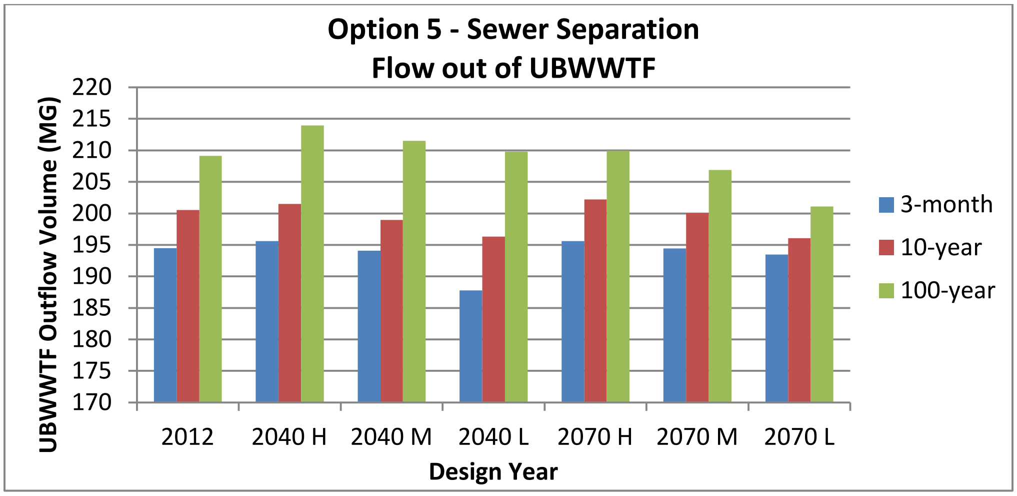


Figure 58: Volume out of UBWWTF for option 5

Option 6 – LID throughout the watershed

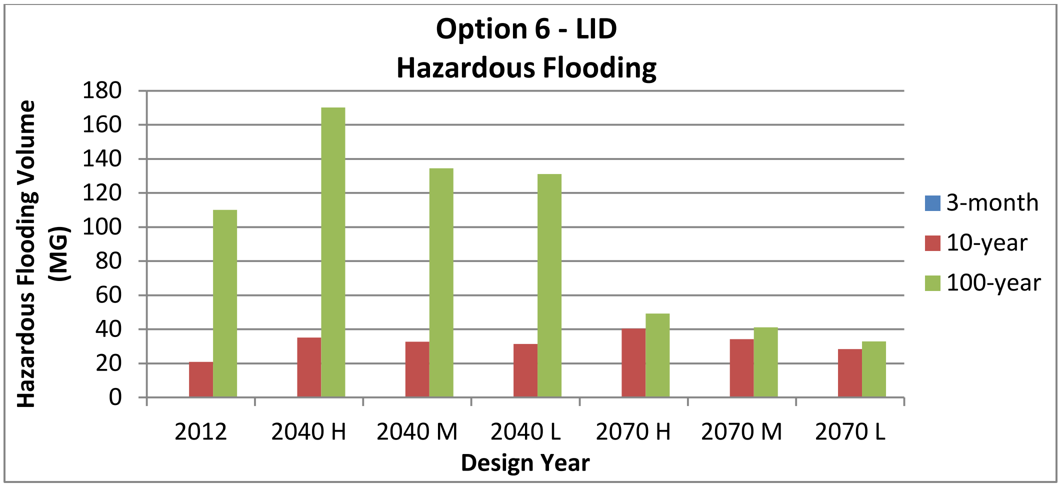


Figure 59: Hazardous flooding for option 6

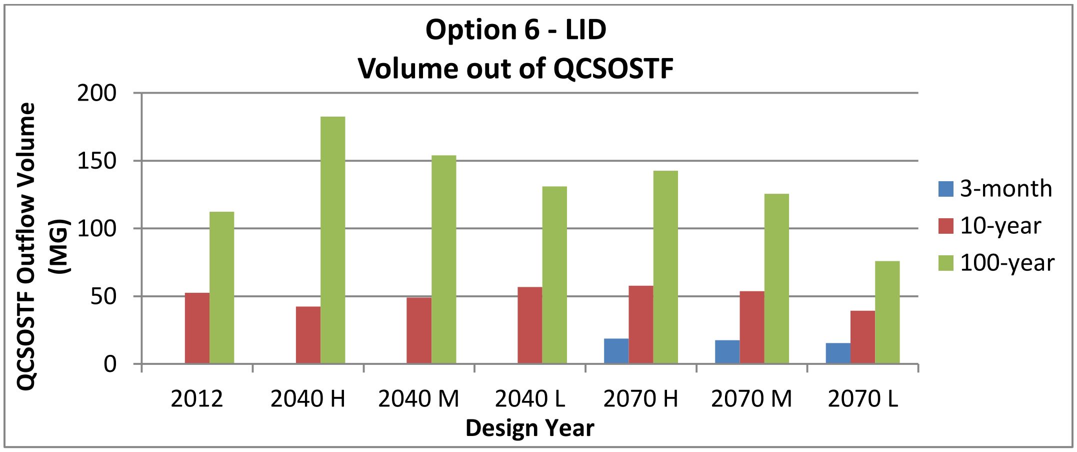


Figure 60: Volume out of QCSOSTF for option 6

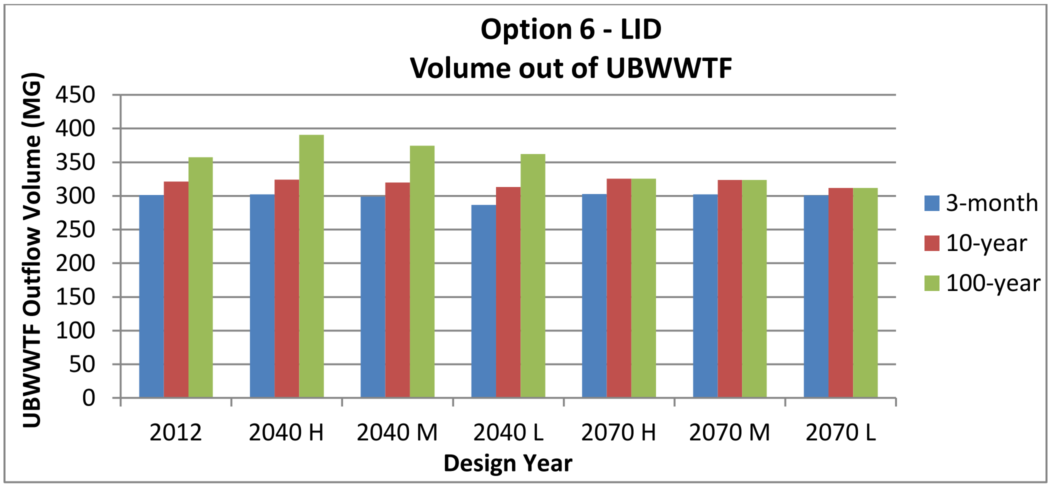


Figure 61: Volume out of UBWWTF for option 6

Option 7 – Combination of LID and sewer separation

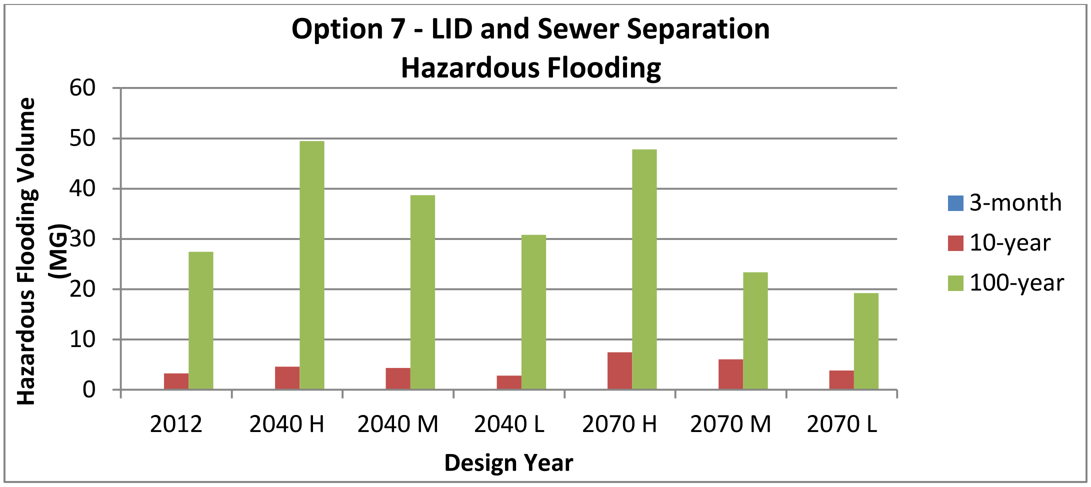


Figure 62: Hazardous flooding for option 7

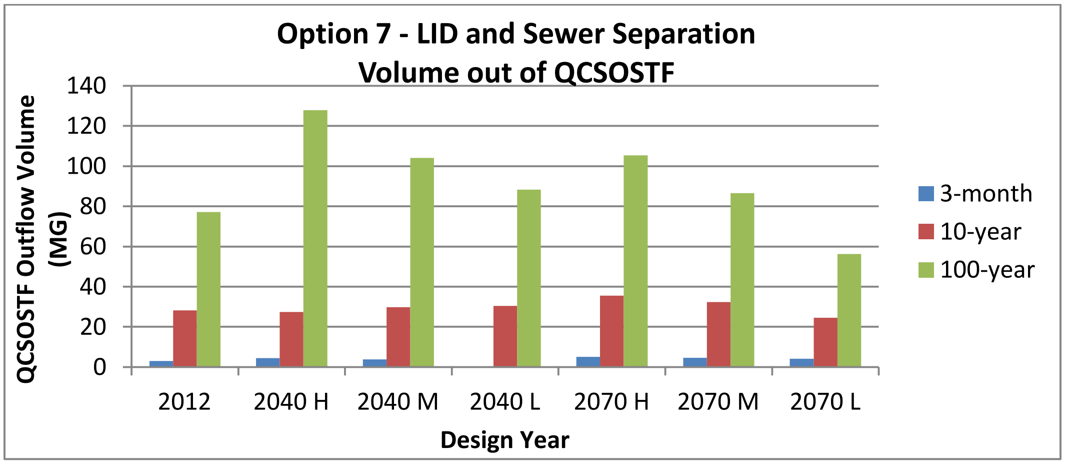


Figure 63: Volume out of QCSOSTF for option 7

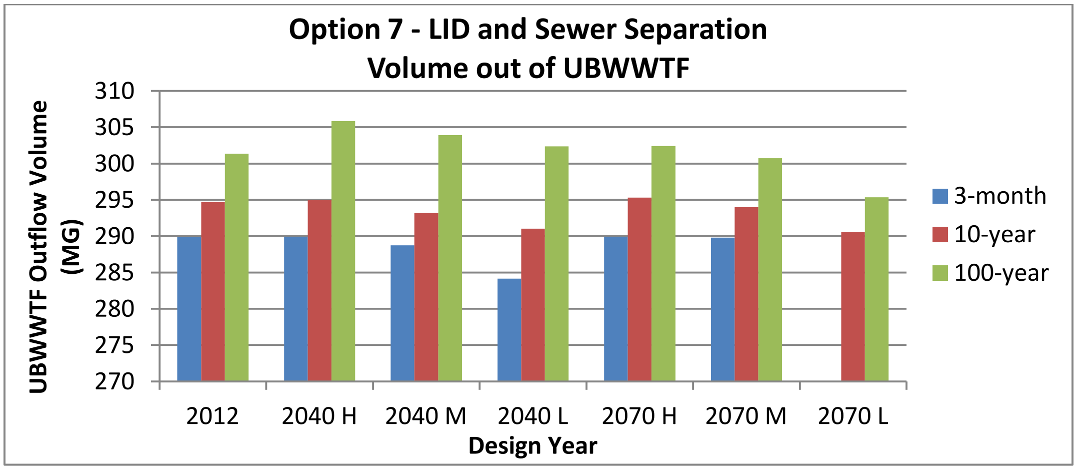


Figure 64: Volume out of UBWWTF for option 7

4.3 Cost Analysis - Design Cost Approach

A design cost approach was used as one technique to analyze the different stormwater management options, and the most cost-effective strategy was determined as the option with the lowest design cost. The design cost for each strategy is made up of constant costs and present variable costs. Constant costs include construction, design and engineering (D&E), and operation and maintenance (O&M) costs. Life-cycle and present worth considerations were also taken into account to find a total present cost in 2010. Variable costs include the cost of treatment at both the Quinsigamond Avenue and Upper Blackstone treatment facilities. The design cost approach is only useful for strategies that meet the goals of all three performance metrics. This means only the options that reduce hazardous flooding and don't increase flows though the UBWWTF and QCSOSTF were considered. Only these options were considered since they are the most beneficial options for Worcester in meeting all performance metrics goals. Since both costs and benefits are analyzed in the net benefits approach, all adaptation options are compared for this approach. Options 2, 4, and 5 were considered for the design cost approach. The design cost approach is described in detail below and described specifically for each adaptation option.

Constant Costs

Constant costs were estimated for 2010 using present worth formulas (Revelle et al., 2004). The interest rate is assumed to be 2.3 %, which is based on information from the Engineering News Record (ENR) construction cost index (ENR, 2012).

$$P = \frac{F}{(1+i)n} \qquad \text{(Equation 1)}$$

P = present value, in 2010 ($)

F = future value ($)

n = number of years annually compounded

i = interest rate (decimal)

$$P = A\left(\frac{(1+i)^n - 1}{i(1+i)^n}\right) \quad \text{(Equation 2)}$$

A = annual amount ($/year)

Variable Costs

Variable costs were estimated and converted to present values in 2010 for each design storm. Expected values were calculated for each year and climate change scenario using the concept of risk analysis. The expected value is the weighted average of all possible values for the variable costs, and this value was estimated by summing the products of all costs and the expected frequency they will occur in a given year.

$$\text{EV} = \int_0^4 f(x)dx \quad \text{(Equation 3)}$$

EV = expected value cost ($)

f(x) = PV = present value cost ($)

x = EEY= number of expected events per year

The number of expected events per year represents an expected frequency for each storm. For example, a 100-year storm is expected to occur once every 100 years, so EEY = 1/100 or 0.01. However, a 3-month storm is a storm that is expected to occur 4 times every year in an average year, so EEY= 4. Expected values were estimated by fitting two linear curves to present value cost data, and the area under the curve was determined as the expected value cost. Expected values were calculated for 2010 and the low, moderate, and high climate change scenarios in 2040 and 2070. After calculating expected value costs, present value expected value (EVPV) costs were determined for low, moderate, and high climate change scenarios by estimating the expected average cost of each scenario over the 60-year lifetime of the adaptation option from 2010 to 2070.

$$EVPV = \int_{2010}^{2070} g(y)dy \qquad \text{(Equation 4)}$$

EVPV = present value expected value cost ($)

g(y) = EV = expected value cost ($)

y = design year

The total constant and variable costs were added together to determine the total cost for the high, moderate, and low climate change scenarios for each option.

Total Costs = Constant Costs + Variable Costs (Equation 5)

Both constant costs and variable costs were estimated and converted to present value costs. For variable costs, expected values were determined for each of three climate change scenarios in 2010, 2040, and 2070. Present value expected value costs were determined over the 60 year timeframe for each climate change scenario

4.3.1 Option 2 – Underground storage throughout the watershed

Constant Costs

Under Option 2, underground storage is implemented throughout the Worcester CSO area. Storage tanks were installed to accommodate hazardous flooding at nodes with greater than 0.5 MGD of flooding. Total storage volumes were installed in 2010 to accommodate the 100-year storm. Additional storage was installed in 2040 to accommodate flooding from the 100-year storm in 2040 and 2070. Construction costs were estimated as $4 per gallon of storage or $29.92 per cubic feet (CDM, 2002), and O&M costs were estimated as $0.40 per cubic feet per year

(EPA, 1999). Design and engineering (D&E) costs were estimated as 20% of construction costs. Table 17 presents a summary of constant costs for the complete underground storage option. Constant costs in 2040 were converted to present value costs in 2010 by converting future values and annual value costs assuming a discount interest rate of 2.3%. Since additional storage was not added in 2070, there were no constant costs determined in 2070 for this adaptation option. Over the 60-year timeframe of the option with an interest rate of 2.3%, a total present value constant cost of $739 M was calculated for option 2. The city of Worcester currently experiences hazardous flooding, so it is expected that this option would be immediately implemented into the Worcester system, costing a total of $739 M to control hazardous flooding throughout the streets of Worcester over a 60-year timeframe with 2.3% interest.

Table 17: Total constant costs for underground storage

	Total Cost			
Year	Construction	D&E	O& M (per year)	Total Present Cost
2010	$ 430 M	$ 86 M	$5.7 M	$ 639 M
2040	$470 M	$ 94 M	$ 3.8 M	$100 M

Notes:

* 2.3 % interest rate (Engineering News-Record, 2012)

* Construction costs based on estimates of $29.92/ft3 (CDM, 2002) and O&M costs based on estimate of $0.40/ft3/year (EPA, 1999)

* D&E costs estimated as 20% of construction costs

Variable Costs

Variable costs include costs for CSO treatment at both the QCSOSTF and UBWWTF. Treatment costs at each facility include all costs for treatment of combined sewage that flows through the Worcester CSO system area. Most flows in the city are directed right to the Upper Blackstone facility for treatment. However, during periods of extreme rainfall wastewater and stormwater flows are directed to the QCSOSTF for treatment so combined sewer treatment is not overwhelming at the UBWWTF. Based on previous cost analysis conducted by the City of Worcester Department of Public Works, it was determined that costs for CSO treatment at the QCSOSTF is estimated to be $4,000 per MG treated. It was also assumed that treatment at the Upper Blackstone facility is approximately equal to treatment at the QCSOSTF. Effluent flows from both treatment facilities were added together to determine the total amount of combined sewage treated for each design storm scenario. Variable costs were estimated for each scenario and converted to present value costs, and these costs are all presented in Table 18.

Table 18: Present value costs for underground storage

Scenario	QCSOSTF Vol. (MG)	UBWWTF Vol. (MG)	Cost	n (years)	Present Value Cost
3mo	0	208	$832,373	0	$832,373
3mo 2040 L	0	190	$761,700	30	$24,819
3mo 2040 M	0	205	$821,744	30	$26,776
3mo 2040 H	0	210	$839,344	30	$27,349
3mo 2070 L	0	208	$830,148	60	$13,525
3mo 2070 M	0	210	$839,344	60	$13,675
3mo 2070 H	0	211	$842,496	60	$13,726
10yr	17	233	$999,072	0	$999,072
10yr 2040 L	21	223	$976,696	30	$31,825
10yr 2040 M	19	230	$997,624	30	$32,506
10yr 2040 H	19	237	$1,021,964	30	$33,300
10yr 2070 L	18	222	$960,056	60	$15,641
10yr 2070 M	22	235	$1,028,392	60	$16,755
10yr 2070 H	22	239	$1,045,256	60	$17,029
100yr	45	271	$1,264,893	0	$1,264,893
100yr 2040 L	46	237	$1,132,304	30	$36,895
100yr 2040 M	53	289	$1,367,448	30	$44,557
100yr 2040 H	60	306	$1,467,460	30	$47,816
100yr 2070 L	31	244	$1,100,952	60	$17,937
100yr 2070 M	46	276	$1,286,428	60	$20,958
100yr 2070 H	50	276	$1,303,568	60	$21,238

After calculating present values for each scenario, expected value costs were determined using risk analysis. For each climate change scenario in 2010, 2040, and 2070, the present value cost was plotted versus the expected number of events per year. Each set of data was linearly fit to provide a simplified process of determining the expected value. Figure 65 shows results for the high climate change scenario in 2040. Similar results were plotted for the moderate and low scenarios in 2040, all climate scenarios in 2070, and the current 2010 scenario.

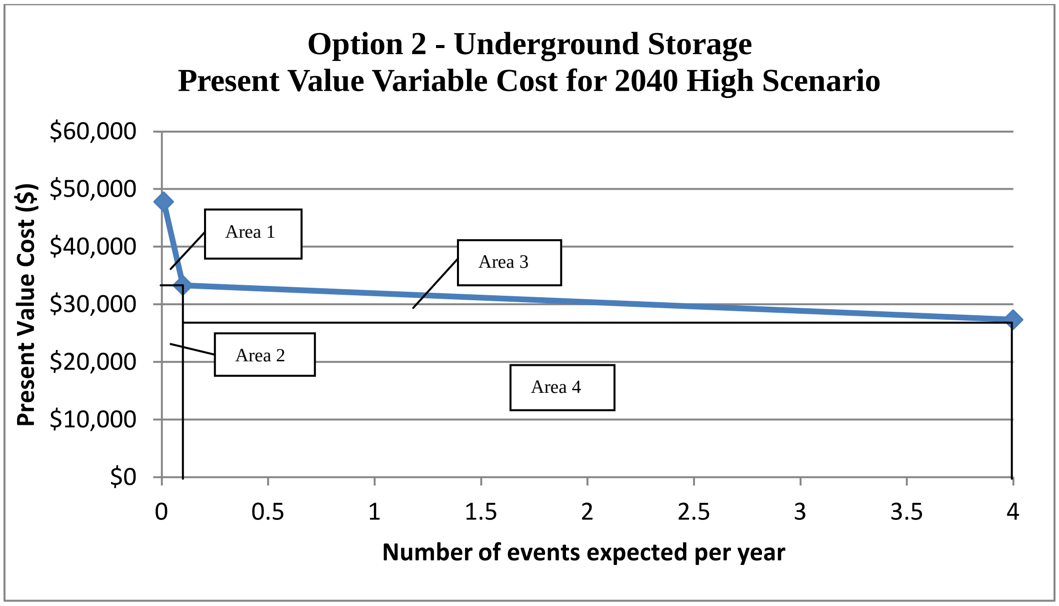


Figure 65: Present value variable cost for option 2 under 2040 high climate change scenario

Expected values were computed by estimating the area underneath the curve shown in Figure 66. Each area can be divided into 4 smaller shapes, with two triangles and two rectangular areas. These four areas were summed to estimate the total present value cost for each scenario. Tables 19-22 present results for each of the four shape areas and the total present value for each scenario. This approach was used to calculate the expected value cost for each climate scenario, and Table 23 presents expected value results.

Table 19: Expected value cost results for underground storage (Shape 1)

			Triangle
Scenario	Shape 1 Base	Shape 1 Height	Shape 1 Area
2010	0.09	265821	11962
2040 L	0.09	5070	228
2040 M	0.09	12050	542
2040 H	0.09	14516	653
2070 L	0.09	2295	103
2070 M	0.09	4204	189
2070 H	0.09	4208	189

Table 20: Expected value cost results for underground storage (Shape 2)

			Rectangle
Scenario	Shape 2 Base	Shape 2 Height	Shape 2 Area
2010	0.09	999072	89916
2040 L	0.09	31825	2864
2040 M	0.09	32506	2926
2040 H	0.09	33300	2997
2070 L	0.09	15641	1408
2070 M	0.09	16755	1508
2070 H	0.09	17029	1533

Table 21: Expected value cost results for underground storage (Shape 3)

			Triangle
Scenario	Shape 3 Base	Shape 3 Height	Shape 3 Area
2010	3.9	166698	325061
2040 L	3.9	7005	13661
2040 M	3.9	5731	11175
2040 H	3.9	5950	11603
2070 L	3.9	2116	4127
2070 M	3.9	3080	6006
2070 H	3.9	3303	6442

Table 22: Expected value cost results for underground storage (Shape 4)

			Rectangle
Scenario	Shape 4 Base	Shape 4 Height	Shape 4 Area
2010	3.9	832373	3246257
2040 L	3.9	24819	96795
2040 M	3.9	26776	104425
2040 H	3.9	27349	106662
2070 L	3.9	13525	52746
2070 M	3.9	13675	53331
2070 H	3.9	13726	53531

Table 23: Expected value costs for underground storage

CC Scenario	Year	Expected Value ($)
	2010	$3,673,196
Low	2040	$113,548
Low	2070	$58,385
	2010	$3,673,196
Median	2040	$119,068
Median	2070	$61,034
	2010	$3,673,196
High	2040	$121,915
High	2070	$61,695

For each climate change scenario, expected value was plotted over the 60-year timeframe from 2010 to 2070. Figures 66, 67, and 68 provide results for the high, moderate, and low scenario, respectively. The present value expected value (EVPV) was estimated for each scenario by determining the area under each curve the same way the expected value costs were determined. Table 24 provides final variable costs for each climate change scenario. A final expected value cost was determined for each scenario by adding the EVPV variable costs and the constant costs, and these results are presented in Table 25. The following procedure for estimated EVPV variable costs was conducted similarly for all options in the design cost approach. It was also used for all options in the net benefits approach, which will be described in Section 4.4.

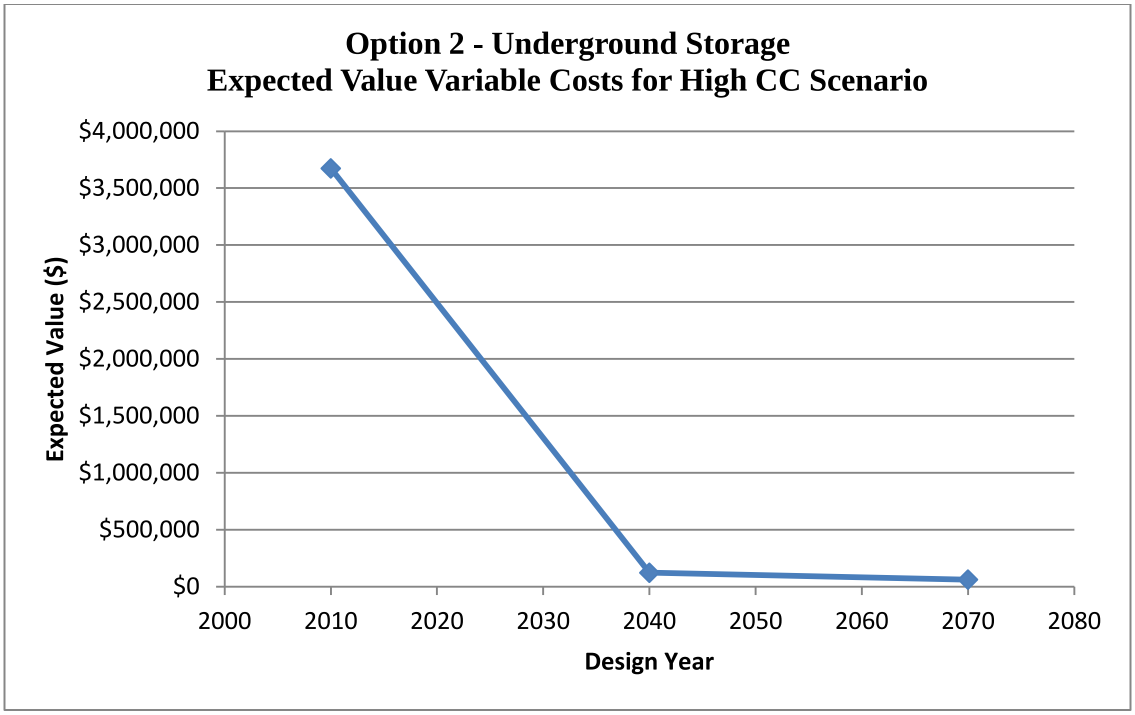


Figure 66: Expected value for high climate change scenario (option 2)

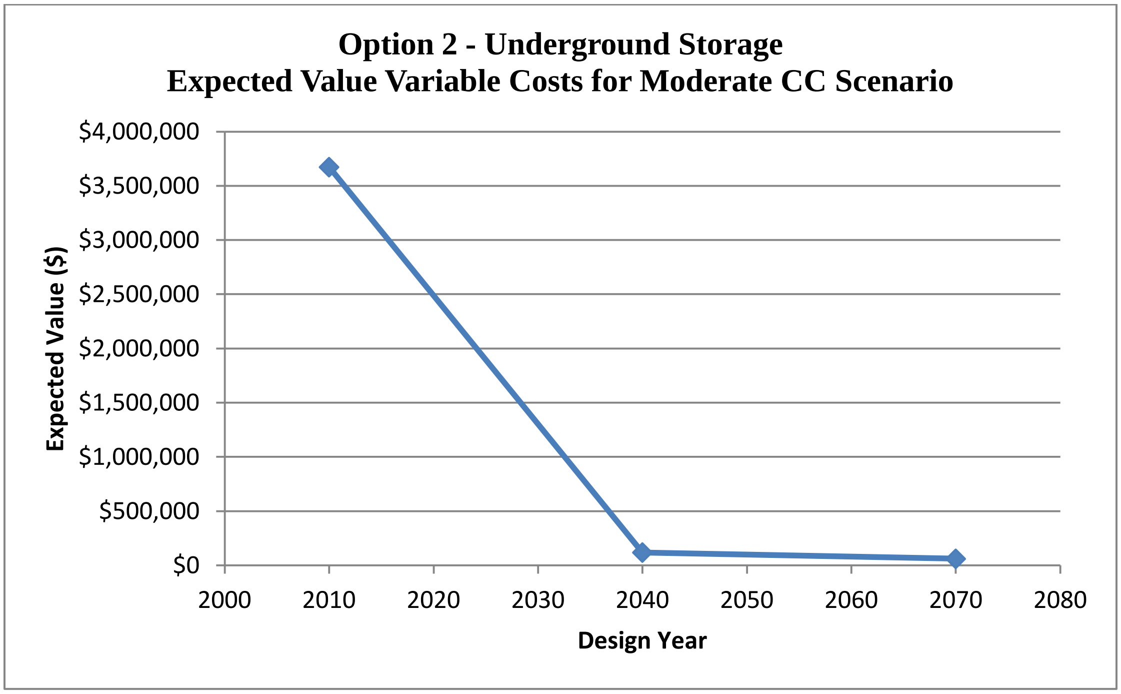


Figure 67: Expected value for moderate climate change scenario (option 2)

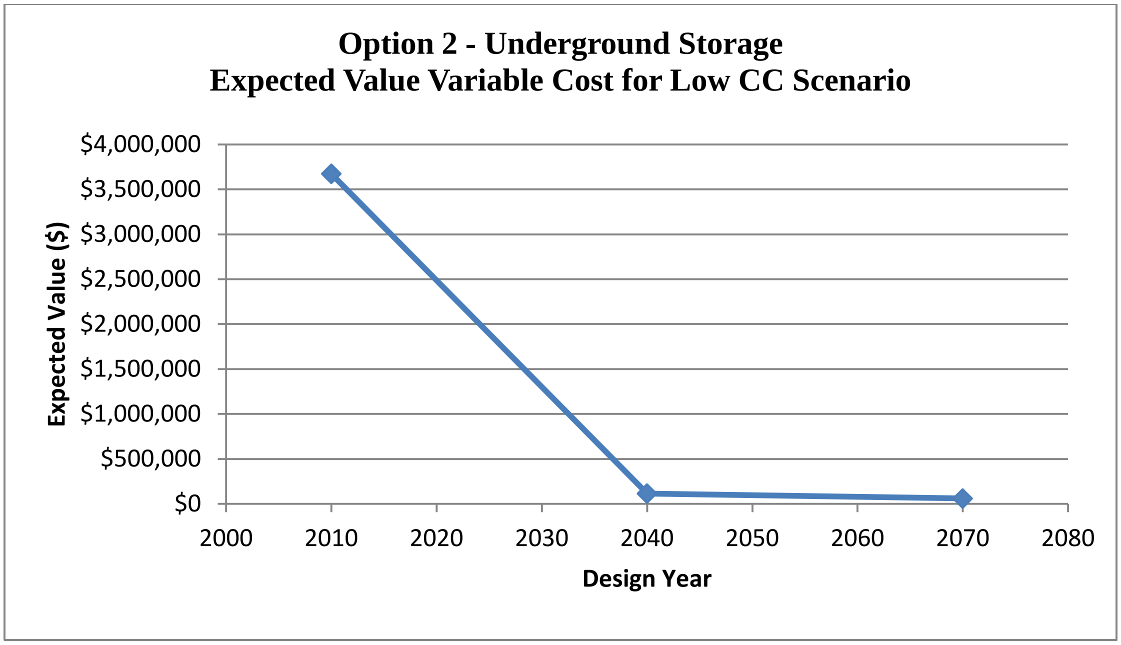


Figure 68: Expected value for low climate change scenario (option 2)

Table 24: EVPV variable costs for underground storage

CC Scenario	EVPV Variable Costs
Low	$59,380,000
Moderate	$59,585,000
High	$59,681,000

Table 25: EVPV total costs for underground storage

CC Scenario	EVPV Total Costs
Low	$798,786,000
Moderate	$798,991,000
High	$799,087,000

4.3.2 Option 4 – Upstream storage and increased QCSOSTF pumping

Constant Costs

Under option 4, underground storage is implemented but only in select locations upstream from the QCSOSTF where hazardous flooding is significant. Storage basins downstream in the system close to the QCSOSTF need to be built with extremely high volumes in order to accommodate hazardous flooding. However, it was determined that it may be unrealistic to build multiple storage tanks as large as 12.4 acres in area. As a result, instead of building storage tanks around the Quinsigamond Avenue area, these tanks were replaced by one large tank that can be installed at Crompton Park. In addition, pumping rates were increased at the QCSOSTF in order to further decrease hazardous flooding around the Quinsigamond Avenue treatment facility. This strategy will help accommodate the increased flooding downstream and save constant costs for the system, but this option will lead to an increase in variable costs compared to option 2 by increasing the capacity for pumping flow through the QCSOSTF. Other issues may occur with increased flows to the Mill Brook, but it is assumed for this study that increased flows do not negatively affect the Mill Brook. Costs for storage were estimated using the same approach as option 2, where construction costs were estimated as $29.92 per cubic foot of storage. Similarly, D&E costs were estimated as 20% of the construction costs, and O&M costs $0.40 per cubic foot per year. Table 26 provides a summary table of present constant costs in 2010, 2040, and 2070, and these costs were summed to determine a total present constant cost over the 60-year timeframe. No added costs were included in 2070 since no additional storage was provided. Over the 60-year timeframe of the option with an interest rate of 2.3%, a total present value constant cost of $433 M was calculated for Option 4.

Table 26: Total constant costs for upstream storage and increased QCSOSTF pumping

	Total Cost			
Year	**Construction**	**D&E**	**O& M (per year)**	**Total Present Cost**
2010	$ 288 M	$ 58 M	$3.8 M	$ 428 M
2040	$116 M	$ 23 M	$ 1.5 M	$5.7 M

Notes:

* 2.3 % interest rate (Engineering News-Record, 2012)

* Construction costs based on estimates of $29.92/ft3 (CDM, 2002) and O&M costs based on estimate of $0.40/ft3/year (EPA, 1999)

* D&E costs estimated as 20% of construction costs

Variable Costs

Variable costs for option 4 include costs for combined sewage treatment at the QCSOSTF and UBWWTF. Option 4 expects to increase flows through the QCSOSTF and UBWWTF due to increased pumping. The same process applied to option 2 was also applied to option 4. Variable costs were estimated and converted to present value costs, and expected values were determined using risk analysis. After determining present value costs for 2010 and each climate change scenario in 2040 and 2070, present value expected value (EVPV) costs were determined by estimating the area under the curves for high, moderate, and low climate change scenarios, with each curve plotting expected value cost over the 60-year timeframe from 2010 to 2070. Present value expected value costs are presented in Table 27. Constant and variable costs were summed to determine final costs estimations for option 4 for each of three climate change scenarios, and these costs are summarized in Table 28.

Table 27: EVPV variable costs for upstream storage and increased QCSOSTF pumping

CC Scenario	EVPV Variable Costs
Low	$63,351,000
Moderate	$63,559,000
High	$63,656,000

Table 28: EVPV total costs for upstream storage and increased QCSOSTF pumping

CC Scenario	EVPV Total Costs
Low	$496,835,000
Moderate	$497,042,000
High	$497,140,000

4.3.3 Option 5 – Sewer Separation

Constant Costs

Under option 5, sewer separation is performed in select subcatchments, as described in Chapter 3. It is necessary to perform sewer separation in three key locations in the Worcester CSO system: Bell Pond, Shrewsbury Street and Southbridge Street. A total of 14 catchments were removed from the system under sewer separation, and all sewer separation was implemented in 2010. A cost analysis for full sewer separation was previously conducted in 2002 by the Worcester Department of Public Works as part of the CSO Long-term Control Plan (CDM, 2002). Two catchments were chosen to represent the entire Worcester CSO area to estimate sewer separation. The representative catchments selected by the city were the North Southbridge Street and Canton Street areas, which are both located in the southern portion of the Worcester CSO area (CDM, 2002). The North Southbridge Street catchment is comprised mostly of industrial land use properties and was used as a good representative of public, commercial, and industrial land. On the other hand, the Canton Street catchment was selected due to its primarily residential land use (CDM, 2002).

Based on previous studies it was assumed that the approximate pipe length of the combined sewer would be equal to the length of the storm drain required for the areas selected (CDM, 2002). It was also assumed that the storm drain size would be the same as the existing CSO pipe that carries stormwater and sanitary flows. The lengths of each pipe size and approximate costs to construct each pipe size were calculated. In addition to all construction costs, it was assumed that both D&E and O&M costs were factored into the total constant costs to determine a total cost in 2002. The total cost and cost per acre of the Canton Street and North Southbridge Street catchments are included in Table 29, and these estimates were used to determine the costs for all separated catchments in the system.

Table 29: Total cost of sewer separation of Canton St. and Northbridge St. catchments

Catchment	Total Cost	Cost Per Acre	Land Use
Canton St	$3,805,000	$66,750	100% residential
North Southbridge St	$9,592,000	$90,490	100% public

The values for cost per acre were applied to all combined catchments in Worcester. Each catchment was categorized based on percentage of residential and commercial/industrial land use. Sewer separation costs were determined using the Canton Street estimate of 100% residential use and the North Southbridge Street estimate of 100% industrial/commercial land use areas. If a catchment had a mix of both types of land use, the cost per acre was adjusted accordingly to correspond with the percentage mix of land use from the two base catchments of North Southbridge Street and Canton Street (CDM, 2002). For example, if a catchment were 50% residential and 50% industrial/commercial, the cost per acre would be the average of the Canton Street and North Southbridge Street catchment costs per acre. Table 30 presents a summary table of all catchments that were separted from the system under option 5 with their corresponding areas, land use, and costs per acre depending on their land use. All industrial and commercial land is categorized as public. Costs for 2002 were converted to present value costs in 2001, assuming an interest rate of 2.3%.

Table 30: Sewer separations costs of separated catchments under option 5

Catchment	Land Use	Area (acres)	Cost Per Acre	2002 Cost	Present Cost
N. Shrewsbury Street	100% residential	223.9	$66,800	$14,956,520	$122,404,160
S. Shrewsbury Street	100% public	118.5	$90,500	$10,724,250	$87,767,262
Southbridge Street N	100 % public	114.1	$90,500	$10,326,050	$84,508,393
Southbridge Street W	60% residential, 40% public	168.7	$76,200	$12,854,940	$105,204,829
Southbridge Street S	50% residential, 50% public	28.8	$78,600	$2,263,680	$18,525,957
Southbridge Street_S	65% industrial, 35% residential	9.032	$82,200	$742,430	$6,076,050
Southbridge St Of	100% industrial	24.7	$90,500	$2,235,350	$18,294,104
Southgate Street	50% residential, 50% public	41.2	$90,500	$3,728,600	$30,514,862
N Laurel Street	20% residential, 80% parks	302.3	$13,400	$4,050,820	$33,151,911
S Laurel Street	100% residential	196.5	$66,800	$13,126,200	$107,424,821
Thomas Street	50% residential, 50% public	48.2	$78,600	$3,788,520	$31,005,248
Worcester Center Bl.	100% industrial	15.3	$90,500	$1,384,650	$11,331,976
N Franklin Street	60% residential, 40% public	107.4	$76,200	$8,183,880	$66,976,874
S Franklin Street	100% industrial	55.5	$90,500	$5,022,750	$41,106,186

Present costs were summed for each catchment and a total present constant cost of $764 M was calculated for option 5.

Variable Costs

Variable costs for option 5 include costs for treatment of flows at the QCSOSTF and UBWWTF. The same process applied to options 2 and 4 was also applied to option 5. A treatment rate of $4,000 per MG was applied to both treatment facilities, and a present value cost was determined for each scenario in 2010, 2040, and 2070. After estimating variable costs and converting them to present values, expected value costs were calculated by summing the area under the curve for present value plots, which were plotted for each climate change scenario in 2010, 2040, and 2070. Similarly, the same risk analysis previously used in options 2 and 4 was also used to determine the present value expected value (EVPV) costs for the high, moderate, and low climate change scenarios for option 5. These values were determined by estimating the area under the curve for plots of expected values for each climate change scenario over the 60-year timeframe. Table 31 presents the results for EVPV costs. Constant and variable costs were summed in order to determine the final present value cost estimations of using sewer separation under each climate change scenario, and these results are presented in Table 32.

Table 31: EVPV variable costs for sewer separation

Scenario	EVPV Variable Costs
Low	$54,953,000
Moderate	$55,027,000
High	$55,083,000

Table 32: EVPV total costs for sewer separation

Scenario	EVPV Variable Costs
Low	$819,245,000
Moderate	$819,319,000
High	$819,375,000

After determining constant and variable costs for options 2, 4, and 5, results from all three options were compared to determine the most cost-effective strategy under all three climate change scenarios (Table 33). Expected value total costs are provided for each option. Results show that option 4, upstream storage with increased QCSOSTF pumping, is the most cost-effective strategy for all climate change scenarios since total costs are the cheapest for this strategy. There are very small differences between each climate change scenario since the majority of the total costs come from constant costs like construction, design and engineering, and annual operation and maintenance.

Table 33: Final design cost results

Option	Low CC	Moderate CC	High CC
Option 2 - Underground Storage	$798,786,000	$798,991,000	$799,087,000
Option 4 - QCSOSTF Storage	$496,835,000	$497,042,000	$497,140,000
Option 5 - Sewer Separation	$819,245,000	$819,319,000	$819,375,000

4.4 Cost Analysis - Net Benefits Approach

In addition to a design cost approach, a net benefits approach was also used to compare the different adaptation options. For this approach, net benefits were estimated for each option by subtracting total costs from benefits. Costs were determined as the sum of constant and variable costs, which were defined in the previous section. Benefits were defined as the difference in variable costs between option 1 and the other adaptation options. If variable costs for each option are less than the baseline scenario (option 1), the difference is quantified as a benefit. However, if variables costs are greater than those for the baseline scenario, the difference is an additional cost or negative benefit. For this study, benefits occur if the variable costs of flow leaving the UBWWTF and QCSOSTF for a particular option are less than the variable costs for the baseline scenario. Benefits also occur for an adaptation option if there is less hazardous flooding than no action.

Net Benefits = Total Benefits – Total Costs (Equation 6)

Total Benefits include the value costs of damages avoided versus the baseline scenario. Total Costs include the sum of constant and variable costs, and variable costs are made up of EVPV costs for hazardous flooding damages and costs for treatment of flow to the QCSOSTF and UBWWTF.

In addition to costs of treatment of flows at the QCSOSTF and UBWWTF, the costs of damages from hazardous flooding were estimated as variable costs and benefits under the net benefits approach. Hazardous flooding damages include all costs from building structural damage, damage to contents in the building and basement, and total pumping and cleaning costs. Building and structural content damages were estimated using the Army Corps of Engineers tables (ACOE, 2003). These tables provide estimates for the total percentage of damage to each building depending on the total flooding depth. Assumptions were made to estimate the number of houses and buildings affected by flooding and the amount of flooding occurred. Based on previous zoning analysis performed using ArcGIS software, the total number of buildings was estimated to be 7,932 for the entire Worcester CSO area. It was assumed that 25% of buildings are affected by hazardous flooding during the 100-year storm for a total of 1,983 buildings. For the 10-year storm, it was assumed that 12.5 % of buildings are affected or 992 buildings in the Worcester CSO area. During the 3-month storm, it was assumed that 0.3% of buildings are affecting by hazardous flooding or 25 buildings. Each building was assumed to be 2,000 square feet in area (Caputo, 2011).

Using this area and the volume of hazardous flooding from model simulation results, the total flood depth was estimated for each climate scenario and design storm in 2010, 2040, and 2070. It was assumed that all hazardous flooding flows into the basement of each building so the volume of hazardous flooding could be converted into CSO flooding depths in each basement. Using the Army Corps of Engineers tables, the total structural damage costs were estimated based on the average assessed value of a house in Worcester, which was estimated to be $183,000 (Trulia, 2012). Table 34 presents a summary of total flooding volume, depth, and present value costs of hazardous flooding damages for each climate change scenario and design storm over the 60-year timeframe from 2010 to 2070 for option 1 (no action).

Table 34: Present value costs for hazardous flooding damages for no action

Scenario	Flooding (MG)	Area (ft^2)	Flood Depth (ft)	% Cost	PV Cost ($)
3mo	0.00	50,000	0	0	0
3mo 2040 L	0.00	50,000	0	0	0
3mo 2040 M	0.00	50,000	0	0	0
3mo 2040 H	0.00	50,000	0	0	0
3mo 2070 L	0.06	50,000	0.16	0.00752	35
3mo 2070 M	0.07	50,000	0.20	0.0094	35
3mo 2070 H	0.10	50,000	0.27	0.01269	35
10yr	22.01	1,984,000	1.48	0.06044	2,808,928
10yr 2040 L	31.53	1,984,000	2.12	0.07932	68,298
10yr 2040 M	33.81	1,984,000	2.28	0.08508	74,180
10yr 2040 H	35.34	1,984,000	2.38	0.08868	85,869
10yr 2070 L	28.79	1,984,000	1.94	0.07332	27,892
10yr 2070 M	34.336	1,984,000	2.31	0.08616	32,360
10yr 2070 H	40.96	1,984,000	2.76	0.10236	42,326
100yr	113.77	3,966,000	3.83	0.14586	17,868,654
100yr 2040 L	104.67	3,966,000	3.53	0.13326	486,552
100yr 2040 M	147.17	3,966,000	4.96	0.19908	500,845
100yr 2040 H	179.40	3,966,000	6.05	0.25465	741,150
100yr 2070 L	91.00	3,966,000	3.07	0.11394	150,051
100yr 2070 M	94.23	3,966,000	3.18	0.11856	177,838
100yr 2070 H	168.19	3,966,000	5.67	0.2351	357,332

Pump-out, cleaning, and disinfection costs from flooding damages were each assumed to be a total of $10,000 per building regardless of the amount of basement flooding (Caputo, 2011).

Benefits and additional costs for CSO treatment at the QCSOSTF and UBWWTF were also estimated in addition to hazardous flooding costs and benefits for options 1 through 7. The same process of risk analysis used to determine EVPV variable costs in the design cost approach was also used for the net benefits approach to determine the net benefits of each adaptation option. Net benefits were calculated and compared for each option, and results are described in the next section.

4.4.1 Option 1 – No Action

Costs

Option 1 involves no action to the CSO system in Worcester and was used as the baseline scenario to compare the other options and be able to quantify benefits. No constant costs are included for option 1, but variable costs can be quantified. Variable costs include costs to treat combined sewage at the QCSOSTF and UBWWTF. They also include total costs of damages from hazardous flooding along with pump-out, cleaning, and disinfection costs. The same process used for options in the design cost approach was also used to quantify EVPV variable costs for the net benefits approach. Table 35 provides a summary table of EVPV variable costs for CSO treatment for the low, moderate, and high climate change scenarios.

Table 35: EVPV variable costs of CSO treatment for no action

Scenario	EVPV Variable Costs
Low	$63,265,000
Moderate	$63,497,000
High	$63,566,000

Hazardous flooding damages were also quantified as variables costs using the same process used for the design cost approach, where risk analysis was used to estimate the expected values in 2010, 2040, and 2070 under each climate change scenario. EVPV variable costs were estimated for each climate change scenario by approximating the area under the curve for the plot of expected value cost over the 60-year timeframe. EVPV variable costs for hazardous flooding damages, which include costs for pump-out, cleaning, and disinfection, are included in Table 36. The total EVPV variable costs for CSO treatment and hazardous flooding were summed to determine the total costs for no action for each climate change scenario, and the results are included in Table 37.

Table 36: EVPV variable costs of hazardous flooding damages for no action

Scenario	EVPV Variable Costs
Low	$422,405,000
Moderate	$425,983,000
High	$430,722,000

Table 37: Total costs for no action

Scenario	Total Costs
Low	$485,670,000
Moderate	$489,480,000
High	$494,288,000

Net Benefits

Since option 1 is the baseline scenario with no action on the system, there are no quantifiable benefits. Total benefits for this option are $0 for each climate change scenario. Net benefits were calculated by subtracting total costs from total benefits, and results are shown in Table 38.

Table 38: Total net benefits for no action

CC Scenario	Benefits	Costs	Net Benefits
Low	$0	$485,670,000	-$485,670,000
Moderate	$0	$489,480,000	-$489,480,000
High	$0	$494,288,000	-$494,288,000

4.4.2 Option 2 – Underground storage throughout the watershed

Costs

Under option 2, costs include all constant and variable costs described in Section 5.2 along with additional costs from hazardous flooding damages. Constant costs for option 2 were calculated to be approximately $739 M. Variable costs from UBWWTF and QCSOSTF flow treatment were described in the previous section and determined through a risk analysis procedure to calculate the EVPV cost for each climate change scenario. In addition to these costs, EVPV costs from flood damages were estimated using the same approach, and results are shown in Table 39. Total costs for this option include the sum of constant costs and all variable costs from CSO treatment and flooding damages. These costs are summarized in Table 40.

Table 39: EVPV variable costs of hazardous flooding damages for underground storage

Scenario	EV PV Variable Costs
Low	$122,970,000
Moderate	$123,494,000
High	$124,937,000

Table 40: Total costs for underground storage

Scenario	Total Costs
Low	$925,641,000
Median	$926,397.000
High	$927,910,000

Net Benefits

Benefits for option 2 include costs that are saved by the reduction of flood damages to buildings and houses in Worcester. Option 2 provides less hazardous flooding and less UBWWTF and QCSOSTF flow volumes than the baseline scenario, and the differences in these costs compared to the no action case were estimated and converted to present values. Present value expected value benefits were calculated as the total benefits for each climate change scenario, and these results are provided in Table 41. Net benefits were quantified as the difference between total costs and total benefits. Table 42 presents final results for the costs, benefits, and net benefits for option 2.

Table 41: Total benefits for underground storage

CC Scenario	Benefits
Low	$299,435,000
Moderate	$302,489,000
High	$305,784,000

Table 42: Total net benefits for underground storage

CC Scenario	Benefits	Costs	Net Benefits
Low	$299,435,000	$925,641,000	-$626,206,000
Moderate	$302,489,000	$926,397,000	-$623,907,000
High	$305,784,000	$927,910,000	-$622,125,000

4.4.3 Option 3 – Underground storage upstream of QCSOSTF

Costs

Under option 3, underground storage was installed in select locations upstream of the QCSOSTF where significant flooding occurred. Since less storage was provided, constant costs were estimated to be less than option 2, where underground storage is installed throughout the watershed. Total constant costs for option 3 were estimated to be $433 M. Variable costs of treatment at the QCSOSTF and UBWWTF were previously calculated in Section 5.2, and additional variable costs include additional costs from flooding. These costs include property and content damages and costs to pump-out, disinfect, and clean the affected basements. The additional hazardous flooding damage costs were determined using the risk analysis approach where EVPV variable costs were calculated by estimating the area under the curve for plots of expected value cost over the 60-year timeframe from 2010 to 2070. EVPV variable costs for hazardous flooding damages were calculated for each climate change scenario, and these results are provided in Table 43. Total costs for option 3 include the sum of all constant costs and variable costs of hazardous flooding damages and treated flows at the QCSOSTF and UBWWTF, and these results are shown in Table 44.

Table 43: EVPV variable costs of hazardous flooding damages for upstream storage

Scenario	EVPV Variable Costs
Low	$181,629,000
Moderate	$183,492,000
High	$186,131,000

Table 44: Total costs for upstream storage

Scenario	Total Costs
Low	$699,574,000
Moderate	$701,605,000
High	$704,303,000

Net Benefits

Similar to option 2, total benefits for option 3 were determined by calculating the difference in variable costs between options 1 and 3. Since option 2 provides less flow to the QCSOSTF and UBWWTF and less hazardous flooding volumes than the baseline scenario, these differences can be quantified as positive benefits. These benefits were calculated and converted to present values, and total benefits are included in Table 45. Final results for net benefits are included in Table 46, which were estimated by subtracting total costs from total benefits.

Table 45: Total benefits for upstream storage

CC Scenario	Benefits
Low	$219,581,000
Moderate	$221,359,000
High	$223,469,000

Table 46: Total net benefits for upstream storage

CC Scenario	Benefits	Costs	Net Benefits
Low	$219,581,000	$699,574,000	-$479,993,000
Moderate	$221,359,000	$701,605,000	-$480,245,000
High	$223,469,000	$704,303,000	-$480,834,000

4.4.4 Option 4 – Underground storage upstream of QCSOSTF and increased QCSOSTF pumping

Costs

Under option 4, underground storage was installed to accommodate flooding greater than 0.5 MG at locations upstream from the QCSOSTF. In addition to providing storage at these locations, the high flooding at locations near the QCSOSTF was accommodated by increasing the pumping rates at the Quinsigamond Avenue facility. The increased pumping leads to an increase in effluent flows from the QCSOSTF, but these changes to the facility also decrease hazardous flooding volumes throughout the Worcester CSO area. Constant costs for this option are the same as option 3 for a total cost of $433 M. However, variable costs for flow treatment at both facilities were increased for this option, and these results were provided in Section 4.3. Additional variable costs include hazardous flood damage costs. These costs were calculated as EVPV costs for each climate change scenario and were determined using the same method used for the previous options. Results for total hazardous flooding EVPV costs are summarized in Table 47. Total costs for option 4 include the sum of all constant costs and variable costs of hazardous flooding damages and treated flows at the QCSOSTF and UBWWTF, and these results are shown in Table 48.

Table 47: EVPV variable costs of hazardous flooding for upstream storage and increased QCSOSTF pumping

Scenario	EVPV Variable Costs
Low	$370,187,000
Moderate	$371,775,000
High	$376,406,000

Table 48: Total costs for upstream storage and increased QCSOSTF pumping

Scenario	Total Costs
Low	$867,021,000
Moderate	$868,817,000
High	$873,545,000

Net Benefits

Total benefits for option 4 were determined by estimating the difference in variable costs between option 4 and the baseline scenario (no action). Since this adaptation option provides less flow to the QCSOSTF and UBWWTF and less hazardous flooding volumes than the baseline scenario, the differences in costs can be quantified as positive benefits. These cost differences between the two options were converted to present values to determine the total benefits for each climate change scenario, and these results are provided in Table 49. Final results for net benefits are included in Table 50, which were estimated by subtracting total costs from total benefits.

Table 49: Total benefits for upstream storage and increased QCSOSTF pumping

CC Scenario	Benefits
Low	$52,133,000
Moderate	$54,147,000
High	$54,227,000

Table 50: Total net benefits for upstream storage and increased QCSOSTF pumping

CC Scenario	Benefits	Costs	Net Benefits
Low	$52,133,000	$867,021,000	-$814,888,000
Moderate	$54,147,000	$868,817,000	-$814,671,000
High	$54,227,000	$873,545,000	-$819,319,000

4.4.5 Option 5 – Sewer Separation

Costs

Under option 5, sewer separation is employed for select areas of the Worcester CSO system. Constant costs for sewer separation are described in Section 4.3, and a total present constant cost of $764 M was estimated for sewer separation. Costs to treat flows at the QCSOSTF and UBWWTF were previously calculated as EVPV variable costs for each climate change scenario. Variable costs associated with hazardous flooding damages were calculated for sewer separation, and these results are provided in Table 51. Total costs for option 5 include the sum of all constant costs and variable costs of hazardous flooding damages and treated flows at the QCSOSTF and UBWWTF, and these results are shown in Table 52.

Table 51: EVPV variable costs of hazardous flooding for sewer separation

Scenario	EVPV Variable Costs
Low	$93,099,000
Moderate	$95,552,000
High	$97,076,000

Table 52: Total costs for sewer separation

Scenario	Total Costs
Low	$912,345,000
Moderate	$914,871,000
High	$916,452,000

Net Benefits

Option 5 provides less flow volumes to both the QCSOSTF and UBWWTF than option 1. It also provides less hazardous flooding volume than the baseline scenario (option 1). These differences in variable costs of treated flows and flooding damages were quantified as positive benefits for the option of sewer separation. The differences in variable costs between option 5 and the baseline scenario were estimated and converted to present values to determine present value expected value benefits for sewer separation. These benefits represent the total benefits for option 5, and the total benefits for each climate change scenario are presented in Table 53. Net benefits were determined by subtracting the total costs from the total benefits, and net benefits are presented in Table 54.

Table 53: Total benefits for sewer separation

CC Scenario	Benefits
Low	$337,618,000
Moderate	$338,901,000
High	$342,129,000

Table 54: Total net benefits for sewer separation

CC Scenario	Benefits	Costs	Net Benefits
Low	$337,618,000	$912,345,000	-$574,726,000
Moderate	$338,901,000	$914,871,000	-$575,970,000
High	$342,129,000	$916,452,000	-$574,322,000

4.4.6 Option 6 – LID throughout the watershed

Costs

Under adaptation option 6, LID was implemented over time throughout the watershed. In 2010, 30% of maximum LID technology was implemented throughout the watershed. In 2040, an additional 50% of LID was installed, and the remaining 20% was implemented throughout the Worcester CSO area in 2070. The following LID techniques were used for this study: dry wells, green roofs, blue roofs, rain barrels, porous pavement, and bioretention. Costs for each technique were estimated using the following assumptions, which are summarized in Table 55. It was assumed that design and engineering (D&E) costs are approximated to be 20% of the total construction cost. For the lifetime of each LID option, it was assumed that dry wells, green roofs, blue roofs, and rain barrels last 30 years before they need to be replaced. However, porous pavement will only last 16 years and needs to be reinstalled twice every 30 years. Bioretention was assumed to have an estimated lifetime of 6 years and needs to be replaced 5 times every 30 years. The annual operation and maintenance costs are included as percentages of construction costs and are dependent on the type of LID.

Table 55: Low Impact Development (LID) costs

LID Option	Construction Cost Rate[1,5,6,7]	D&E Cost Rate	Annual O&M Costs (% of construction costs)[2,3]	Lifetime (years)[1,2,4]	# of re-installation every 30 years
Drywell	\$64 / ft^3	\$8 / ft^3 / yr	13%	30	1
Green Roof	\$20 / ft^2	\$1.70 / ft^2 / yr	9%	30	1
Blue Roof	\$4 / ft^2	\$0.04 / ft^2 / yr	1%	30	1
Rain Barrel	\$158 / rain barrel	\$1.58 / rain barrel /yr	1%	30	1
Porous Pavement	\$8 / ft^2	\$0.12 / ft^2 / yr	2%	16	2
Bioretention	\$30 / ft^2	\$1.80 / ft^2 / yr	6%	6	5

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)
5. (LID – Stormwater, Urban Design Tools, 2012)
6. (MMSD, 2005)
7. (Philadelphia Water Department, 2012)

Table 56 presents the total present costs for LID in 2010, 2040, and 2070. These costs include total construction, D&E, and O&M costs. Over the 60-year timeframe from 2010 to 2070 with an interest rate of 2.3%, the present value constant cost of LID is \$1.005 B.

Table 56: Total constant costs for LID

	Cost		
Year	Construction / D&E Cost	O&M Present Cost	Total Present Cost
2010	$410 M	$320 M	$730 M
2040	$10.5 M	$263 M	$274 M
2007	$0.8 M	$0.0 M	$0.8 M

Variable costs for option 6 include QCSOSTF and UBWWTF treatment of flows and hazardous flooding damages. Variable costs were estimated using the same methods implemented for previous options. Expected value costs were calculated and converted to present value expected value costs for each climate change scenario. EVPV variable costs for both hazardous flooding damages and treatment facility flows were added together to estimate the total EVPV variable costs for high, moderate, and low climate change scenarios. These results are included in Table 57. All constant and variable costs were summed to obtain the final costs for each climate change scenario for option 6 (Table 58).

Table 57: Total EVPV variable costs for LID

Scenario	Total EVPV Variable Costs
Low	$464,289,000
Moderate	$466,816,000
High	$471,249,000

Table 58: Total costs for LID

Scenario	Total Costs
Low	$1,469,440,000
Moderate	$1,471,966,000
High	$1,476,399,000

Net Benefits

Option 6 does not meet all the design goals for this study since the implementation of LID actually increases the amount of flow volume leaving both the QCSOSTF and UBWWTF. As a result, the variable costs of treating flow at the treatment facilities provide a negative benefit for option 6. However, this adaptation strategy does provide less hazardous flooding volumes than the baseline scenario. The difference in total variable costs compared to the baseline scenario were quantified as benefits and converted to present values. Total benefits for option 6 for each climate change scenario are presented in Table 59. The total net benefits were determined by calculating the difference between costs and benefits, and these results are provided in Table 60.

Table 59: Total benefits for LID

CC Scenario	Benefits
Low	$21,382,000
Moderate	$22,665,000
High	$23,039,000

Table 60: Total net benefits for LID

CC Scenario	Benefits	Costs	Net Benefits
Low	$21,382,000	$1,469,439,000	-$1,448,058,000
Moderate	$22,665,000	$1,471,966,000	-$1,449,301,000
High	$23,039,000	$1,476,399,000	-$1,453,360,000

4.4.7 Option 7 – Combination of LID and sewer separation

Costs

Option 7 involves combining sewer separation with the implementation of LID in the remaining subcatchments that aren't separated from the Worcester CSO system. Constant costs for sewer separation were estimated in Section 4.3, and a total constant cost of $764 M was determined. The remaining constant costs were determined by estimating the total present cost of LID construction, D&E, and O&M for the subcatchments remaining following sewer separation. Table 61 presents the total present constant costs for LID for option 7 in 2010, 2040, and 2070. These costs include total construction, D&E, and O&M costs.

Table 61: Total constant costs for LID and sewer separation

	Cost		
Year	Construction / D&E Cost	O&M Present Cost	Total Present Cost
2010	$210 M	$166 M	$376 M
2040	$3.3 M	$252 M	$255 M
2007	$0.8 M	$0.0 M	$0.8 M

Over the 60-year timeframe from 2010 to 2070 with an interest rate of 2.3%, the present value constant cost of LID in option 7 is $632 M. The total constant cost of option 7 was determined by summing the sewer separation and LID costs for a total cost of $1.396 B.

Variable costs include treatment of flows at the QCSOSTF and UBWWTF and hazardous flooding damages. Total variable costs were calculated and converted to present value expected value (EVPV) costs. The total variable costs for each climate change scenario are presented in Table 62. All constant and variable costs were summed to obtain the final costs for each climate change scenario for option 7 (Table 63).

Table 62: Total EVPV variable costs for LID and sewer separation

Scenario	Total EVPV Variable Costs
Low	$172,976,000
Moderate	$175,533,000
High	$177,082,000

Table 63: Total costs for LID and sewer separation

Scenario	Total Costs
Low	$1,569,968,000
Moderate	$1,572,524,000
High	$1,574,073,000

Net Benefits

Option 7 provides less flow volumes to the QCSOSTF and hazardous flood volumes than the baseline scenario, but it does not meet the design goal of avoiding the increase in UBWWTF flow volumes. The differences in variable costs between option 7 and the baseline scenario were estimated and converted to present values for each climate change scenario, and these values were defined as benefits. Benefits include the difference in cost between options 1 and 7 for treatment of flows to the QCSOSTF and UBWWTF and hazardous flood damages. Total benefits for option 7 for each climate change scenario are presented in Table 64. The total net benefits were determined by calculating the difference between costs and benefits, and these results are provided in Table 65.

Table 64: Total benefits for LID and sewer separation

CC Scenario	Benefits
Low	$312,694,000
Moderate	$313,947,000
High	$317,206,000

Table 65: Total net benefits for LID and sewer separation

CC Scenario	Benefits	Costs	Net Benefits
Low	$312,694,000	$1,569,968,000	-$1,257,274,000
Moderate	$313,947,000	$1,572,524,000	-$1,258,577,000
High	$317,206,000	$1,574,073,000	-$1,256,867,000

Net benefits were compared for all seven adaptation options for stormwater management under climate change. Table 66 presents results for the total net benefits for each option for low, moderate, and high climate change scenarios. Results are also graphically displayed in Figure 69. Results show that option 3, upstream underground storage, is the most beneficial strategy because it has the highest net benefits (or lowest negative net benefits) for all climate change scenarios.

Table 66: Final net benefits results for Worcester

	CC Scenario		
Option	**Low CC**	**Moderate CC**	**High CC**
Option 1 - No Action	-$485,670,000	-$489,480,000	-$494,288,000
Option 2 - Storage	-$626,206,000	-$623,907,000	-$622,125,000
Option 3 - Upstream storage	-$479,993,000	-$480,245,000	-$480,834,000
Option 4 - Upstream storage / QCSOSTF pumping	-$814,888,000	-$814,671,000	-$819,319,000
Option 5 - Sewer separation	-$574,726,000	-$575,970,000	-$574,322,000
Option 6 - LID	-$1,448,058,000	-$1,449,301,000	-$1,453,360,000
Option 7 - LID and sewer separation	-$1,257,274,000	-$1,258,577,000	-$1,256,867,000

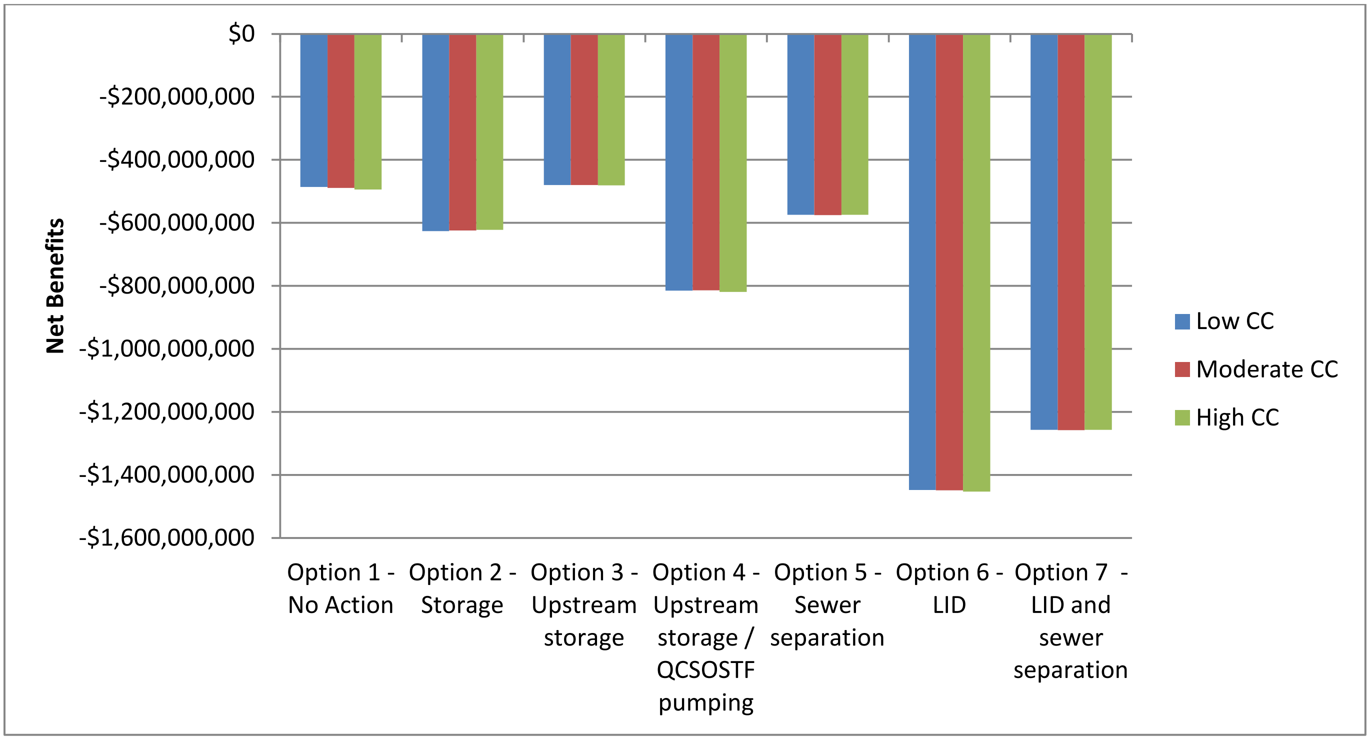


Figure 69: Final net benefits results for Worcester

4.5 Discussion of Results

Two cost analysis approaches were used for this study in order to determine the most effective best management practice for managing climate change in the future under the uncertainty of climate change. These approaches included a design cost approach and net benefits approach. For the design cost approach, the total costs were compared for options that met the goals of the study, which included decreasing hazardous flooding throughout the city and controlling the increase of flows through both the QCSOSTF and UBWWTF. These goals are achieved by the utilization of options 2, 4, and 5. Option 5 involves the strategy of sewer separation in certain areas throughout the Worcester CSO system. This option was deemed to be the most costly option under the design cost approach. Option 2 involves installing underground storage throughout the watershed, and total cost results show that it was the second most cost-effective option. The most cost-effective option for managing hazardous flooding and treatment system outflows was option 4, which is the implementation of underground storage upstream of the QCSOSTF and increased pumping capacity at the Quinsigamond facility. This option utilizes more realistic storage than option 2, which involves underground storage throughout the watershed. In order to accommodate a high amount of flooding near the QCSOSTF, one large underground storage tank was installed in the area of Crompton Park and pumping rates at the Quinsigamond facility were increased in order to increase the capacity of flows through the facility. Although this option led to the increase in flow treatment costs to the QCSOSTF and UBWWTF compared to option 2, the savings in underground storage costs allowed for a total cost that was less than the other options analyzed for this study.

For the net benefits approach, all seven options were compared to determine the most beneficial strategy for controlling flows and hazardous flooding in the Worcester CSO facility under climate change. According to the net benefits approach, it was determined that option 3 is the most effective approach since net benefits were the highest. However, negative benefits were calculated for all seven scenarios, meaning that all of the options analyzed have long-term net costs. It was determined by the net benefits approach that upstream underground storage is the most beneficial approach, and it is the only adaptation option that has more net benefits (or less net costs) than the baseline scenario. This option shows that more realistic storage can be implemented throughout the watershed, and these savings in storage construction costs still hold over the 60-year timeframe. Although option 4 was the most cost-effective option for the design cost approach, it was not one of the most beneficial options for the net benefits approach since added costs from increased QCSOSTF flows decreased the benefits of this option compared to the baseline scenario. Option 6 and 7 were the least beneficial approaches, and these negative benefits were contributed mostly by the high construction costs for LID. While LID has become a more effective and popular approach over the years it is still a relatively new and expensive technology. Since the Worcester CSO area is relatively large in total area, a great deal of LID is required to control flows and hazardous flooding in the system. As a result, construction costs for LID were very high compared to other options. In reality, it is expected that a combination of underground storage and changes to the pumping and controls at the QCSOSTF will serve as the most effective option going forward for managing CSO flows in the future under the uncertainty of climate change.

In addition, a study was conducted by Lauren Caputo of Tufts University on the combined sewer system in Somerville, MA. This case study served as an excellent comparison to the Worcester CSO system to learn more about different cities in New England and how they are affected by the expected increase of extreme storms through climate change. Somerville is a highly-dense urban city that is much smaller in total area than Worcester. It is located in the eastern part of Massachusetts directly west of Boston. For the Somerville CSO study, five different options were selected to manage increased CSO flow volumes and hazardous flooding in the future: no action, underground storage, LID, sewer separation, and a combination of sewer separation and LID. Table 67 and Figure 70 present final net benefit results for each option in Somerville (Caputo, 2011).

Table 67: Final net benefits results for Somerville
(Caputo, 2011)

	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

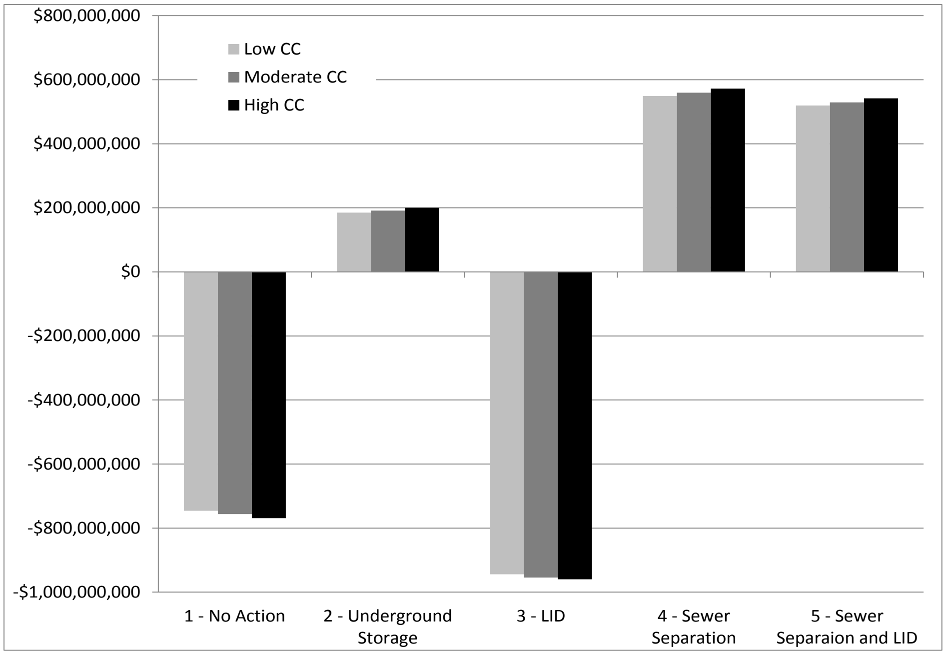


Figure 70: Final net benefits results for Somerville
(Caputo, 2011)

For the CSO system in Somerville, it was determined that sewer separation is the most beneficial strategy. For the Somerville system, sewer separation was implemented for the entire CSO area. Since the Somerville CSO area is almost four times as small in size as the Worcester CSO area, sewer separation was able to be implemented for the entire watershed without adding too many long-term construction costs. For the same reason, LID is much more effective in Somerville since not as much of it is implemented and long-term costs do not make a large negative impact on the overall net benefits. However, underground storage is a much more effective approach for Worcester since there is more pervious land available in Worcester for storage construction. In addition to limited space, Somerville is located near the Boston Harbor and Mystic River, so there are more impacts from rises in sea levels that make underground storage challenging. The Worcester system also benefits from the Quinsigamond Avenue and Upper Blackstone treatment facilities, and there is more room for improvement in the system in terms of updates to treatment facility storage and pumping that can benefit the system and its ability to manage CSOs in the future.

5.0 CONCLUSION

5.1 Summary

In today's society, it has become more important for urban areas to manage stormwater to prepare for climate change. Studies conducted over the past decade have indicated that the increase of extreme storm events is expected under future climate change scenarios, and these extreme storms will have major impacts on urban areas with high percentages of impervious cover. However, many traditional stormwater management techniques used in major cities all over the country do not consider climate change in their stormwater design. This study focuses on the combined sewer system in Worcester, Massachusetts and introduces the idea of robust decision making and stormwater management planning for climate change uncertainty. This study is part of a collaborative effort with students and professors from Tufts University, and several comparisons have been drawn between the studies in both Somerville in Worcester, which both utilize similar methods of climate change planning for stormwater management.

This study involves the use of robust decision making and analysis of best management practices (BMPs) as options for adapting to climate change in the design of stormwater management systems. In order to be considered a robust strategy, each adaptation option needed to control hazardous flooding for all design storms under all climate change scenarios. As a result, it was necessary to control flooding and avoid increases in flows through the QCSOSTF and UBWWTF for the 100-year design storm under a high climate change scenario over the 60-year timeframe from 2010 to 2070.

The design cost approach and net benefits approach were used to analyze long-term costs for these options. According to the design cost approach, it was determined that the use of underground storage should be installed in Worcester in locations where significant amounts of hazardous flooding occur. In addition to underground storage upstream of the QCSOSTF, the installation of one large storage tank was installed near Crompton Park to replace the numerous storage tanks that are installed in option 2. Finally, pumping rates were increased at the QCSOSTF to increase the capacity for flow to the QCSOSTF and decrease the amount of flooding occurring in locations near the facility. A net benefits approach was also used to compare the potential benefits of each option compared to the baseline scenario. For this approach, it was determined that option 3 is the most beneficial option, which includes the installation of underground storage upstream of the QCSOSTF in areas where hazardous flooding is significant (greater than 0.5 MG).

After analyzing model results using cost analysis approaches, it was determined that underground storage can be installed to control hazardous flooding and the increase of flows through the QCSOSTF and UBWWTF under all climate change scenarios. However, underground storage should be installed in select locations upstream of the Quinsigamond Avenue facility. Option 1 involves installing underground storage tanks at a total of 25 nodes throughout the Worcester system, with five tanks installed in 2010 that are as large as 2 acres in total area, and one storage tank needs to be a total of 8 acres in area in order to control hazardous flooding. However, it was determined through cost analysis that this approach is too costly, and it is more realistic to install underground storage in only select locations throughout the Worcester CSO area. This option will help save enough money on construction over the long-run compared to installing storage throughout the watershed, but it will still decrease hazardous flooding throughout the watershed and control the increase of CSO flow volumes through the QCSOSTF. In addition to installing storage at 18 upstream nodes, underground storage should also be installed at 3 nodes located near Quinsigamond Avenue.

Additional storage should be installed in 2040 to accommodate increased hazardous flooding in the future. Although upstream underground storage was determined to be the most cost-effective option, it does not meet all the design goals for this study. Model simulation results show that this adaptation option leads to the increase in flows through the Upper Blackstone treatment facility. Results from the design cost approach show that option 4 is the most cost-effective option for stormwater management under climate change. In addition to installing underground storage in select locations throughout the watershed, considerations be made to increase the pumping capacity at the QCSOSTF. For this study, pump flows were adjusted at specific depths in order to allow more combined sewage to flow through the facility to decrease the effects of flooding downstream.

5.2 Limitations

There were many assumptions made throughout the study that were necessary in order to complete the study, as only a limited amount of information was available. As a result, these assumptions introduced approximations for many different aspects of this research. Several assumptions were made relating to the configuration of the SWMM model. For model calibration, it was assumed that previous model inputs developed in 2001 are representative of the Worcester CSO system in 2012. The exception to this is the pumping control rules at the QCSOSTF, which were updated in 2008. During calibration and validation of the model, the current SWMM model was adjusted to include new control rules into the system, and these changes improved effluent discharge flows at the Quinsigamond facility and improved the accuracy of the model flows compared to observed data. A number of assumptions were also made for the design of each BMP option, and these assumptions made a significant effect on the amount of LID implemented and their respective costs. For the purposes of this study, conservative costs were approximated for the design and construction of LID techniques in order to attempt to accurately quantify the costs of LID. These assumptions may explain why the total construction costs for LID and the combination of LID and sewer separation were higher than expected. Assumptions were also made in order to calculate and determine the amount of hazardous flooding in basement and cost calculations for hazardous flooding damages. The cost values used for treatment of combined sewage and wastewater flows at the QCSOSTF and UBWWTF were also approximated and may not be entirely representative of current and future costs for treatment at these facilities. Other assumptions were made throughout this study in order to provide the most accurate representation of the effects of BMP options on the Worcester CSO system and the real implications of climate change on stormwater management.

The effects of climate change in water quantity of flows in Worcester were the only considerations for this study. However, water quality should also be included in future studies to provide a more realistic estimate of costs and benefits of different BMP options. In particular, LID did not perform well for the Worcester system in terms of water quantity and its ability to control CSO flows and flooding. However, LID provides more water quality benefits than water quantity benefits, and this may be a significant reason why this option did not perform well for this study. In order to obtain more accurate present value expected value costs for different adaptations options under climate change, a wider range of benefits should be considered. These benefits may include long-term environmental benefits, social benefits, and overall economic benefits. Environmental benefits may include improved water quality, air quality, and habitat protection. Specifically for Worcester, the improvement of land use, watershed health, and restoration of habitats and impaired water are important considerations that will be affected by climate change. The use of green infrastructure may also introduce further economic benefits that include increasing land value and aesthetics, reducing energy costs and consumptions, and increasing the life cycle of buildings and infrastructure in Worcester (EPA, 2011b). Finally, green infrastructure and the introduction of best management practices can introduce societal benefits through public education, establishing urban greenways, and improving the attractiveness of streets and rooftops with more green space (EPA, 2011b). All of these considerations may have significant impacts on the results of net benefits for BMP options, and they allow for further study of managing stormwater in urban areas under climate change.

5.3 Further Study

There is a great deal of research that still needs to be done on stormwater management and the ability to manage these systems under the uncertainty of climate change. Research continues to be ongoing where engineers and scientists are finding more ways to accurately quantify the effects of climate change and better manage stormwater to prepare for climate change uncertainty. For this study, a methodology was defined that compares design costs and net benefits for seven different stormwater management strategies for the Worcester CSO system. However, this is one of several methods that may have been used for the analysis of adaptation options and different designs and performance metrics.

Specifically for Worcester, other options for managing future stormwater flows under climate change may have been explored. A variety of alternatives have been investigated by the Worcester Department of Public Works (DPW) as possible options for controlling CSO flows and flooding in Worcester. Plans have been made for increasing the peak capacity of the UBWWTF from 154 MGD to 160 MGD. A series of high flow management alternatives have been considered at the Upper Blackstone facility, including increased storage and the diversion of influent wet weather flows. In addition to increasing peak treatment capacity, secondary treatment capacity would be increased from 80 MGD to 120 MGD (CDM, 2002). While these improvements will have some benefits on the water quantity in the system, it will have more major impacts on the water quality of the Blackstone River since they will help improve the UBWWTF's ability to accept more flow from the QCSOSTF.

The use of control stations and real-time control technology are other options that may be considered for future studies in Worcester. Studies have been conducted for considerations to modify the current control stations at Kelly Square and Harding Street. The Kelly Square Control Station was constructed in the 1980s in the Harding Street Overflow Collector as part of CSO control improvements implemented at that time (CDM, 2002). The control station provides additional storage for flows from the overflow collector to the Western Interceptor. Evaluations have been made by Worcester DPW for improving the control station and the activation of a leaf gate at the station (CDM, 2002). However, flooding risks are a major concern that in the past have outweighed any values of activating the gate. Alternatives have been evaluated to explore new operating protocols to ensure that gate operations do not cause additional flooding in the area. The Harding Street Control Station is a new control station that is similar to Kelly Square in structure with a hinged leaf gate, but this gate would be raised and lowered remotely depending on conditions in order to maximize storage. No connections would be necessary to divert flow between drainage basins. Real-time controls have been installed in the past as part of efforts to control the volume of CSOs in the system. Real-time controls include a data gathering system that monitors rainfall, pumping rates, treatment rates, and regulator positions throughout the CSO system. Global real-time technology continues to improve and has become a widely-used means of flow optimization for the management of stormwater in urban areas.

A combination of the use of real-time controls and increased pumping and storage at the QCSOSTF and UBWWTF are further options that should be considered for analysis of CSO and hazardous flooding control in Worcester. In addition, these adaptation options may be analyzed for other types of benefits, including environmental, social, and economic benefits. While this study provides a framework for exploring beneficial and cost-effective options for stormwater management in Worcester, there are many other options and potential areas of research that may be further explored for urban planning under climate change in Worcester and other urban areas across the United States and around the world.

List of References

Arisz, Hans, and Brian C. Burrell. "Urban Drainage Infrastructure Planning and Design Considering Climate Change." (2006): 1-9. Print.

Army Corps of Engineers (ACOE). “Economic Guidance Memorandum (EGM) 04-01, Generic Depth-Damage Relationships for Residential Structures with Basements.” Washington, D.C. 17 p. October 10, 2003.

Caine, T. "One Roof, Two Roofs, Green Roofs, Blue Roofs | Intercon." *New Steps in Sustainability*. Intercon, 4 Oct. 2010. Web. 12 Jan. 2012. <http://progressivetimes.wordpress.com/2010/10/04/one-roof-two-roofs-green-roofs-blue-roofs/>.

Caputo, Lauren. “Application of a Methodology to Determine Robust Stormwater & CSO Management Strategies under Climate Change: A Case Study in Somerville, Massachusetts.” Thesis. Tufts University, 2011. Medford: Tufts University, 2011. Print.

CDM. “Phase I CSO Long-term Control Plan Report”. Tech. Worcester: Worcester, Massachusetts Department of Public Works, 2002. Print. March 2002.

CDM. “Phase II CSO Long-term Control Plan Report.” Rep. Worcester: Worcester, Massachusetts Department of Public Works, 2004. Print. January 2004.

Chow, Ven, David Maidment and Larry Mays. Applied Hydrology. McGraw-Hill Science/Engineering/Math. 1988.

City of New York, 2012. "Blue Roof and Green Roof." *Nyc.gov*. Web. 3 Jan. 2012. <http://www.nyc.gov/html/dep/html/stormwater/green_pilot_project_ps118.shtml>.

City of Worcester, MA. "Managing Worcester's Combined Sewer System." *Welcome to the City of Worcester, MA*. 2012. Web. 1 Feb. 2012. <http://www.worcesterma.gov/dpw/water-sewer-operations/combined-sewer-system>.

Climap. "General Circulation Models (GCMs)." ZenSci Consult I/S, 2012. Web. 12 Mar. 2012. <http://climap.net/general-circulation-models-gcms>.

Cornell University. “Extreme Precipitation in New York & New England: An Interactive Web Tool for Extreme Precipitation Analysis”. Version 1.02. Copyright 2010- 2011. Web. March 1, 2011. <http://precip.eas.cornell.edu/>.

Curran, Eileen. "Dangerous Floods Hit Worcester Area." *NECN*. New England Cable News, 8 Sept. 2011. Web. 14 Mar. 2012. <http://www.necn.com/09/08/11/Dangerous-floods-hit-Worcester-area/landing.html?blockID=561176>.

Damodaram, Chandana, and Marcio H. Giacomoni, C. Prakash Khedun, Hillary Holmes, Andrea Ryan, William Saour, and Emily M. Zechman. “Simulation of Combined Best Management Practices and Low Impact Development for Sustainable Stormwater Management.” *Journal of Water Resources Planning and Management.* 46.5 2010: pp. 907-918. October 2010.

ENR: Engineering News Record. “Building and Construction Cost Indexes.” The McGraw-Hill Companies, Inc., 2012. Web. 29 Mar. 2012. <http://enr.construction.com/economics/>.

EPA - Environmental Protection Agency. "Combined Sewer Overflow (CSO) Control Policy." *Federal Register*. 19 Apr. 1994. Web. 2 Mar. 2012. <http://www.epa.gov/npdes/pubs/owm0111.pdf>.

EPA - Environmental Protection Agency. "EPA - CSO Control Policy." United States Environmental Protection Agency, 12 Sept. 2002. Web. 8 Jan. 2012. <http://cfpub.epa.gov/npdes/cso/cpolicy.cfm?program_id=5>.

EPA - Environmental Protection Agency. "Green Roofs." *US Environmental Protection Agency*. U.S. EPA, 20 Dec. 2011. Web. 2 Jan. 2012

EPA - Environmental Protection Agency. “Low Impact Development (LID).” March 2011. Web. July 5, 2011. <http://www.epa.gov/owow/NPS/lid/>.

EPA - Environmental Protection Agency. “Office of Wastewater Management." *U.S. EPA*. 12 Mar. 2009. Web. 18 Jan. 2012. <http://cfpub.epa.gov/npdes/index.cfm>.

EPA - Environmental Protection Agency. "Sewer Separation." *Combined Sewer Overflow Management Fact Sheet*. United States Environmental Protection Agency, Sept. 1999. Web. 12 Jan. 2012. <http://water.epa.gov/scitech/wastetech/upload/2002_06_28_mtb_sepa.pdf>.

EPA - Environmental Protection Agency. "Storm Water Management Model (SWMM)." 2012. Web. 12 Jan. 2012. <http://www.epa.gov/nrmrl/wswrd/wq/models/swmm/>.

EPA - Environmental Protection Agency. "Storm Water Management Model | Urban Watershed Management Research | US EPA."*US Environmental Protection Agency*. United States Environmental Protection Agency, 5 Jan. 2012. Web. 10 Jan. 2012. <http://www.epa.gov/nrmrl/wswrd/wq/models/swmm/>.

EPA - Environmental Protection Agency *“*United States Environmental Protection Agency.” 24 June 2011. Web. 14 Jan. 2012. <http://cfpub.epa.gov/npdes/stormwater/munic.cfm>. <http://epa.gov/heatisland/mitigation/greenroofs.htm>.

Gately, Robert F., and Lawrence A. Schafer. “Computer Operated Combined Sewer Overflow Treatment Facility at Worcester, MA.” Rep. 2007. Print.

Google. "Google Maps." *Quinsigamond Avenue - Worcester, MA*. 2012. Web. 10 Jan. 2012. <http://maps.google.com/>.

Greenworks. "Porous Pavement." *Managing Stormwater*. 2011. Web. 10 Dec. 2011. <http://greenworks.tv/stormwater/porouspavement.htm>.

Guitierrez, S. “US EPA’s Urban Watershed Research Program in BMPs and Restoration for Water Quality Improvement.” Field R., et al, editors, BMP Technology in Urban Watersheds, Current and Future Directions, American Society of Civil Engineers, 2006.

Hansen, N. Wayne. *Worcester Massachusetts and the Surrounding Area. Viewed From The South Looking To The North. Taken from 3700 Feet in A Cessna 150 Airplane.* 2006. Photograph. Worcester.

Hejazi, Mohamad I., and Glenn E. Moglen. "The Effect of Climate and Land Use Change on Flow Duration in the Maryland Piedmont Region." *Hydrological Processes* 22 (2008): 4710-722. Print.

IPCC, 2001: *Climate Change 2001: The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change* [Houghton, J.T.,Y. Ding, D.J. Griggs, M. Noguer, P.J. van der Linden, X. Dai, K. Maskell, and C.A.

Kasco Marine, Inc. "Retention Ponds." *Got Algae? Site for Water Quality Management*. 2006. Web. 14 Jan. 2012. <http://www.gotalgae.com/retention_ponds.htm>.

King County. "Combined Sewer Overflow Control." *CSO Control Program*. Web. 13 Apr. 2012. <http://www.kingcounty.gov/environment/wastewater/CSO/FAQ.aspx>.

Kirshen, Paul, Kenneth Strzepek, and Susan Roudebush. *Guidance Tools for Planning and Management of Urban Drainage Systems under a Changing Climate*. Thesis. Tufts University, 2010. Medford, 2010. Print.

Lake Superior Streams. "Stormwater Management - Bioretention Basins." *Lake Superior - Duluth Streams*. Web. 7 Jan. 2012. <http://www.lakesuperiorstreams.org/stormwater/toolkit/bioretention.html>.

Low Impact Development Center, Inc. "LID Urban Design Tools - Bioretention." *Low Impact Development (LID) Urban Design Tools*. 2007. Web. 5 Jan. 2012. <http://www.lid-stormwater.net/bio_benefits.htm>.

Mailhot, Alain, and Sophie Duchesne. "Design Criteria of Urban Drainage Infrastructures under Climate Change." *Journal of Water Resources Planning and Management* (2010): 201-08. Print.

Mass.gov. "Policies & Guidance Documents." *Combined Sewer Overflows*. Mass DEP, 2012. Web. 21 Jan. 2012. <http://www.mass.gov/dep/water/laws/policies.htm>.

Massachusetts Department of Environmental Protection (MassDEP). "Massachusetts Stormwater Handbook." Vol. 2 Ch.2: Structural BMP. 2008.

Massachusetts Department of Environmental Protection (MassDEP). "Stormwater Handbook." Vol. 2: Stormwater Technical Handbook. March 1997

Massachusetts Living. "Worcester, Massachusetts." *Massachusetts Internet Magazine*. Multimedia, Inc., 2012. Web. 21 Oct. 2011. <http://www.maliving.com/mass/towns/worcester/>.

Mass GIS. "Massachusetts Geographic Information System." *Office of Geographic Information (Mass GIS)*. Commonwealth of Massachusetts, 2012. Web. 30 Jan. 2012. <http://www.mass.gov/mgis/massgis.htm>.

MMSD. *The Application of Stormwater Runoff Reduction Best Management Practices in Metropolitan Milwaukee*. Rep. Milwaukee: Milwaukee Metropolitan Reduction Program, 2005. Print.

Monahan, John. "Challenge Boosts Two Cities' Populations." *Telegram & Gazette*. 20 Nov. 2009. Web. 22 Mar. 2012. <http://www.telegram.com/>.

Montalto, Frank, Christopher Behr, Katherine Alfredo, Max Wolf, Matvey Arye, and Mary Walsh. "Rapid assessment of the cost-effectiveness of low impact development for CSO control." *Landscape and Urban Planning*. Science Direct. March 2007. pp. 117-131.

National Weather Service. "Daily Temperature Records." National Oceanic and Atmospheric Administration, 15 Apr. 2012. Web. 2 Feb. 2012. <http://weather.gov/>.

NYC Environmental Protection "Blue Roof." *Flickr*. Yahoo!, 30 Nov. 2011. Web. 12 Feb. 2012. <http://www.flickr.com/photos/nycep/6433201761/>.

Powell, Anthony. 2008. "An Analysis of the Change of Design Storms due to Future Climate Predictions." Master's Thesis, University of Colorado at Boulder Graduate School and the Civil, Environmental, and Architectural Engineering Department. 95 p.

Philadelphia Water Department. "Dry Wells." 2012. Web. 4 Apr. 2012. <http://www.malvern.org/htms/documents/drywell.pdf>.

Public Works and Parks. "City Parks." *Welcome to the City of Worcester, MA*. City of Worcester, MA, 2012. Web. 5 Feb. 2012. <http://www.worcesterma.gov/dpw/parks-rec/city-parks>.

Revelle, Charles S., Earl E. Whitlatch, and Jeff R. Wright. Civil and Environmental Systems Engineering. 2nd Ed. Prentice Hall, August 2003.

Rossman, Lewis A. July 2010. *Stormwater Management Model User's Manual*. Version 5.0. U.S. Environmental Protection Agency (US EPA).

Sample, David J., James P. Heaney, Leonard T. Wright, Chi-Yuan Fan, Fu-Hsiung Lai, and Richard Field. "Costs of Best Management Practices and Associated Land for Urban Stormwater Control." *Journal of Water Resources Planning and Management* (2003): 59-68. Print.

Stone Bilt Concepts. "StoneBilt Concepts - Precast Concrete Pavers Specifications and Info." *StoneBilt Concepts - Cast Concrete Alternative to Natural Stone Pavers*. 2011. Web. 11 Jan. 2012. <http://www.stonebiltconcepts.com/technical-downloads.html>.

Trulia. "Worcester, MA Real Estate Overview." 2012. Web. 27 Mar. 2012. <http://www.trulia.com/real_estate/Worcester-Massachusetts/>.

UBWPAD. "Treatment Facilities." *Upper Blackstone Water Pollution Abatement District*. 2012. Web. 23 Dec. 2011. <http://www.ubwpad.org/>.

United Nations Educational, Scientific, and Cultural Organization (UNESCO). 2006. *Water, A Shared Responsibility, The UN World Water Development Report 2*. Berghahn Books, New York, NY, USA.

United States Environmental Protection Agency. "EPA Regulations - Office of Wastewater Management." *U.S. EPA ColdFusion Server*. 6 Mar. 2009. Web. 14 Jan. 2012. <http://cfpub.epa.gov/npdes/regs.cfm?program_id=6>.

United States Environmental Protection Agency. "What Is a Rain Barrel?" *Epa.gov*, Aug. 2009. Web. 26 Dec. 2011. <http://www.epa.gov/region3/p2/what-is-rainbarrel.pdf>.

U.S. Environmental Protection Agency (USEPA). September 1999. *Combined Sewer Overflow Technology Fact Sheet.* Office of Water. p. 7-11 <http://cfpub1.epa.gov/npdes/cso/ninecontrols.cfm?program_id=5>.

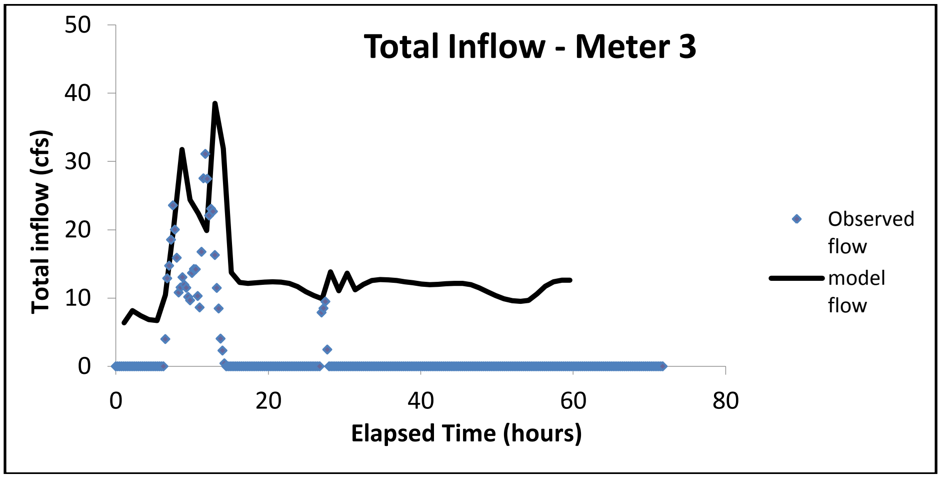
U.S. Environmental Protection Agency. Rep. Aug. 2010. Web. <http://www.epa.gov>.

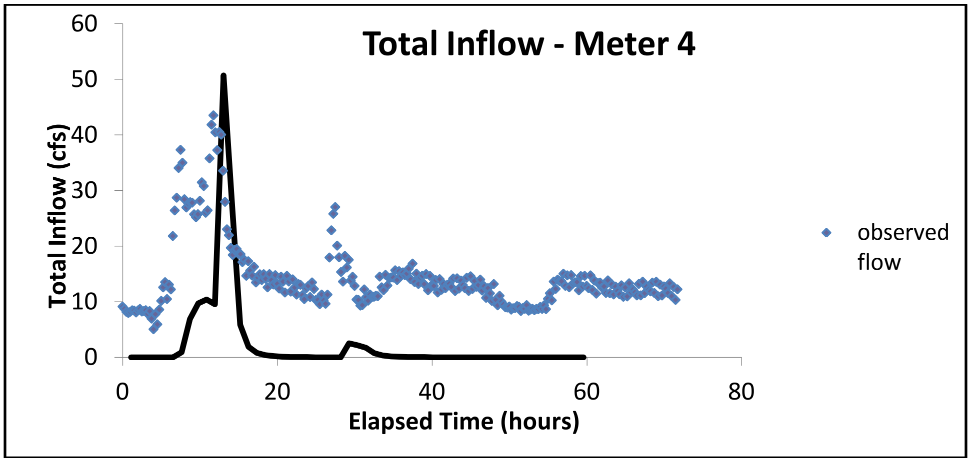
U.S. EPA."EPA - Stormwater Menu of BMP." U.S. Environmental Protection Agency, 9 Apr. 2007. Web. 1 Nov. 2010. "EPA - Stormwater Discharges From Municipal Separate Storm Sewer Systems (MS4s)."

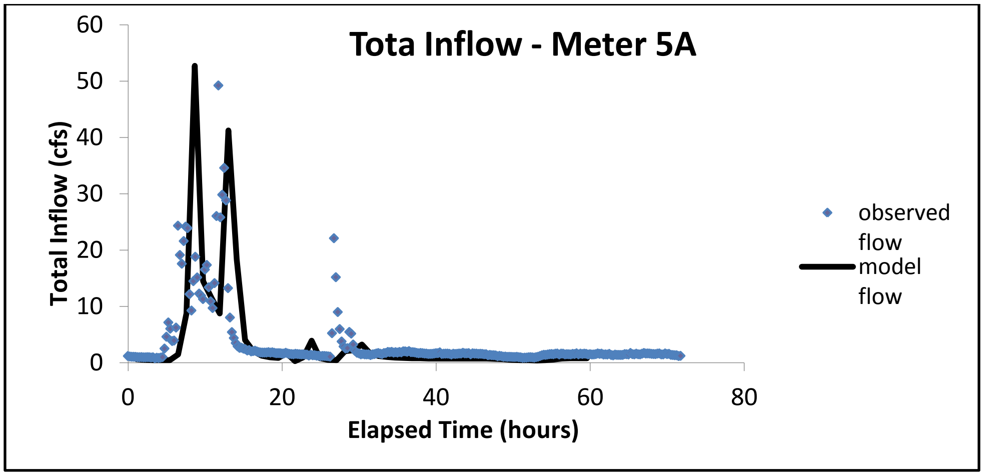
APPENDIX

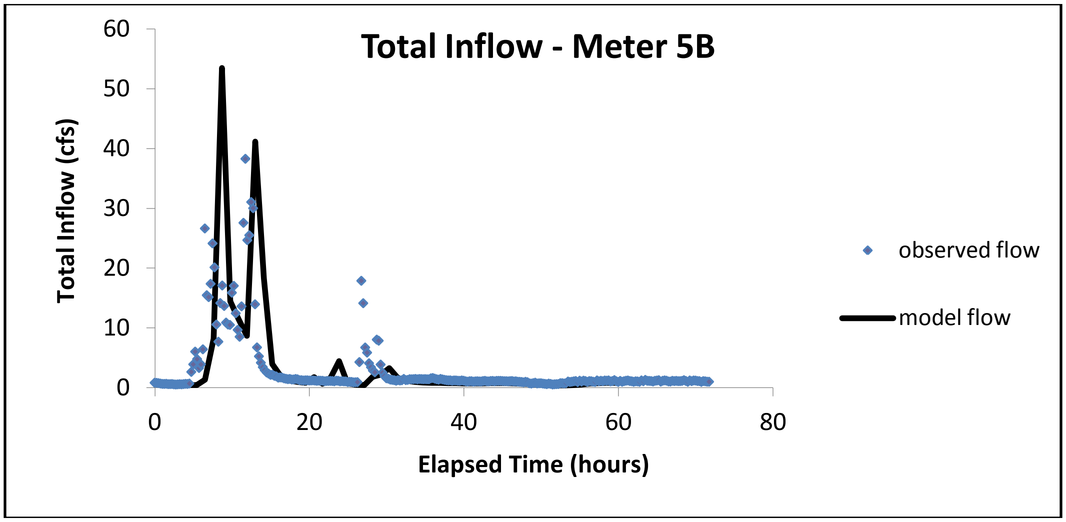
Appendix A: Model Calibration Results

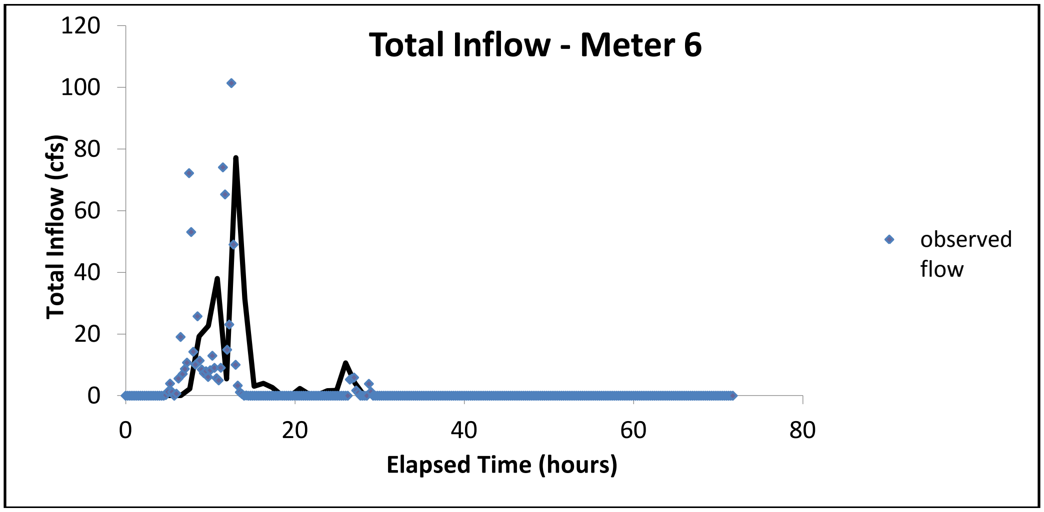
June 2-4, 2001

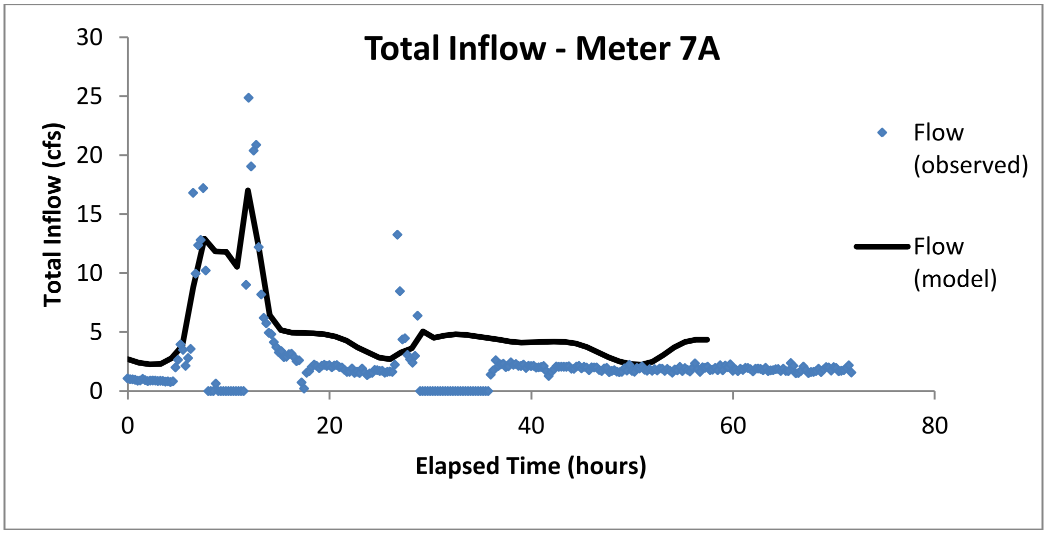


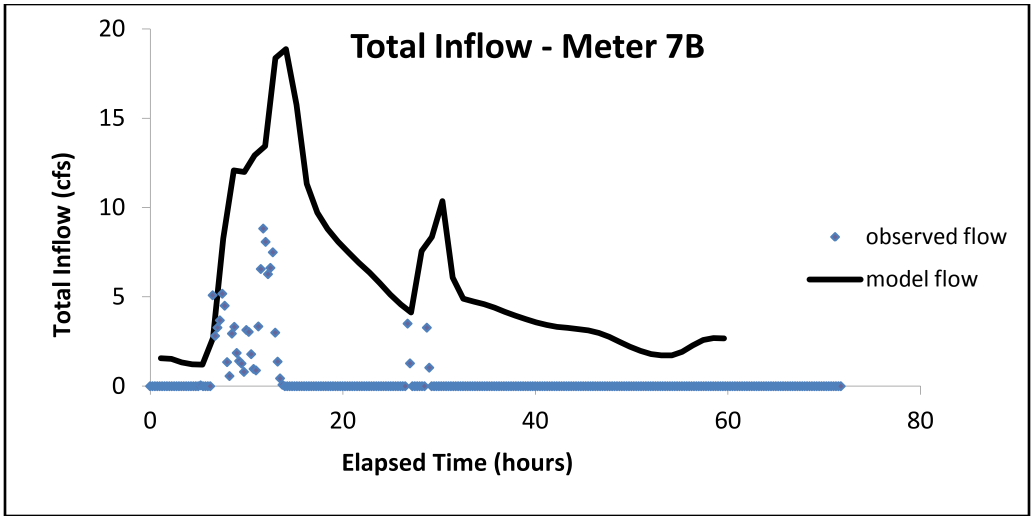


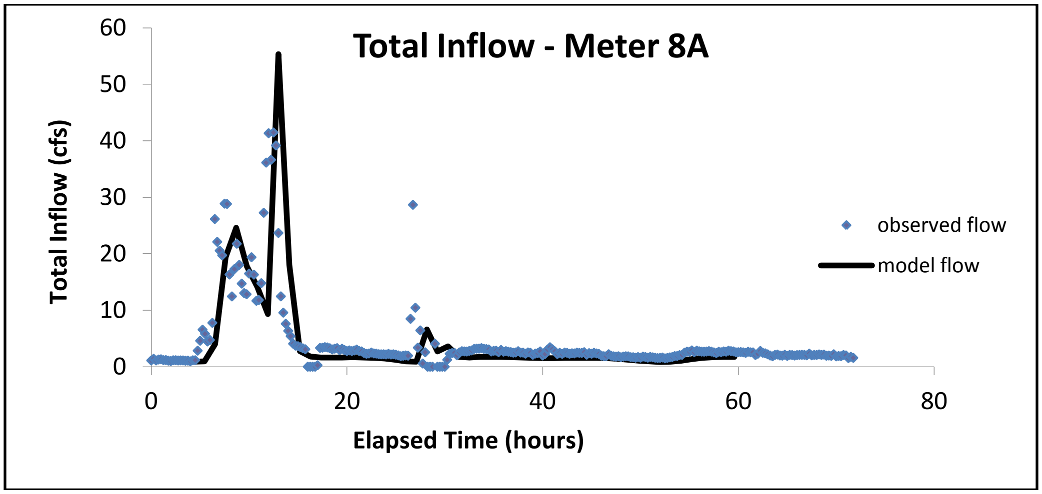


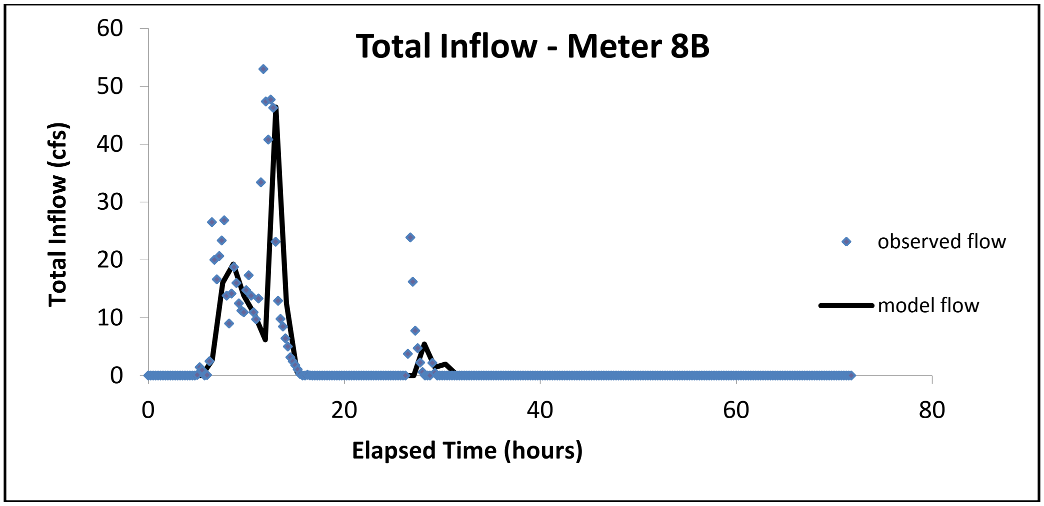

Total Inflow - Meter 5B
Total Inflow (cfs)
60
50
40
30
20
10
0
0
20
40
60
80
Elapsed Time (hours)
observed flow
model flow

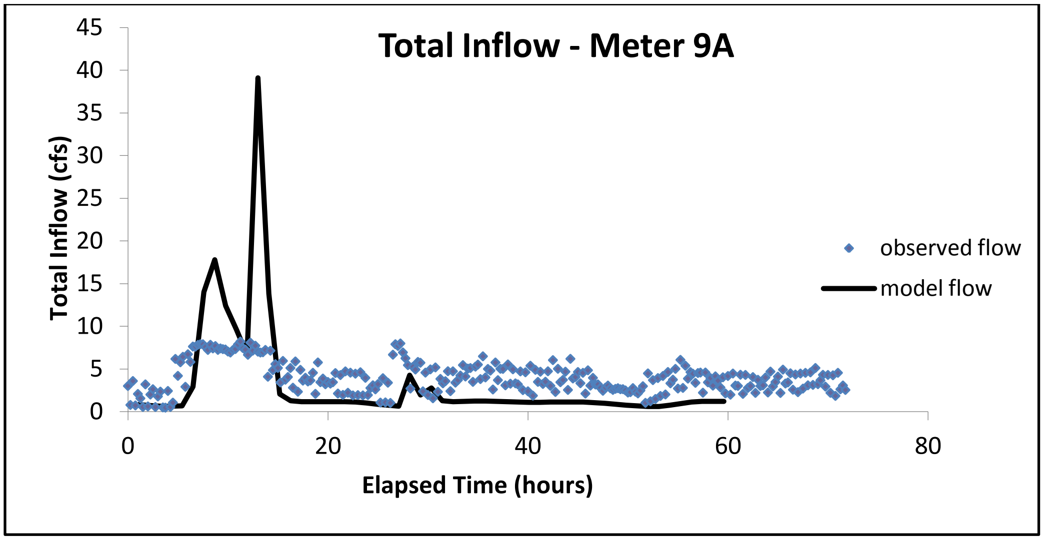

Total Inflow - Meter 6
Total Inflow (cfs)
120
100
80
60
40
20
0
0
20
40
60
80
Elapsed Time (hours)
observed flow

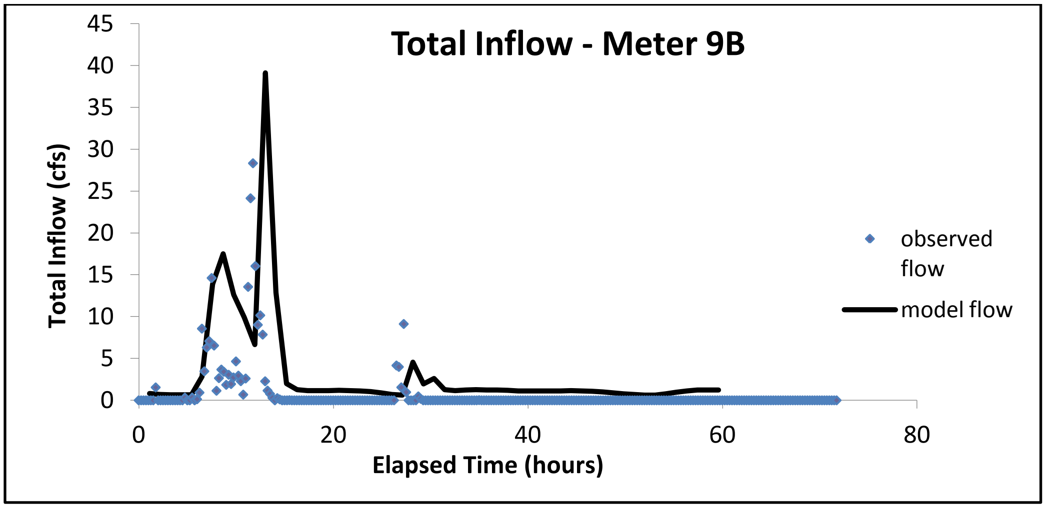

Total Inflow - Meter 7A
Total Inflow (cfs)
30
25
20
15
10
5
0
0
20
40
60
80
Elapsed Time (hours)
Flow (observed)
Flow (model)

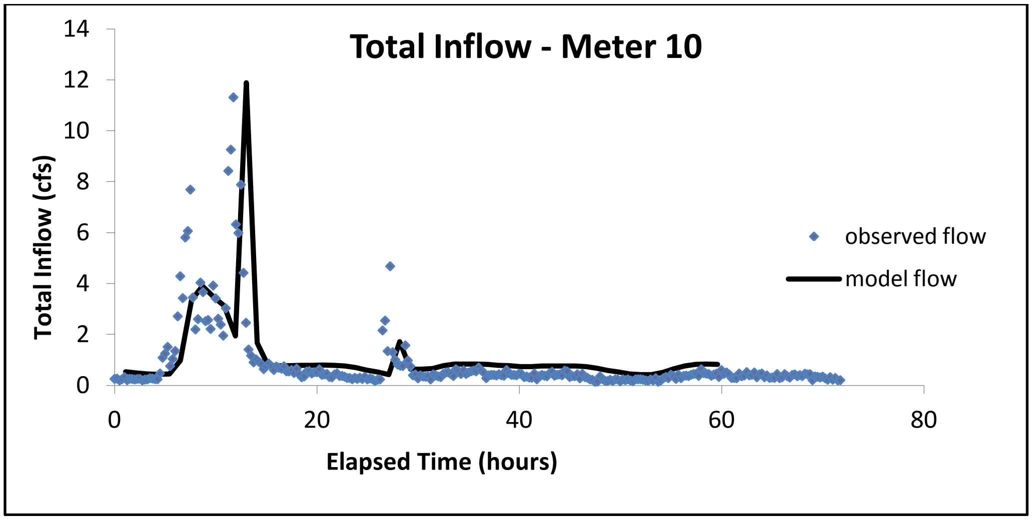

Total Inflow - Meter 7B
Total Inflow (cfs)
20
15
10
5
0
0
20
40
60
80
Elapsed Time (hours)
◆ observed flow
model flow

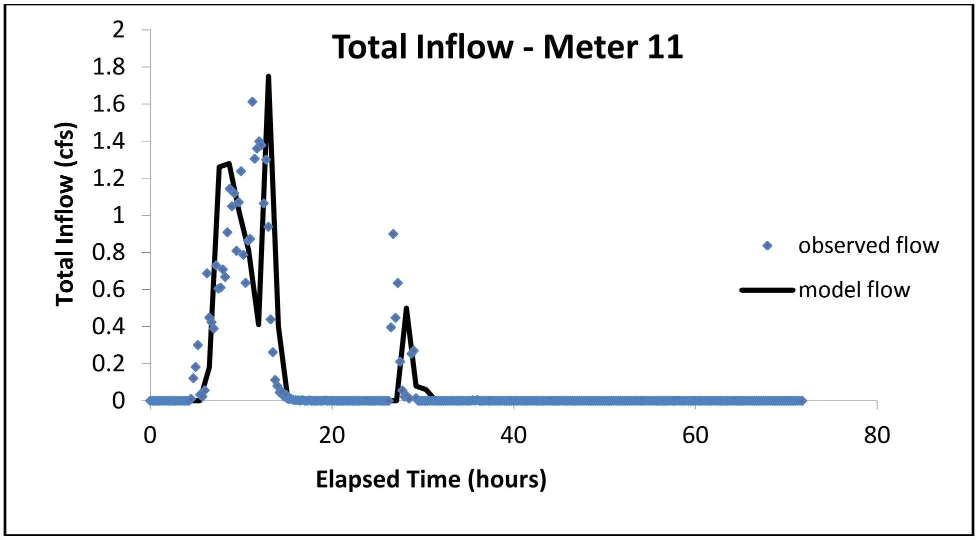

Total Inflow - Meter 8A
Total Inflow (cfs)
60
50
40
30
20
10
0
0
20
40
60
80
Elapsed Time (hours)
◆ observed flow
model flow

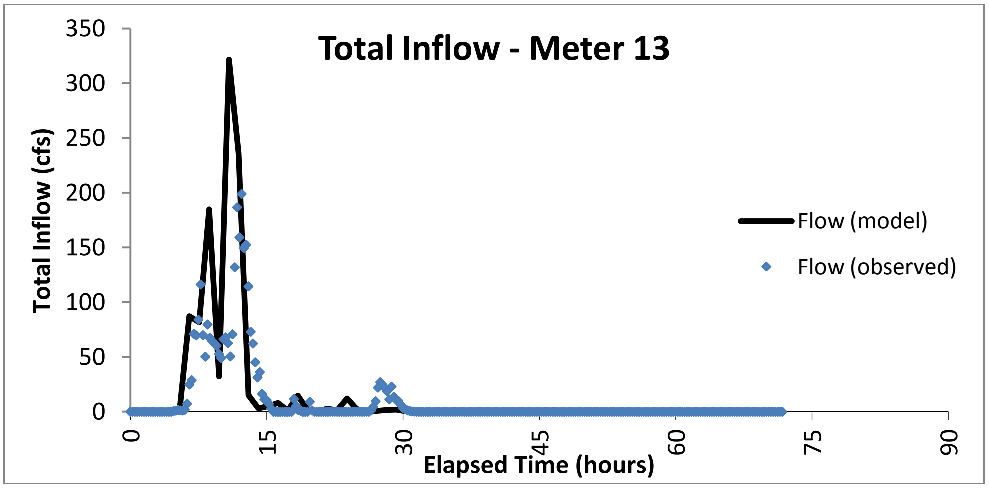

Total Inflow - Meter 8B
Total Inflow (cfs)
60
50
40
30
20
10
0
0
20
40
60
80
Elapsed Time (hours)
◆ observed flow
model flow

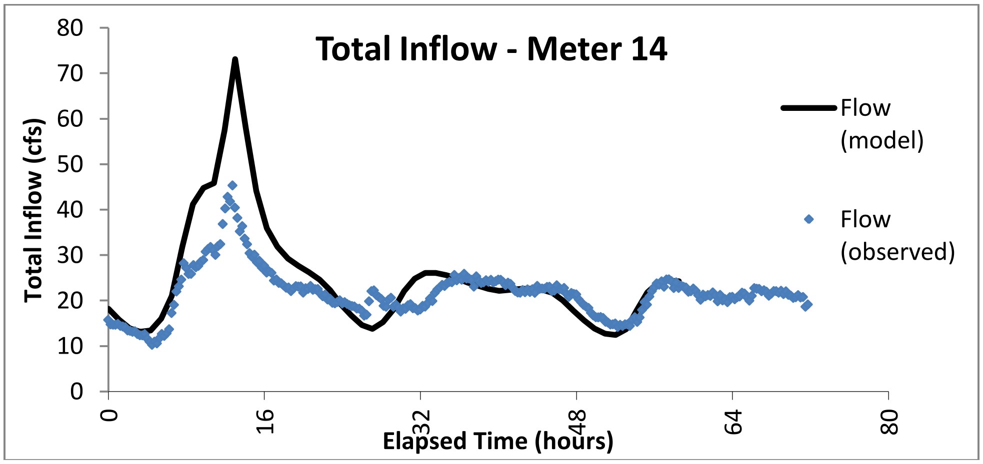

Total Inflow - Meter 9A
Total Inflow (cfs)
45
40
35
30
25
20
15
10
5
0
0
20
40
60
80
Elapsed Time (hours)
observed flow
model flow

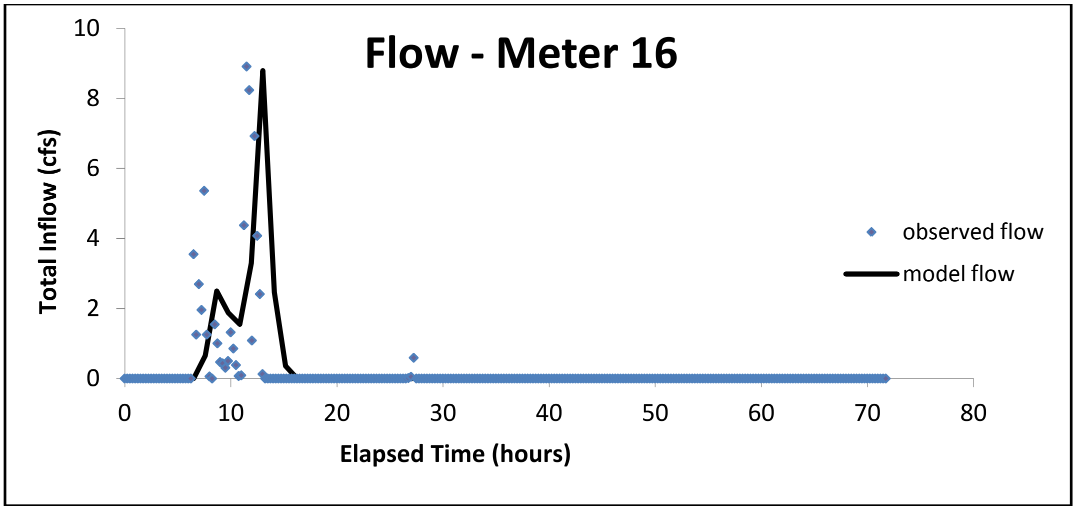

Total Inflow - Meter 9B
Total Inflow (cfs)
45
40
35
30
25
20
15
10
5
0
0
20
40
60
80
Elapsed Time (hours)
observed flow
model flow


Total Inflow - Meter 10
Total Inflow (cfs)
14
12
10
8
6
4
2
0
0
20
40
60
80
Elapsed Time (hours)
observed flow
model flow

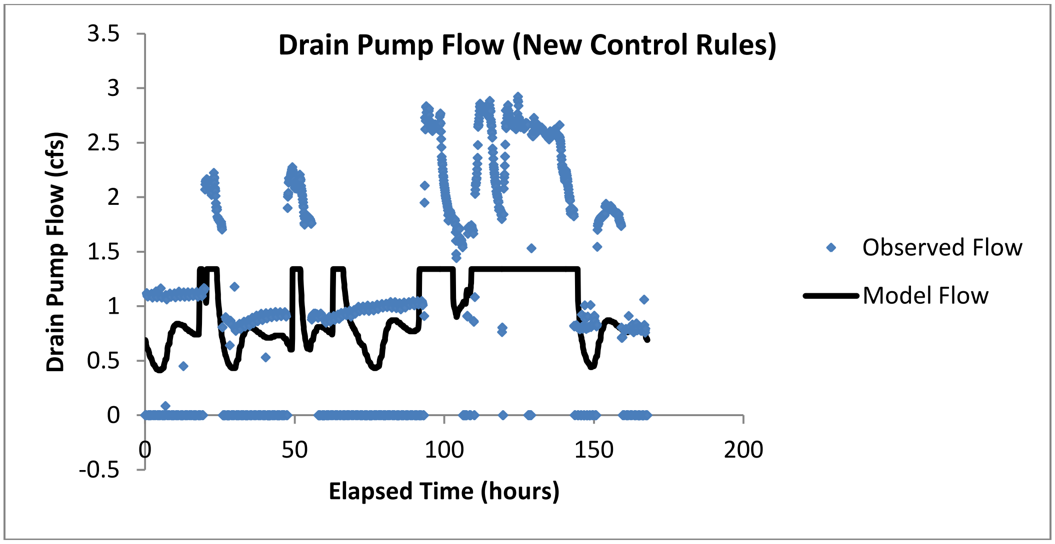

Total Inflow - Meter 11
Total Inflow (cfs)
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0
20
40
60
80
Elapsed Time (hours)
observed flow
model flow

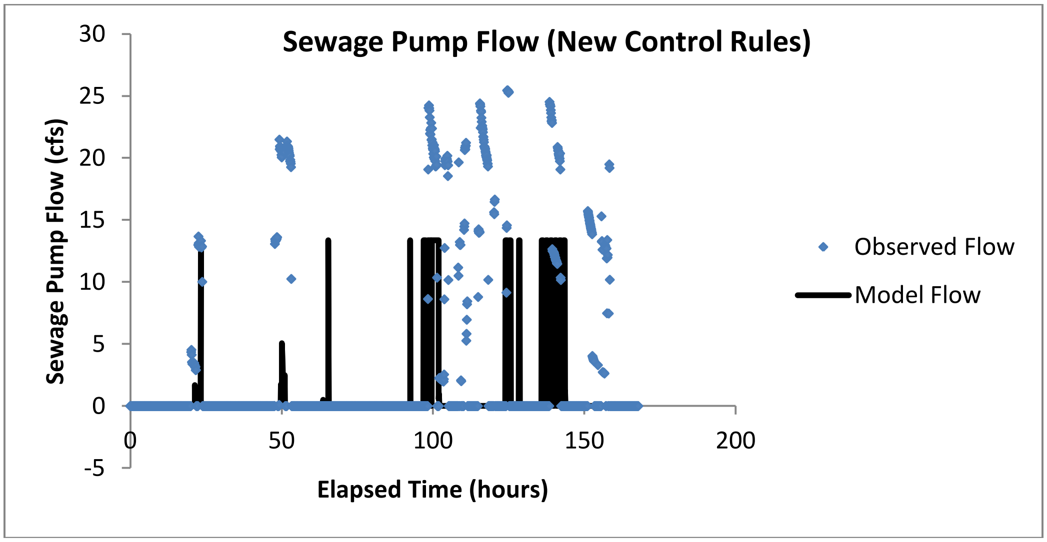

Total Inflow - Meter 13
Total Inflow (cfs)
350
300
250
200
150
100
50
0
0
15
30
45
60
75
90
Elapsed Time (hours)
Flow (model)
Flow (observed)


Total Inflow - Meter 14
Total Inflow (cfs)
80
70
60
50
40
30
20
10
0
0
16
32
48
64
80
Elapsed Time (hours)
Flow (model)
Flow (observed)

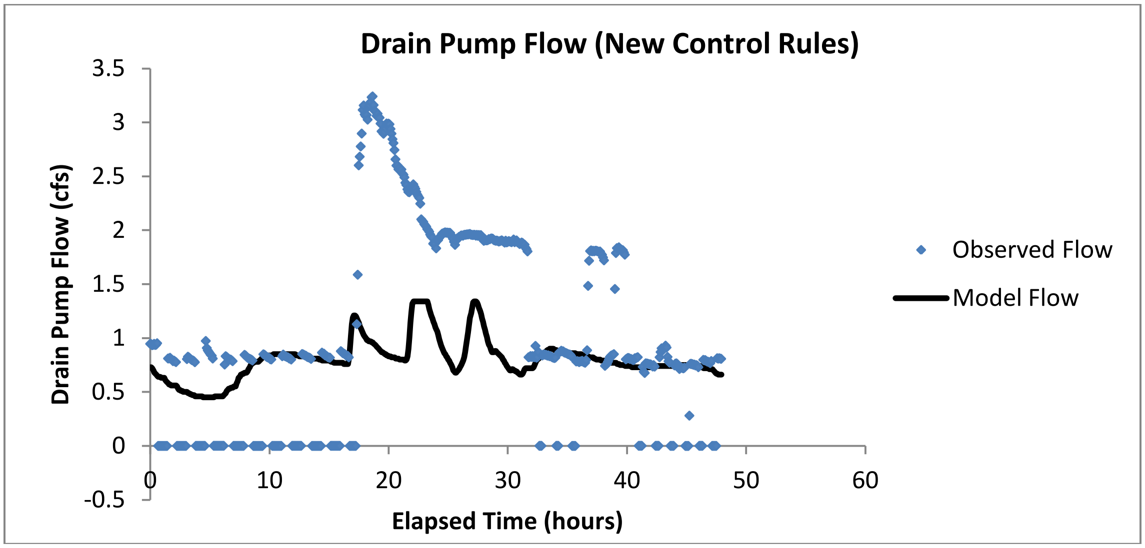


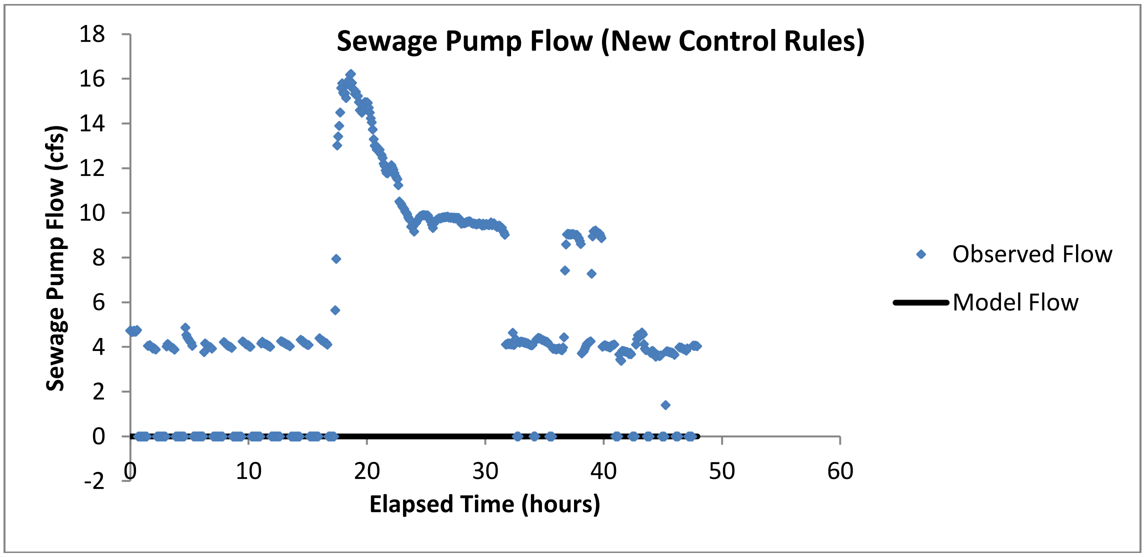
July 19-25, 2008



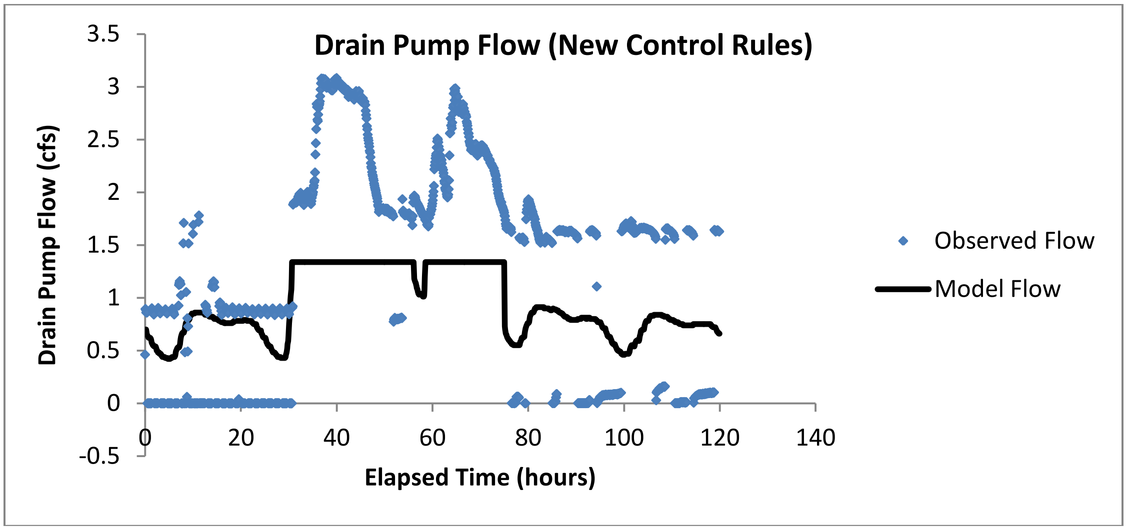


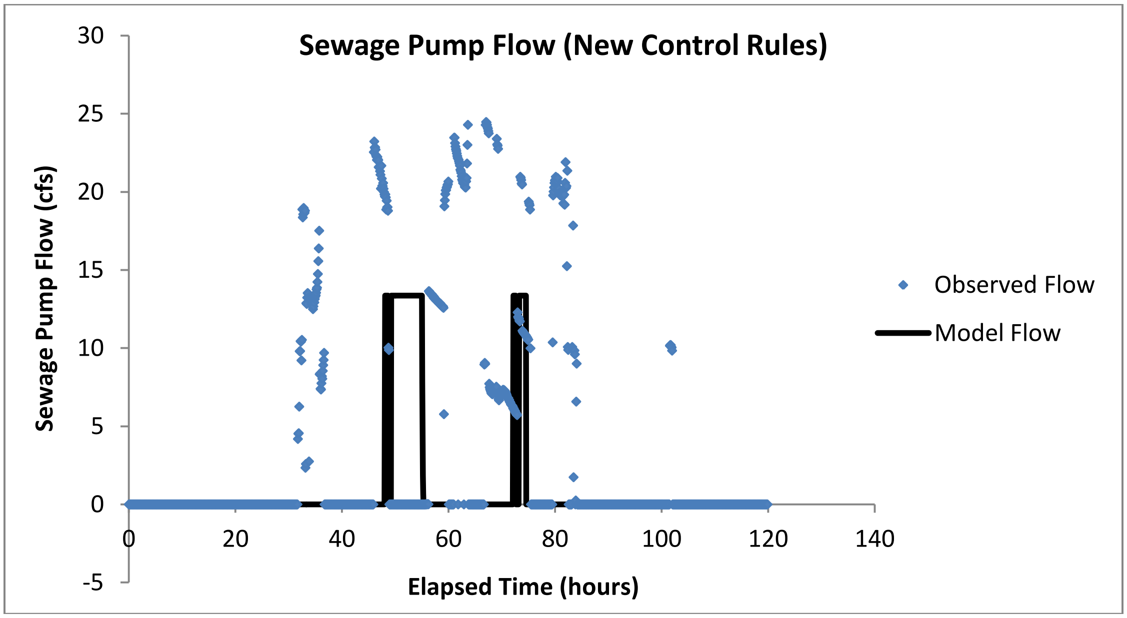
August 10-11, 2008





September 25-29, 2008





Appendix B: Model Simulation Results

Option 1: No Action

Storm	Scenario	Flooding (MG)	QCSOSTF Flow Volume (MG)	UBWWTF Flow Volume (MG)
3-month	2012	0.000	0.000	208.095
3-month	2040 H	0.000	0.000	209.678
3-month	2040 M	0.000	0.000	205.792
3-month	2040 L	0.000	0.000	191.148
3-month	2070 H	0.101	13.180	210.440
3-month	2070 M	0.073	12.257	209.678
3-month	2070 L	0.059	10.971	207.269
10-year	2012	22.012	45.662	232.708
10-year	2040 H	35.341	43.018	235.886
10-year	2040 M	33.807	46.967	229.068
10-year	2040 L	31.531	50.619	221.323
10-year	2070 H	40.962	54.936	243.571
10-year	2070 M	34.336	52.978	241.311
10-year	2070 L	28.787	40.510	219.631
100-year	2012	113.773	107.000	271.232
100-year	2040 H	179.402	135.282	305.648
100-year	2040 M	147.174	119.775	287.660
100-year	2040 L	104.674	104.674	235.886
100-year	2070 H	168.190	109.875	274.416
100-year	2070 M	94.230	103.335	274.271
100-year	2070 L	91.001	71.623	243.571

Option 2: Underground storage throughout the watershed

Storm	Scenario	Flooding (MG)	QCSOSTF Flow Volume (MG)	UBWWTF Flow Volume (MG)
3-month	2012	0.000	0.000	208.093
3-month	2040 H	0.000	0.000	209.836
3-month	2040 M	0.000	0.000	205.436
3-month	2040 L	0.000	0.000	190.425
3-month	2070 H	0.003	0.000	210.624
3-month	2070 M	0.002	0.000	209.836
3-month	2070 L	0.002	0.000	207.537
10-year	2012	4.886	17.132	232.636
10-year	2040 H	4.584	18.804	236.687
10-year	2040 M	3.960	19.025	230.381
10-year	2040 L	3.646	21.398	222.776
10-year	2070 H	4.519	22.449	238.865
10-year	2070 M	3.455	22.434	234.664
10-year	2070 L	2.978	18.117	221.897
100-year	2012	31.967	44.947	271.276
100-year	2040 H	46.388	60.423	306.442
100-year	2040 M	26.737	52.705	289.157
100-year	2040 L	25.974	46.389	236.687
100-year	2070 H	43.954	49.737	276.155
100-year	2070 M	19.070	45.928	275.679
100-year	2070 L	16.041	30.745	244.493

Option 3: Underground storage upstream of QCSOSTF

Storm	Scenario	Flooding (MG)	QCSOSTF Flow Volume (MG)	UBWWTF Flow Volume (MG)
3-month	2012	0	0	301.742
3-month	2040 H	0	0	302.787
3-month	2040 M	0	0	299.737
3-month	2040 L	0	0	287.021
3-month	2070 H	0	0	303.391
3-month	2070 M	0	0	302.787
3-month	2070 L	0	0	301.461
10-year	2012	7.61	27.925	321.71
10-year	2040 H	11.81	24.653	324.980
10-year	2040 M	10.685	26.528	320.738
10-year	2040 L	9.923	30.556	313.671
10-year	2070 H	16.038	31.291	327.061
10-year	2070 M	12.146	30.044	324.512
10-year	2070 L	9.184	22.943	312.526
100-year	2012	42.712	55.02	357.2
100-year	2040 H	77.382	109.970	388.566
100-year	2040 M	59.679	79.282	372.448
100-year	2040 L	49.573	61.548	361.263
100-year	2070 H	72.774	73.536	360.250
100-year	2070 M	55.616	59.738	360.249
100-year	2070 L	48.559	37.696	333.028

Option 4: Underground storage upstream of QCSOSTF and increased QCSOSTF pumping

Storm	Scenario	Flooding (MG)	QCSOSTF Flow Volume (MG)	UBWWTF Flow Volume (MG)
3-month	2012	0.000	0.000	208.093
3-month	2040 H	0.000	0.000	209.668
3-month	2040 M	0.000	0.000	205.605
3-month	2040 L	0.000	0.000	191.148
3-month	2070 H	0.009	0.000	210.426
3-month	2070 M	0.002	0.000	209.668
3-month	2070 L	0.002	0.000	207.245
10-year	2012	20.083	48.494	232.718
10-year	2040 H	11.371	23.723	235.863
10-year	2040 M	8.159	25.119	229.028
10-year	2040 L	8.072	27.978	220.963
10-year	2070 H	14.119	29.694	238.154
10-year	2070 M	11.698	27.705	233.138
10-year	2070 L	6.598	22.264	219.804
100-year	2012	92.028	103.472	271.401
100-year	2040 H	70.709	111.027	305.024
100-year	2040 M	58.889	84.029	287.481
100-year	2040 L	54.755	58.889	235.863
100-year	2070 H	65.683	77.086	274.255
100-year	2070 M	34.887	57.346	274.210
100-year	2070 L	34.111	39.166	243.496

Option 5: Sewer Separation

Storm	Scenario	Flooding (MG)	QCSOSTF Flow Volume (MG)	UBWWTF Flow Volume (MG)
3-month	2012	0	0.000	194.493
3-month	2040 H	0.000	0.000	195.619
3-month	2040 M	0.000	0.000	194.062
3-month	2040 L	0.000	0.000	187.784
3-month	2070 H	0.093	0.000	195.619
3-month	2070 M	0.071	0.000	194.436
3-month	2070 L	0.059	0.000	193.463
10-year	2012	3.294	28.303	200.519
10-year	2040 H	5.968	28.359	201.476
10-year	2040 M	5.031	27.592	198.958
10-year	2040 L	3.643	31.126	196.306
10-year	2070 H	7.315	36.780	202.189
10-year	2070 M	6.726	33.714	200.046
10-year	2070 L	4.009	25.935	196.056
100-year	2012	28.390	64.729	209.130
100-year	2040 H	48.156	94.740	213.946
100-year	2040 M	38.281	78.233	211.507
100-year	2040 L	31.115	68.545	209.799
100-year	2070 H	47.874	79.861	209.936
100-year	2070 M	22.663	71.519	206.890
100-year	2070 L	20.343	51.699	201.071

Option 6: Low Impact Development (LID) throughout the watershed

Storm	Scenario	Flooding (MG)	QCSOSTF Flow Volume (MG)	UBWWTF Flow Volume (MG)
3-month	2012	0	0	301.462
3-month	2040 H	0	0	302.12
3-month	2040 M	0	0	299.044
3-month	2040 L	0	0	286.387
3-month	2070 H	0.223	18.775	302.598
3-month	2070 M	0.08	17.550	302.253
3-month	2070 L	0.065	15.471	300.833
10-year	2012	20.822	52.606	321.442
10-year	2040 H	35.171	42.526	323.912
10-year	2040 M	32.753	49.160	319.809
10-year	2040 L	31.407	56.935	313.329
10-year	2070 H	40.329	57.715	325.756
10-year	2070 M	34.299	53.783	323.468
10-year	2070 L	28.455	39.343	311.666
100-year	2012	110.133	112.456	357.45
100-year	2040 H	170.223	182.716	390.847
100-year	2040 M	134.442	153.957	374.496
100-year	2040 L	131.093	131.093	362.350
100-year	2070 H	49.203	142.713	325.756
100-year	2070 M	41.091	125.559	323.468
100-year	2070 L	32.966	76.056	311.666

Option 7: Combination of LID and sewer separation

Storm	Scenario	Flooding (MG)	QCSOSTF Flow Volume (MG)	UBWWTF Flow Volume (MG)
3-month	2012	0	3.087	289.901
3-month	2040 H	0	4.376	289.939
3-month	2040 M	0	3.749	288.745
3-month	2040 L	0	0	284.156
3-month	2070 H	0.1	5.074	289.935
3-month	2070 M	0.076	4.525	289.810
3-month	2070 L	0.062	4.195	288.894
10-year	2012	3.246	28.147	294.689
10-year	2040 H	4.631	27.355	294.985
10-year	2040 M	4.371	29.761	293.212
10-year	2040 L	2.821	30.502	291.030
10-year	2070 H	7.502	35.602	295.292
10-year	2070 M	6.046	32.401	293.991
10-year	2070 L	3.848	24.491	290.538
100-year	2012	27.476	77.162	301.356
100-year	2040 H	49.486	127.796	305.837
100-year	2040 M	38.683	104.072	303.919
100-year	2040 L	30.809	88.261	302.384
100-year	2070 H	47.782	105.419	302.421
100-year	2070 M	23.399	86.479	300.745
100-year	2070 L	19.26	56.257	295.363