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A Screening Assessment of the Potential Impacts of Climate Change on Combined Sewer Overflow (CSO) Mitigation in the Great Lakes and New England Regions

National Center for Environmental Assessment
Office of Research and Development, Washington, DC 20460

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LIST OF ABBREVIATIONS AND ACRONYMS

AOGCM	Atmosphere-Ocean General Circulation Model
CSO	Combined Sewer Overflow
CSS	Combined Sewer System
IPCC	Intergovernmental Panel on Climate Change
LTCP	Long-Term Control Plan
NMC	Nine Minimum Controls
TMDL	Total Maximum Daily Load
VEMAP	Vegetation/Ecosystem Modeling and Analysis Project

PREFACE

The U.S. Environmental Protection Agency's Global Change Research Program (GCRP) is an assessment-oriented program within the Office of Research and Development that focuses on assessing how potential changes in climate and other global environmental stressors may impact water quality, air quality, aquatic ecosystems, and human health in the United States. The Program's focus on water quality is consistent with the *Research Strategy* of the U.S. Climate Change Research Program—the federal umbrella organization for climate change science in the U.S. government—and is responsive to U.S. EPA's mission and responsibilities as defined by the Clean Water Act and the Safe Drinking Water Act. The GCRP's water quality assessments also address an important research gap. In the 2001 *National Assessment of the Potential Consequences of Climate Change in the United States* (Gleick, 2000), water quality was addressed only in the context of the health risks associated with contaminated drinking water. A comprehensive assessment of the potential impacts of global change on water quality was not included.

This report is a screening-level assessment of the potential implications of future climate change on combined sewer overflows (CSOs) in the New England and the Great Lakes Regions. It is not a detailed analysis of individual systems. Rather, the purpose is to determine whether the potential implications of climate change on CSOs in these regions warrant further consideration and study. Wastewater treatment infrastructure was identified as a priority concern because of the essential service provided by these systems to protect public health and ecosystems. Investments in wastewater treatment infrastructure are also long-term, capital-intensive, and, in many cases, irreversible in the short- to medium-term. Thus, today's decisions could influence the ability of treatment facilities to accommodate changes in climate for decades into the future.

This final report reflects a consideration of comments received on an External Review Draft dated September 2006 (EPA/600/R-07/033A) provided by an external letter review, and comments received during a 30-day public review period (March 29, 2007 through April 28, 2007).

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1. EXECUTIVE SUMMARY

Combined sewer systems (CSSs) collect and co-treat storm water and municipal wastewater. During high intensity rainfall events, the capacity of CSSs can be exceeded resulting in the discharge of untreated storm water and wastewater directly into receiving waters. These combined sewer overflow events (CSOs) can introduce high concentrations of microbial pathogens and other pollutants into receiving waters.

The frequency and severity of CSO events is strongly influenced by climatic factors governing the occurrence of urban stormwater runoff, particularly the form (i.e., rain or snow), the amount, and the intensity of precipitation. Under U.S. EPA's CSO Control Policy, CSS communities are required to implement mitigation measures as a component of the National Pollutant Discharge Elimination System (NPDES) permitting process. CSO mitigation measures include infrastructure upgrades to increase system capacity (e.g., storage) and stormwater management to reduce the volume of runoff entering CSSs. Such practices are typically engineered to handle precipitation or runoff events of a given intensity, duration, or frequency, and most often there is an implicit assumption that precipitation and hydrology are statistically stationary (e.g., constant mean, variance, autocorrelation structure) over time.

During the last century, much of the United States experienced increased ambient air temperatures and altered precipitation patterns (NAST, 2000). Projections of future climate suggest these trends are likely to continue and potentially accelerate during the next century (IPCC, 2007). If realized, these changes could present a significant risk to the future performance of CSS infrastructure—including CSO mitigation. Little is known, however, about the extent of this risk.

This screening-level report assesses the potential order of magnitude of climate change impacts on CSO mitigation in the New England and Great Lakes Regions. The purpose is to determine whether the potential implications of climate change on CSOs in these regions warrant further consideration and study, and secondly, to evaluate the need for decision support tools and information enabling CSS managers to better incorporate consideration of climate change into their decision making processes. As such, this assessment and report is only a first step towards understanding a complex issue, the implications of which will vary significantly in different locations and for different systems. Results are thus not intended, nor the methods appropriate, to provide site-specific information on the potential impacts or mitigation requirements for any individual system or facility.

A simple, precipitation "benchmarking" approach was used to examine the extent to which CSO long-term control plans may be under-designed if planners assume that past precipitation conditions are representative of future conditions. We assumed that each CSO community in the New England and Great Lakes Regions will design their system to achieve an average of four CSO events per year (i.e., the Presumption approach threshold), and they will base their design on historical precipitation data. The benchmark daily precipitation event (daily total) equaled or exceeded, on average, four times per year was determined based on historical and projected future precipitation data. The extent to which CSO mitigation may be under-designed, if based on historical precipitation, was then determined by estimating changes in the frequency of the historical benchmark event under future climate conditions. The additional system capacity required to meet the mitigation target in the future was determined based on estimated future changes in the magnitude of the benchmark daily event and an assumed range of runoff coefficients describing proportional changes in stormwater runoff resulting from changes in precipitation.

Daily precipitation data representative of historical and projected future climate conditions were obtained from the Vegetation/Ecosystem Modeling and Analysis Project – Phase 2 (VEMAP Phase 2). VEMAP data representative of historical climate conditions were developed using monthly average station data from Historical Climate Network and Cooperative Network weather stations. Daily precipitation totals representative of historical climate were generated from monthly average station values using a modified version of the stochastic weather generator WGEN (Richardson and Wright, 1984). VEMAP data representative of future climate conditions were developed based on transient climate modeling experiments using two coupled atmosphere-ocean general circulation models (AOGCM): the Hadley Centre Model (HADCM2) and the Canadian Climate Centre Model (CCCM). Daily precipitation totals representative of future climate were generated based on monthly average AOGCM outputs using WGEN (Richardson and Wright, 1984).

Regional average estimates of potential impacts on CSOs were determined by mapping the 317 active CSS communities located in the Great Lakes and New England Regions to the nearest grid location where VEMAP data was available, analyzing the VEMAP data at each of these locations, and weighting the results from each VEMAP grid location within each region according to the number of CSS communities represented by that grid location

Results suggest that if future climate change includes increased precipitation and stormwater runoff volumes, the efficacy of CSO mitigation efforts may be diminished. Specifically, in the Great Lakes Region, projected long-term (2060–2099) changes in precipitation suggest that if CSO mitigation efforts are designed based on historical precipitation, many systems could experience increases in the frequency of CSO events beyond their design capacity resulting in increases in overflow volume discharged to receiving waters.

In the New England Region, projected near-term (2025–2050) changes in precipitation are inconsistent, with projections based on the Hadley and Canadian AOGCM models disagreeing on the direction of change. This difference in direction complicates interpretation of the results and highlights uncertainties associated with the AOGCM climate projections. The near-term results for the New England Region are best considered inconclusive; neither result confirms nor refutes the likelihood of future climate change impacts on CSOs. This analysis did not include long-term (2060–2099) projections of change in the New England Region—a limitation that precludes any direct comparison of impacts in the two study regions. Future study is required to address this issue in the New England Region.

It must be noted that the methodology used in this study involves a number of simplifying assumptions and limitations. Key limitations include the inherent uncertainty in AOGCM projections, methods for downscaling to daily data, the lack of consideration of snow and snowmelt, and the use of simple scaling factors to estimate stormwater runoff rather than detailed modeling of individual CSSs.

Investments in water infrastructure tend to be long-term, capital-intensive, and, in many cases, irreversible in the short- to medium-term. It is thus prudent to consider that today's decisions could influence the ability of treatment facilities to accommodate changes in climate for decades into the future. Faced with the prospect of future climate change, opportunities may exist where current CSO mitigation efforts can be upgraded at little additional cost to provide an added margin of safety to account both for near-term extreme events and the potential future effects of climate change. No-regrets opportunities may also exist where actions taken today to address current, other water quality concerns can provide additional benefits in the context of adapting to climate change.

Finally, it is important to recognize that each CSS and CSS community has a unique set of attributes, existing challenges, constraints, and other factors that must be considered in determining what reasonable and appropriate actions should be taken to manage any increase in risk associated with climate change. The focus of this report, CSOs, is not meant to imply that CSOs are the single or even the greatest source of water quality impairment in these areas. Other sources of impairment including non-point loading from agriculture, urban development, and other sources also occur in the study regions. Accordingly, responding to climate change will require a holistic approach that considers climate change in the context of other impacts on CSSs and regional water quality to determine what reasonable and appropriate actions can be taken.

Although limited in scope, this screening-level analysis provides a first step towards a better understanding of climate change impacts on CSOs in the New England and Great Lakes Regions. Results suggest that certain systems may be vulnerable to future climate change and that there is a need for more detailed, site-specific analyses including the development of decision support tools and information. Regardless of whether or not CSS managers choose to include climate change in their long-term planning, it is preferable that the decision be intentional and not due to lack of awareness of the problem.

2. INTRODUCTION

Combined sewer systems (CSSs) collect and co-treat storm water and municipal wastewater. During high intensity rainfall events, the capacity of CSSs can be exceeded resulting in the discharge of untreated storm water and wastewater directly into receiving waters. These combined sewer overflow events (CSOs) can result in high concentrations of microbial pathogens, biochemical oxygen demand, suspended solids, and other pollutants in receiving waters.

The frequency and severity of CSO events is strongly influenced by climatic factors governing the occurrence of urban stormwater runoff, particularly the form (i.e., rain or snow), amount, and intensity of precipitation. Under U.S. Environmental Protection Agency (U.S. EPA)'s CSO Control Policy, CSS communities are required to implement mitigation measures as a component of the National Pollutant Discharge Elimination System (NPDES) permitting process. CSO mitigation measures include infrastructure upgrades to increase system capacity (e.g., storage) and stormwater management to reduce the volume of runoff entering CSSs. Such practices are typically engineered to handle precipitation or runoff events of a given intensity, duration, or frequency, and most often there is an implicit assumption that precipitation and hydrology are statistically stationary (e.g., constant mean, variance, autocorrelation structure) over time. The rules guiding mitigation requirements are also based in part on an understanding of how different characteristics of precipitation events affect sewer performance.

The Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) states that warming of the climate system is now unequivocal, as is evident from observations of increases in global average air and ocean temperatures, widespread melting of snow and ice, and rising global average sea level (IPCC, 2007). The IPCC also reports that if greenhouse gas emissions continue at or above current rates, changes in the global climate system during the 21st century will very likely be larger than those observed during the 20th century. In the United States, observed climate change during the last century varied regionally but generally included warming temperatures and an increased frequency of heavy precipitation events (IPCC, 2001). Anticipated future changes also vary regionally, but throughout most of the United States changes include continued warming temperatures and increases in heavy precipitation events (IPCC, 2007). If realized, these changes could present a significant risk to the performance of CSS infrastructure including efforts to mitigate CSOs. Specifically, regions experiencing an increased frequency of high intensity rainfall events may also experience an increased risk of CSO events and associated water quality impairment. In the United Kingdom, an assessment of climate change projections for the year 2080 suggests that future climate change could result in increased flooding and CSO frequency (Wilkinson and Balmforth, 2004). Generally, however, little is known about the extent of this risk.

This screening-level report assesses the potential order of magnitude of climate change impacts on CSO mitigation in the New England and Great Lakes Regions. The purpose is to determine whether the potential implications of climate change on CSOs in these regions warrant further consideration and study, and to evaluate the need for decision support tools and information enabling CSS managers to better incorporate consideration of climate change into their decision making processes. As such, this assessment is only a first step towards understanding a complex issue, the implications of which will vary significantly in different locations and for different systems. A simple, precipitation “benchmarking” approach was used to examine the extent to which CSO long-term control plans (LTCPs) may be under-designed if it is assumed that past precipitation conditions are representative of future conditions. The study is not intended, nor are the methods appropriate, to provide detailed, site-specific information on the potential impacts or mitigation requirements for any individual system or facility. The New England and Great Lakes Regions were selected for study because CSSs in these two regions account for nearly half of the total 746 CSS communities in the United States (U.S. EPA, 2004).

2.1. COMBINED SEWER SYSTEMS AND COMBINED SEWER OVERFLOWS

A CSS collects storm water and sanitary wastewater in a common conveyance system and routes them to a treatment plant (U.S. EPA, 2004). The storm water component fluctuates with the weather: during rainfall events, the collection system and treatment plant must accommodate more volume due to runoff entering the system directly through street catch basins and gutter downspouts. By design, when the volume of water entering a CSS exceeds the system’s capacity, excess water is discharged at different points in the system into receiving waters through CSO outfalls.

The water that is discharged to receiving waters during a CSO event is typically a mixture of raw or partially treated (screened for solids) sewage, other industrial wastewaters, and storm water. The sewage component is typically of greatest concern due to bacterial and/or viral contamination. These discharges usually occur in response to wet weather and are known as CSOs. The term CSO refers to any discharge from a CSS prior to the treatment plant (U.S. EPA, 2004). The U.S. EPA (2004) estimates that 850 billion gallons of overflow are discharged into the nation’s waters each year.

According to U.S. EPA’s 2004 Report to Congress on the Impacts and Control of CSOs and Sanitary Sewer Overflows (SSOs), there are 746 communities with combined systems and a total of 9,348 CSO outfalls identified and regulated by the NPDES permits (U.S. EPA, 2004).

Combined sewer systems are found in 31 states and the District of Columbia, with the majority located in older cities found in the Great Lakes and New England Regions (see Figure 1).

Figure 1. Distribution of combined sewer systems in the United States.

Source: U.S. EPA, 2004.

2.1.1. History

Construction of municipal sewer systems began in the 1880s. Prior to then, sewage was collected in cesspools and privy vaults (Burian et al., 2000). Populations were sparse enough that aesthetic concerns were not great, and the health risks were not well understood. As population densities grew during the 19^{th} century, the need to remove waste became more critical. Cities had two initial goals in constructing sewers: (1) as populations grew larger and more concentrated, privies and cesspools were no longer sanitary or aesthetically acceptable. Sewers were constructed to remove wastes from population areas, (2) heavy rains could render unpaved streets impassable, so storm waters needed to be quickly conveyed to rivers or lakes. The two designs common to this time period were dedicated sanitary sewers and combined sewers to convey sewage and storm water. A third option, separate sanitary and storm sewers, was viewed as too costly for most communities (Burian et al., 2000).

At this time, waste waters were not treated; the purpose of sewer systems was simply to convey the water away from the population and into some receiving waterbody. The design choice depended on the community's needs. In general, smaller communities opted for sanitary systems only. Larger cities used combined systems because they efficiently and effectively removed both storm and wastewater (U.S. EPA, 2004). In some cases, a combined system was chosen because storm water would flush the sewage out of the system into receiving waters (Burian et al., 2000; Schladweiler, 2005). At the turn of the 20th century, these systems were linked to significant reductions in waterborne disease outbreaks within the cities they served. There were, however, consequences with respect to water quality in receiving waters.

As the first sewer systems were being built, CSSs were a dramatic improvement over cesspools and open sewers. However, as populations grew, impacts of discharges into receiving waters grew as well. CSOs result mainly from two different events associated with CSSs: (1) insufficient conveyance capacity within a portion of the sewer system and resultant surcharging and overflow through manholes or designed outfalls and (2) insufficient capacity at the wastewater treatment facility. In the latter case, the excess combined sewage must bypass the facility and be discharged at a specified outfall. This effluent is often screened to remove solids (primary treatment) before discharging.

2.1.2. Effects on Water Quality and Public Health

CSOs present a threat to water quality and public health. The pollutants found in CSOs include microbial pathogens, suspended solids, nutrients, toxics, and debris. Pollutant concentrations vary, but they can be high enough to cause violations of water quality standards. It is common for local rivers and streams to be considered dangerous to human health after heavy rains due to CSO pollution. It is difficult to attribute the violation of water quality standards exclusively to CSO discharges, because CSOs occur during storm events when some of the same pollutants are washed directly into receiving waters by storm water runoff.

Despite the difficulty of attributing causality to particular sources, the U.S. EPA has compared data on CSO locations with data on 305(b) assessed water segments and 303(d) impaired waters in 19 states (U.S. EPA, 2004).[1] The study found that of a total of 59,335 assessed segments, 25% were impaired. For 733 segments that were within a mile downstream of a CSO outfall, 75% were impaired. Though it is difficult to determine how much of the impairment is due to the CSO, the high percentage of impairment associated with CSOs suggests some correlation (U.S. EPA, 2004). CSOs should be considered as a potential source of pollution during Total Maximum Daily Load (TMDL) development, and in some communities substantial load reductions have been assigned to CSOs as a result of the TMDL process (U.S. EPA, 2004).

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[1]305(b) and 303(d) are references to sections of the Clean Water Act that mandate assessment of water bodies, and identification of impaired waters, respectively.

CSOs also present risks to public health and the natural aquatic ecosystems. Humans can become sick by drinking contaminated water, eating contaminated shellfish, or coming in direct contact with contaminated water. The most common symptoms of pathogenic illness are diarrhea and nausea, but respiratory and other problems can occur as well. Toxics present in CSO discharges include metals and synthetic organic chemicals. Less is known about the risks of biologically active chemicals such as antibiotics, hormones, and steroids (U.S. EPA, 2004).

2.2. CSO CONTROLS

Efforts to manage the risks of CSOs have evolved over the last several decades. Following the passage of the Clean Water Act in 1972, publicly owned wastewater treatment works (POTWs) were required to incorporate secondary treatment into their wastewater treatment processes. Effluent from the treatment plant had to be treated, but it was unclear how CSOs—discharges from the collection system, not the treatment plant—would be treated by the law. A 1980 court ruling declared that CSO outfalls did not have to be subjected to the secondary treatment required of discharges from a POTW. However, the discharges do fall under the National Pollutant Discharge Elimination System (NPDES) permit program (U.S. EPA, 2004). Under NPDES, all facilities which discharge pollutants from any point source into waters of the United States are required to obtain a permit. The permit holder must provide treatment based on technology accessible to all permittees in a particular industrial category (U.S. EPA, 2006).

In 1989, the U.S. EPA issued the National CSO Control Strategy, which encouraged states to develop statewide permitting strategies to ensure that all CSSs were subject to a discharge permit. The strategy also recommended six minimum measures for controlling CSOs. As the control strategy was being implemented, environmental groups pushed for further action against CSOs, while many municipalities also called for greater clarity and a national approach (U.S. EPA, 2004). In 1994, the U.S. EPA published the CSO Control Policy to establish objectives for CSS communities in order to reduce the environmental impacts of CSOs. Four key elements of the CSO Control Policy are meant to enable communities to cost effectively reduce overflows and meet the objectives of the Clean Water Act:

(1) Provide clear levels of control that would be presumed to meet appropriate health and environmental objectives;

(2) Provide sufficient flexibility to municipalities, especially financially disadvantaged communities, to consider the site-specific nature of CSOs and to determine the most cost effective means of reducing pollutants and meeting Clean Water Act objectives and requirements;

(3) Allow a phased approach to implementation of CSO controls considering a community's financial capability; and,

(4) Provide for review and revision, as appropriate, of water quality standards and their implementation procedures when developing CSO control plans to reflect the site-specific wet weather impacts of CSOs.

2.2.1. Nine Minimum Controls and Long-Term Control Plans

The national CSO Control Policy also requires communities to implement nine minimum controls (referred to as NMC) and to develop a LTCP to reduce the frequency and adverse impact of CSOs. The NMC are expected to maximize the effectiveness of existing systems. Among the controls are properly operating and maintaining the system; maximizing the flow to the POTW from the collection system; eliminating overflows during dry weather; and notifying the public of the occurrence and impacts of overflows. In addition to implementing the NMC, communities are expected to develop LTCPs that will ultimately result in compliance with the requirements of the Clean Water Act.

The development and implementation of LTCPs are in various stages of completion, but all of the 746 communities that have CSSs must develop plans to comply with the CSO Control Policy. Permit holders designing modifications to their systems generally base their plans on historical weather data. The infrastructure investments made to implement LTCPs are expected to have life expectancies of several decades, and the costs will be considerable. There is no comprehensive source of individual municipal expenditures for CSO control because there are multiple funding sources for CSO projects. However, the U.S. EPA has compiled expenditures, to date, for 48 communities, roughly 6% of the nation's total. Those expenditures totaled $6 billion and ranged from $134,000 to $2.2 billion per community. The U.S. EPA estimates that the capital costs of future CSO control over the next 20 years will exceed $50 billion (U.S. EPA, 2004).

2.2.2. CSO Control Policy Mitigation Requirements

The U.S. EPA's CSO Control Policy allows for three basic approaches to be taken in order to meet CSO mitigation requirements: First, a system may allow no more than four overflow events per year (though the permitting authority may allow an additional two). Second, a system may eliminate or capture at least 85%, by volume, of the combined sewage collected in the system during a precipitation event. These first two approaches are considered to be "presumptive" in nature. Finally, the system may eliminate or remove no less than the mass of the pollutants identified as causing the water quality impairment for the volume that would be eliminated or captured by the 85% approach (U.S. EPA, 1994). This final, or "Demonstration" approach, allows communities to demonstrate that their system, though not meeting the criteria of the Presumption approach, is adequate to enable receiving waters to meet water quality standards and protect designated uses (U.S. EPA, 2004).

Investments in CSO control tend to be long-term, capital-intensive, and, in many cases, irreversible in the short- to medium-term. Given the influence of climate on stormwater runoff and the occurrence of CSO events, it is thus prudent to consider the potential impacts of climate change on the effectiveness of efforts to mitigate CSOs over the next several decades. To the extent that climate change may result in increased precipitation, if CSO mitigation is designed based on *current* climate and/or hydrology (e.g., calculations of required system storage capacity), it is possible that mitigation actions taken as part of CSO long term planning may not be sufficient to meet the desired objective.

2.3. STUDY GOALS

The goal of this screening-level analysis is to assess the potential order of magnitude of climate change impacts on CSO mitigation in the New England and Great Lakes Regions. The purpose is to determine whether the potential implications of climate change on CSOs in these regions warrant further consideration and study, and to evaluate the need for decision support tools and information enabling CSS managers to better incorporate consideration of climate change into their decision making processes. As such, this assessment and report is only a first step towards understanding a complex issue, the implications of which will vary significantly in different locations and for different systems. An improved understanding of the potential impacts of climate change on CSOs is important because the occurrence and mitigation of CSO events is highly sensitive to climate, is one of the highest-priority programs at the state and federal level, and will involve significant investment in wastewater collection, storage, and treatment infrastructure. CSOs are also a timely subject of strategic discussion due to the large gap in funds available versus funds needed for treatment system improvements.

A simple, screening-level approach is used to examine the extent to which CSO long-term control plans may be under-designed if planners assume that past precipitation conditions are representative of future conditions. An informal survey of U.S. EPA staff indicated that the most common approach to LTCPs in the New England and Great Lakes Regions was the Presumption approach: controlling and providing a minimum level of treatment to all but four overflow events per year. This study considers the following two questions:

(1) If CSSs currently meet the U.S. EPA's CSO Control Policy Presumption approach of four events per year based on *historical* precipitation, what is the potential change in CSO event frequency in the future as a result of climate change?

(2) What is the potential required change in the design capacity of mitigation measures needed to meet the Presumption approach of four CSO events per year in the future as a result of climate change?

Focusing on the four-events-per-year Presumption approach threshold provides a useful benchmark for assessing impacts. This requirement alone, however, is not indicative of compliance with the Clean Water Act. The analysis thus takes a relatively simple approach to a complex problem. The study is not intended, nor are the methods appropriate, to provide detailed, site-specific information on the potential impacts or mitigation requirements for any individual system or facility. Analysis of the spatial variability of potential changes within each region is also not addressed in this study. The New England and Great Lakes Regions were selected as the focus of this study because of the large number of CSSs in these areas. It should be noted, however, that results in the New England and Great Lakes Regions cannot be directly compared to one another because work in the different regions was conducted as part of two separate projects, and there are methodological differences in the future time periods considered.

It should also be noted that CSOs are just one of many potential sources of water quality impairment in the New England and Great Lakes Regions. The focus of this report, CSOs, is not meant to imply that CSOs are the single or even the greatest source of water quality impairment in these areas. Other sources of impairment including non-point loading from agriculture, urban development, and other sources may also be highly sensitive to precipitation changes associated with climate change. Accordingly, responding to climate change will require a holistic approach that considers climate change in the context of other impacts on local or regional water quality to determine what reasonable and appropriate actions can be taken.

3. METHODS

This study uses a simple, precipitation benchmarking approach to assess how future changes in precipitation could impact the frequency and volume of CSO events in the New England and Great Lakes Regions. The desired mitigation target for CSSs in each region was assumed to be the LTCP Presumption standard of reducing CSO frequency to no more than four events per year. Using this mitigation target, the historical benchmark daily event (daily total precipitation) that is equaled or exceeded, on average, four times per year was determined. The extent to which CSO mitigation may be under-designed if based on historical precipitation was then determined by estimating changes in the frequency of the historical benchmark event under future climate conditions. The additional system capacity required to meet the mitigation target in the future was estimated based on future changes in the magnitude of the benchmark daily precipitation event and an assumed range of runoff scaling factors describing the proportional changes in stormwater runoff resulting from changes precipitation.

The precipitation benchmarking approach provides a simple and straightforward method for assessing order-of-magnitude changes in each of the study regions. Detailed modeling of individual CSSs to account for specific characteristics of each sewershed affecting the generation and routing of stormwater runoff was not conducted due to the size (large) of geographic area considered. Results are thus not intended to provide site-specific information on mitigation requirements for any individual system or facility. The subsequent sections provide a more detailed discussion of the methodology.

3.1. CSS SELECTION

A national list of CSS locations was obtained from a 2004 U.S. EPA *Report to Congress* (U.S. EPA, 2004). Latitude and longitude were determined for each CSS by cross referencing NPDES permit numbers with location information in the Permit Compliance System, or based on city location. CSS communities within the Great Lakes and New England Regions were selected as described in the following sections.

3.1.1. Great Lakes Region

The Great Lakes are part of the largest freshwater system in the world, and are bounded by eight states: Minnesota, Wisconsin, Michigan, Illinois, Indiana, Ohio, Pennsylvania, and New York (U.S. EPA, 2004; GLRA, 2000). A total of 182 CSS communities with active CSO permits were identified within the Great Lakes Region (within the Great Lakes watershed); Table 1 presents a breakdown of CSS communities within the Great Lakes Region by state.

Table 1. Great Lakes region CSS communities by state

State	Number of CSS Communities
Ohio	47
Michigan	46
Illinois	34
Indiana	24
New York (in Great Lakes watershed)	23
Minnesota	3
Pennsylvania	3
Wisconsin	2
Total	**182**

3.1.2. New England Region

The New England Region was defined to include seven states: Maine, New Hampshire, Vermont, Massachusetts, Connecticut, Rhode Island, and New York (excluding New York City). A total of 135 active CSO permits were identified in the New England Region (U.S. EPA, 2004). Table 2 shows the breakdown of CSS communities by state in the New England Region.

Table 2. New England region CSS communities by state

State	Number of CSS Communities
New York (upstate)	53
Maine	39
Massachusetts	22
Vermont	7
New Hampshire	6
Connecticut	5
Rhode Island	3
Total	**135**

3.2. PRECIPITATION BENCHMARKING APPROACH

There is considerable heterogeneity among CSSs in terms of baseline water quality conditions, progress toward complying with the U.S. EPA's national CSO Control Policy, and the site-specific approaches that will be used to reduce the frequency of CSO events. The U.S. EPA requires, however, that all CSS communities develop a LTCP that includes an evaluation of alternatives to meet CWA requirements by using either the Presumption approach or the Demonstration approach. One of the most common design objectives of LTCPs is to achieve the U.S. EPA's Presumption approach threshold of no more than an average of four CSO events per year. Under this criterion, a CSO event is defined as any overflow from a CSS that does not receive the minimum level of treatment defined in the CSO Control Policy.

In this study, it is assumed that each CSO community in the New England and Great Lakes Regions will design their system to achieve an average of four CSO events per year (i.e., the Presumption approach threshold), and will base their design on historical precipitation data. The benchmark daily total precipitation that is equaled or exceeded, on average, four times per year was determined based on historical and future precipitation data. The extent to which CSO mitigation may be under-designed if based on historical precipitation was then determined by estimating changes in the frequency of the historical benchmark event under future climate conditions. Potential increases in system capacity required to meet the mitigation target in the future was estimated based on future changes in the magnitude of the benchmark daily precipitation event and an assumed range of runoff scaling factors describing the proportional changes in stormwater runoff resulting from changes precipitation.

Daily precipitation data representative of historical and projected future climate conditions were obtained from the Vegetation/Ecosystem Modeling and Analysis Project—Phase 2 (hereafter referred to as VEMAP), administered by the National Center for Atmospheric Research (NCAR) data group. VEMAP data representative of historical climate conditions were developed using monthly average station data from Historical Climate Network and Cooperative Network weather stations. Daily precipitation totals were generated from monthly average station values using a modified version of the stochastic weather generator WGEN (Richardson and Wright, 1984). Station data were spatially interpolated to a grid with intervals of one degree latitude by one degree longitude (110 Km latitude and approximately 80 Km longitude in these study regions) using PRISM (Parameter-elevation Regressions on Independent Slopes Model) (Daly et al., 1994).

VEMAP data representative of future climate conditions were developed for each VEMAP grid location based on transient climate modeling experiments for a simulated period from 1994 to 2100 using two coupled atmosphere-ocean general circulation models (AOGCM): the Hadley Centre Model (HADCM2) and the Canadian Climate Centre Model (CCCM). Daily precipitation totals were developed based on monthly average AOGCM outputs using WGEN (Richardson and Wright, 1984).[2] Detailed documentation and discussion of the VEMAP Phase 2 data can be found in the VEMAP Phase 2 Users Guide (Rosenbloom et al., 2003).

It should be noted that the VEMAP data sets used in this study are subject to a number of uncertainties and limitations related to the AOGCM projections, the daily precipitation totals generated using WGEN, and other modeling methods and assumptions. The AOGCM modeling experiments used to develop the VEMAP data sets are several years old and subject to inherent modeling uncertainties. The future data sets used in this study should thus not be considered predictions, but rather as representative, plausible futures. In addition, VEMAP daily data were developed using a stochastic weather generator and thus may not represent extremes well. Analysis by the VEMAP team determined that frequency distributions and extremes of daily data from WGEN compare well to those of observed station data (Rosenbloom et al., 2003). However, because daily data were developed using a weather generator, the values should only be considered estimates. Finally, the daily precipitation totals available from VEMAP do not allow consideration of sub-daily event characteristics known to influence the frequency and magnitude of CSO events (e.g., system response to a thunderstorm yielding 2 inches of rain in one hour versus a steady rain that accumulates 2 inches over a full 24-hour period). A more detailed discussion of the VEMAP data can be found in the VEMAP Phase 2 Users Guide (Rosenbloom et al., 2003).

Although subject to uncertainty, VEMAP data was used in this screening-level assessment because it was readily available, and because the data set is well known and documented. Use of VEMAP data set also simplified the analysis by providing historical and projected future climate data on the same geographic footing (a one-degree grid).

Regional-average estimates of potential CSO impacts were conducted by first mapping each of the 317 active CSS communities in the Great Lakes and New England Regions to the nearest VEMAP grid location. Analyses of precipitation data were then conducted for each VEMAP grid location with at least one associated CSS. Estimates of the regional average changes for all CSSs within each study region were determined by weighting results from each VEMAP grid location within each region according to the number of CSS communities represented by that point.

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[2] WGEN is a weather simulation model developed at the USDA-ARS Grassland, Soil and Water Research Laboratory that is used to scale down monthly AOGCM outputs to a daily time-step. The model uses a probability function (first-order Markov chain) where the chance of precipitation is conditioned on the wet or dry status of the previous day, and the intensity is based on a gamma distribution where small intensity events occur more frequently than large intensity events.

The analysis of precipitation data at each VEMAP grid location was conducted in two ways: using the daily precipitation totals and using the 4-day moving average of daily totals. Evaluation of the 1- and 4-day averages accounts for potential differences in the temporal characteristics of storage in CSO mitigation measures (i.e., the time lag between onset of precipitation and peak flows within a CSS). The choice of 1- and 4-day timeframes provided approximate lower and upper bounds on both (a) time of travel within the sewershed or area draining to the treatment plant (from "upstream" boundaries to the treatment plant) and (b) the effects of multiple rain events in quick succession. In addition, the analysis was simplified by treating all precipitation as rainfall; making no accommodation for the occurrence of snowfall or snowmelt.

In the Great Lakes Region, 40 years of historical precipitation data representative of the period from 1954–1993 were compared to 40 years of projected future precipitation data representative of the period from 2060–2099. In the New England Region, 25 years of historical precipitation data representative of the period from 1968–1993 were compared to 25 years of projected future precipitation data representative of the period from 2025–2050. As indicated earlier, it is important to note that the different future time periods considered in the two study regions preclude direct comparison of results. Work in the two regions was done at different times as two independent projects. Work in the New England Region was done subsequent to that in the Great Lakes Region, and the focus on the period from 2025–2050 in this region was intended to provide information more relevant to near–term decision making.

As mentioned previously, it was assumed that CSSs in each study region will design their systems to meet the four-event per year standard based on historical daily precipitation totals. This served as the historical benchmark daily event for each system. In theory there will be only four events (in an average year) that exceed this benchmark if a CSS community is meeting the objectives of the CSO Control Policy. In the case of the Great Lakes Region, the benchmark event was identified as the 160th largest daily precipitation event (daily total) in each of the 40-year, aggregated 1- and 4-day moving average precipitation data sets (four events per year * 40 years of data). The magnitude of benchmark events for the Great Lakes Region were determined by ranking the VEMAP daily precipitation totals, and selecting the 160th largest event. For the New England Region, the benchmark event was identified as the 100th largest daily precipitation event in each of the 25-year, aggregated 1- and 4-day precipitation data sets (four events per year * 25 years of data). Benchmark events for the New England Region were determined by ranking the VEMAP daily precipitation totals and selecting the 100th largest event. Note that in each case this methodology provides a simple estimate of the daily precipitation event (1- or 4-day) with a recurrence interval of 3 months. Formal frequency analysis based on an assumed statistical distribution of daily precipitation was not considered necessary for this screening analysis given the other uncertainties inherent in the approach. Using this methodology, the benchmark 1- and 4-day daily precipitation events needing to be captured to meet the LTCP Presumption standard of no more than four CSO events per year were estimated at each VEMAP grid location under conditions representative of historical and future climate (based on CCCM and HADCCM2 AOGCM projections).

The extent to which CSO mitigation may be under-designed if based on historical precipitation was estimated by determining changes in the frequency of the historical benchmark daily precipitation event under future climate conditions. Potential future changes in system storage capacity required to meet the mitigation target in the future were then estimated based on changes in the magnitude of the four-event-per-year benchmark event, and estimates of changes in stormwater runoff generated by these changes in precipitation. Detailed modeling of stormwater for individual systems was beyond the scope of this study. Rather, for each VEMAP location and projected change in precipitation, percent changes in stormwater runoff (relative to historical conditions) were estimated by applying a high- and low-range multiplier (scaling factors) to projected percent changes in benchmark daily precipitation events. Potential future changes in system capacity (expressed as a percent relative to that necessary to meet the four-events-per-year Presumption standard under historical climate conditions) to meet the four-events-per-year mitigation target in the future were then assumed equal to percent changes in stormwater runoff volume.

It is important to note that the benchmarking approach used in this study does not consider the unique attributes of any individual CSS, and it is not intended to provide site-specific information for any individual CSS community. Rather, the approach is intended as a simple, screening-level assessment of the potential order of magnitude of climate change impacts in each study region. More detailed study and modeling are required to determine specific mitigation design specifications for individual CSS communities. The estimates of potential increases in system capacity also assume that infrastructure upgrades are the predominant approach used in CSO mitigation. In practice, stormwater management can be implemented to reduce the volume of runoff that enters a CSS, thus reducing the need for changes in CSS infrastructure. Although not explicitly addressed, however, the range of scaling factors used to estimate stormwater runoff does capture a range of potential changes in hydrologic response that, in part, could result from changes in future stormwater management practices.

4. RESULTS AND DISCUSSION

4.1. CHANGES IN CSO EVENT FREQUENCY

The extent to which CSO mitigation may be under-designed if based on historical precipitation was estimated by determining changes in the frequency of the historical benchmark event under future climate conditions. It is assumed that municipalities will design mitigation measures (e.g., a deep storage tunnel or stormwater management practices to reduce runoff) to meet the four-event-per-year Presumption approach threshold, and if historical precipitation is used as the design standard, the effectiveness of those mitigation measures could be reduced in the future. The metric presented in this section is the estimated percent change in CSO event frequency relative to the four events per year allowed under the LTCP Presumption approach. For example, a 50% increase in CSO event frequency would equate to two additional CSO events per year, on average, or a total of six CSO events per year if the mitigation measures were designed using historical precipitation data.

4.1.1. Great Lakes Region

In the Great Lakes Region, the regional average annual CSO frequency during the future period from 2060–2099 was estimated to increase between 13% (based on the CCCM, 1-day averaging period) and 70% (based on the HADCM2, 4-day averaging period) relative to the assumed historical condition of four events per year. In other words, the average number of CSO events per year would increase to 4.5 using the lowest projected average change, and 7.1 using the highest average projected change (see Table 3).

Table 3. Regional average percent change in CSO frequency in the Great Lakes region, 2060–2099. The percent change is expressed relative to the four events/year standard, e.g., a 50% change equals two additional CSO events/year.

Moving Average	CCCM	HADCM2
1-Day	13.4%	49.4%
4-Day	18.8%	70.0%

Figure 2 shows the distribution of the percentage change in CSO frequency (number of communities) in the Great Lakes Region based on a 1-day moving average of daily precipitation. The HADCM2 projects an increase in daily precipitation totals for all locations, while the

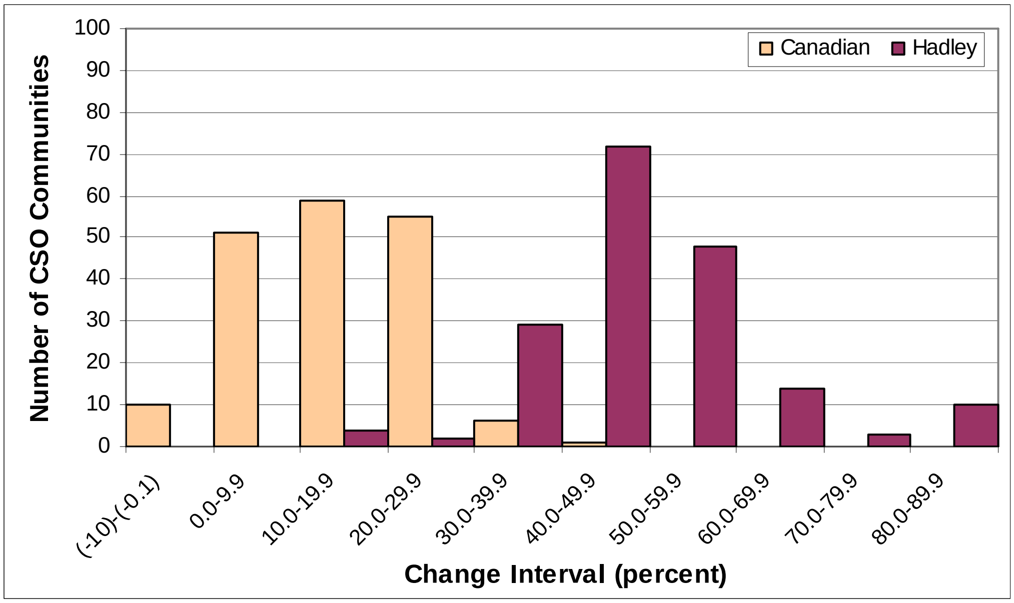

Figure 2. Percent change in frequency of CSO events in the Great Lakes region relative to historical values based on Canadian (CCCM) and Hadley (HADCM2) Model climate projections for the future period from 2060–2099 (1-day).

CCCM projects decreases at 10 of the communities (5%). Accordingly, based on the CCCM, there are 10 communities that are projected to experience a decrease in CSO frequency of 10 to 0.1%. At the other end of the spectrum, the HADCM2 predicts an 80 to 90% increase in CSO frequency for 10 communities. For these 10 CSS communities, this would mean an additional 32 CSO events per year, on average. Figure 3 shows a similar plot based on the 4-day averaging period. These results generally indicate wider distributions and greater impacts (though for the CCCM, there is an increase in the number of communities with fewer CSO events). Figure 4 shows the cumulative distributions for the HADCM2 and CCCM for both averaging periods.

4.1.2. New England Region

In the New England Region, the regional average annual CSO frequency during the future period from 2025–2050 was estimated to change from -24% and 14% relative to the assumed historical condition of four events per year (Table 4). In other words, the average number of CSO events per year would decrease to 3.0 using the lowest projected average change and increase to 4.6 using the highest average projected change.

Figure 5 shows the distribution of the percentage change in CSO frequency (number of communities) in the New England Region based on a 1-day moving average of daily

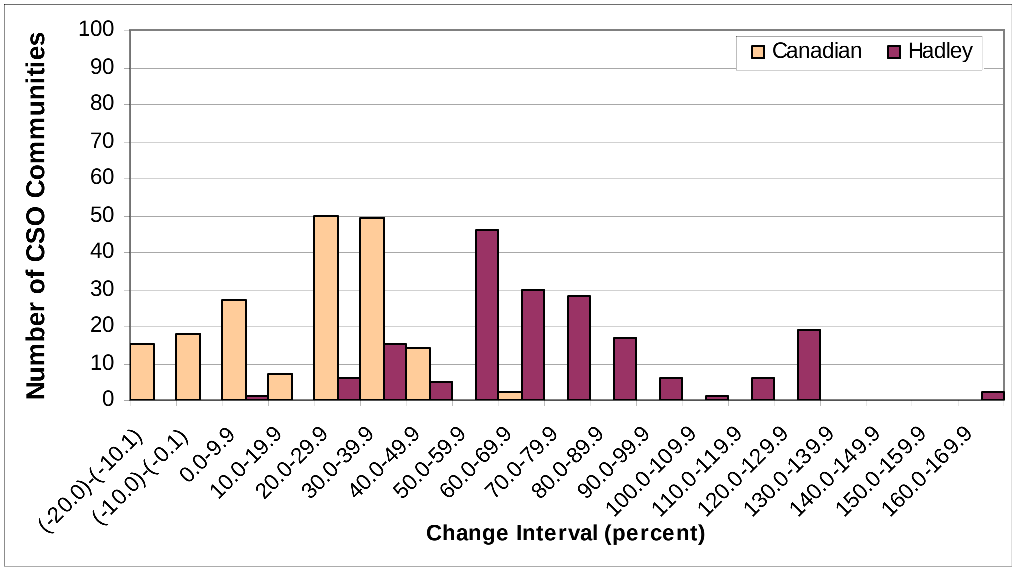

Figure 3. Percent change in frequency of CSO events in the Great Lakes region relative to historical values based on Canadian (CCCM) and Hadley (HADCM2) Model climate projections for the future period from 2060–2099 (4-day).

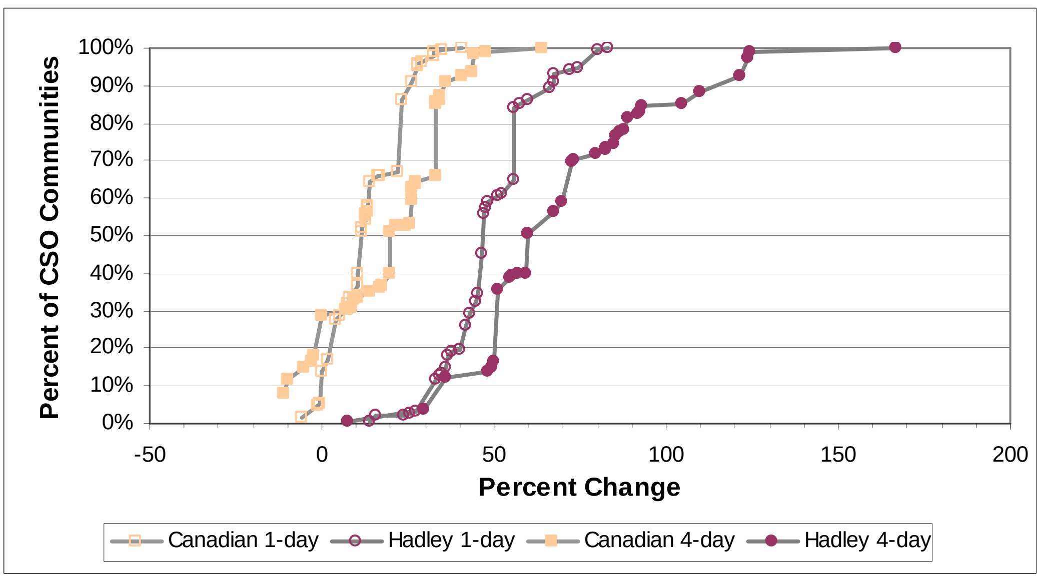

Figure 4. Cumulative distribution of percent change in CSO frequency in the Great Lakes region relative to historical values based on future climate projections for the period 2060–2099.

Table 4. Regional average percent change in CSO frequency in the New England region, 2025–2050. The percent change is expressed relative to the four events/year standard, e.g., a 50% change equals two, additional CSO events/year.

Moving Average	CCCM	HADCM2
1-Day	-10.4%	8.8%
4-Day	-24.5%	14.4%

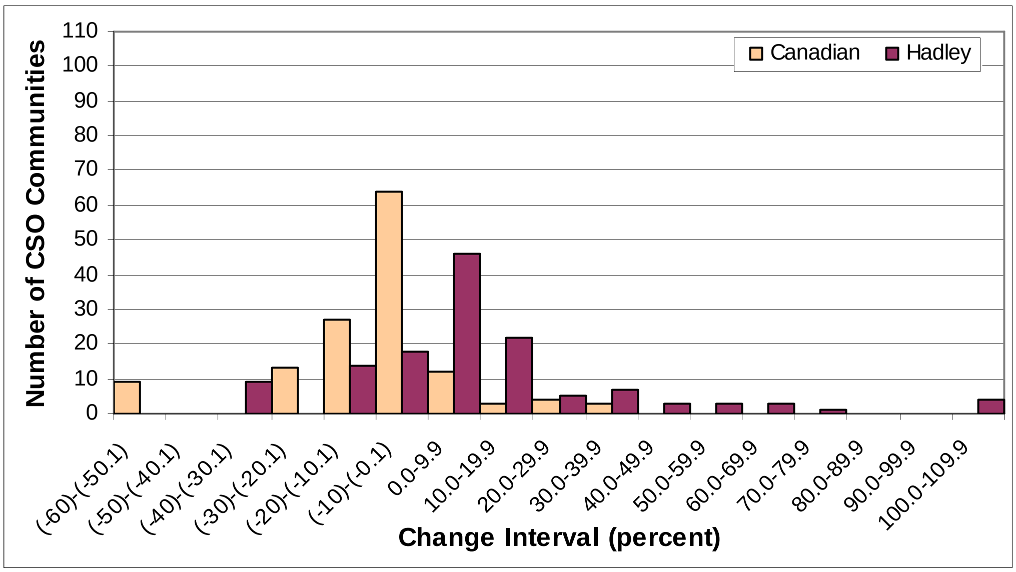

Figure 5. Percent change in frequency of CSO events in the New England region relative to historical values based on Canadian (CCCM) and Hadley (HADCM2) Model climate projections for the future period 2025–2050 (1-day averaging period).

precipitation totals. The HADCM2 model projects an increase in daily precipitation totals for the majority of locations, while the CCCM model projects decreases for the majority of the communities. Based on the CCCM model, there are 10 communities that are projected to experience an increase in CSO frequency of more than 10%, 76 communities that will have less than a ±10% change, and 49 communities that are projected to experience a decrease in CSO frequency of more than -10%. Alternatively, the HADCM2 model predicts 48 communities to have an increase in CSO frequency of more than 10%, 64 communities with less than a ±10% change, and 23 communities with decreases in CSO frequency exceeding -10%. Figure 6 shows similar plot based on the 4-day averaging data. Figure 7 shows the cumulative distributions for the HADCM2 and CCCM models for both averaging periods.

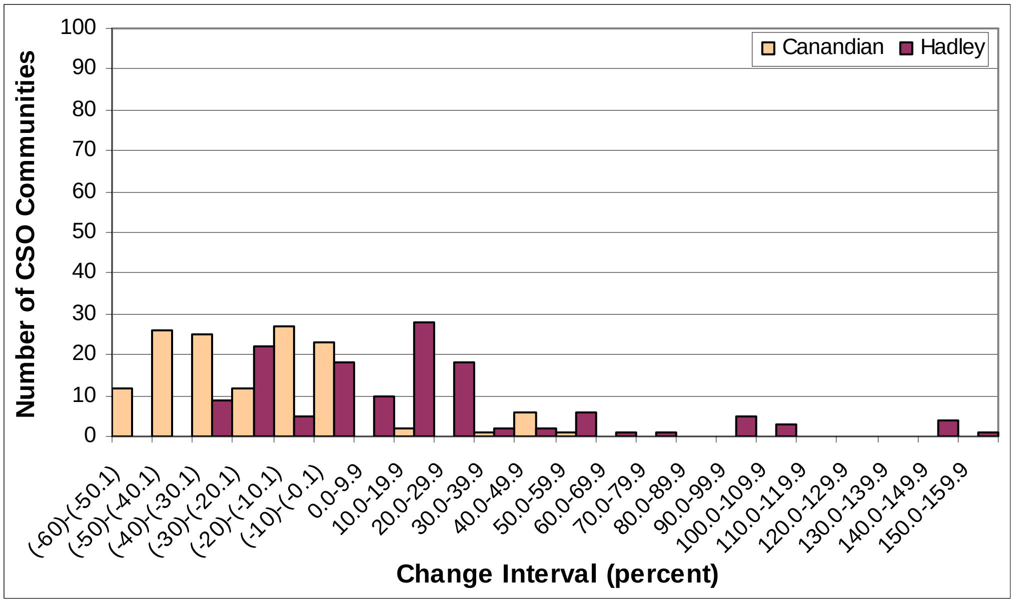

Figure 6. Percent change in frequency of CSO events in the New England region relative to historical values based on Canadian (CCCM) and Hadley (HADCM2) Model climate projections for the future period 2025–2050 (4-day averaging period).

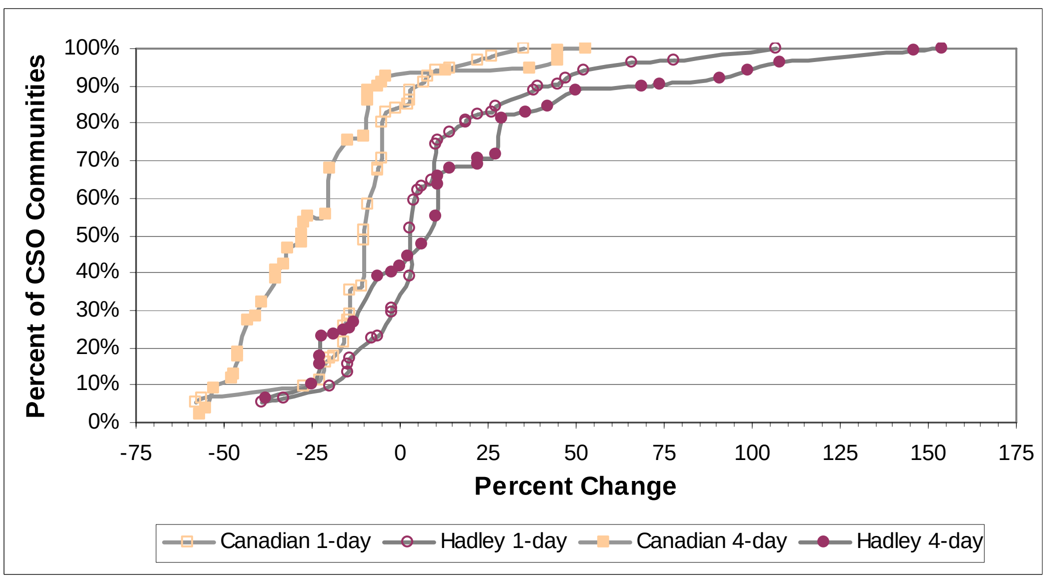

Figure 7. Cumulative distribution of percent change in CSO event frequency in the New England region relative to historical values based on future climate projections for the period 2025–2050.

The inconsistency in direction of projected precipitation changes in the New England Region complicates interpretation of the results. For example, with the CCCM model, if control measures in the New England Region are designed based on historical precipitation characteristics, climate-related changes could result in a 10-25% decrease in CSO events depending on the averaging period considered, i.e., an increase in the effectiveness of mitigation measures. A similar analysis based on the Hadley model suggests a 9–14% increase in overflows. The relatively near-term period 2025–2050 was selected as the focus of this analysis to be more relevant to current decision making. It is possible, however, that these near-term projections do not capture longer term trends that may not become detectable until farther into the future. Despite the inconclusive results in the New England Region in the near term, resource limitations did not permit analysis of additional future time periods (e.g., 2060–2099) in the New England Region.

4.2. POTENTIAL MITIGATION REQUIREMENTS

A second objective of this assessment is to estimate the potential required changes in system capacity to meet the four-event-per-year mitigation target under future climate conditions. This information may be useful to municipalities interested in implementing CSO mitigation measures (e.g., a storage basin) that are robust to future changes in climate. Two metrics are presented in this section to address this general question: (1) the estimated percent change in the future magnitude of the benchmark daily event that must be captured to meet the four-events-per-year Presumption standard relative to the historical value, and (2) the estimated percent changes in stormwater runoff volume resulting from changes in daily precipitation that must be accommodated by the system. Each metric provides an indication of how CSO mitigation design parameters could be modified to account for future climate change, albeit the actual mitigation measures required for any specific CSS will vary considerably depending on the specific attributes of the system.

It should also be noted that estimates of potential increases in system capacity assume that CSS infrastructure upgrades are the predominant approach used in CSO mitigation. Stormwater management to reduce the runoff entering CSSs is not explicitly considered, although the scaling factors used to estimate stormwater runoff capture a range of potential changes in hydrologic response.

4.2.1. Potential Changes in Benchmark Daily Precipitation

Changes in the magnitude of the benchmark daily precipitation event that must be captured to meet the four-events-per-year Presumption approach standard are indicative of the potential changes in system capacity required to meet this mitigation target under future climate conditions. The relationship between different attributes of precipitation and the volume of timing of stormwater runoff is complex and highly variable. By assuming a simple relationship between daily precipitation totals and stormwater runoff, however, the changes in CSS capacity that would be needed to adapt to future climate change can be approximated. For example, if a 1:1 correspondence is assumed between daily precipitation and stormwater runoff generated, a 10% increase in the benchmark daily event would imply that the design of the system would need to be sized for a roughly 10% increase in runoff volume to account for climate change.

4.2.1.1. *Great Lakes Region*

In the Great Lakes Region, the regional, average daily total precipitation corresponding to a recurrence interval of 4 events per year during the future period from 2060–2099 is projected to increase from approximately 5 to 16% relative to historical values (see Table 5).

Table 5. Regional average percent change in the benchmark daily total precipitation in the Great Lakes region during the future period 2060–2099. Changes are expressed relative to historical values.

Moving Average	CCCM	HADCM2
1-Day	4.8%	16.2%
4-Day	5.1%	14.9%

CSS communities in certain parts of the Great Lakes Region, however, are projected to experience future reductions in the benchmark daily event. Figure 8 shows the distributions of projected changes in the four-event benchmark daily total precipitation in the Great Lakes Region based on a 1-day moving average of daily precipitation. Projections based on the CCCM model suggest four CSS communities will experience a decrease ranging from -5 to –0.1 percent in the benchmark event. At the other end of the spectrum, projections based on the HADCM2 model suggest a relatively large 25% to 29.9% increase in the benchmark daily event for two communities. The range of values is attributed to spatial variability in climate change projections for different locations within each region (i.e., the VEMAP grid locations to which CSS individual communities are mapped). Figure 9 shows the distributions of projected changes in the four-event benchmark daily total precipitation based on the 4-day averaging period. Figure 10 shows the cumulative distributions of projected changes in benchmark daily total precipitation from the HADCM2 and CCCM models for the 1- and 4-day averaging periods.

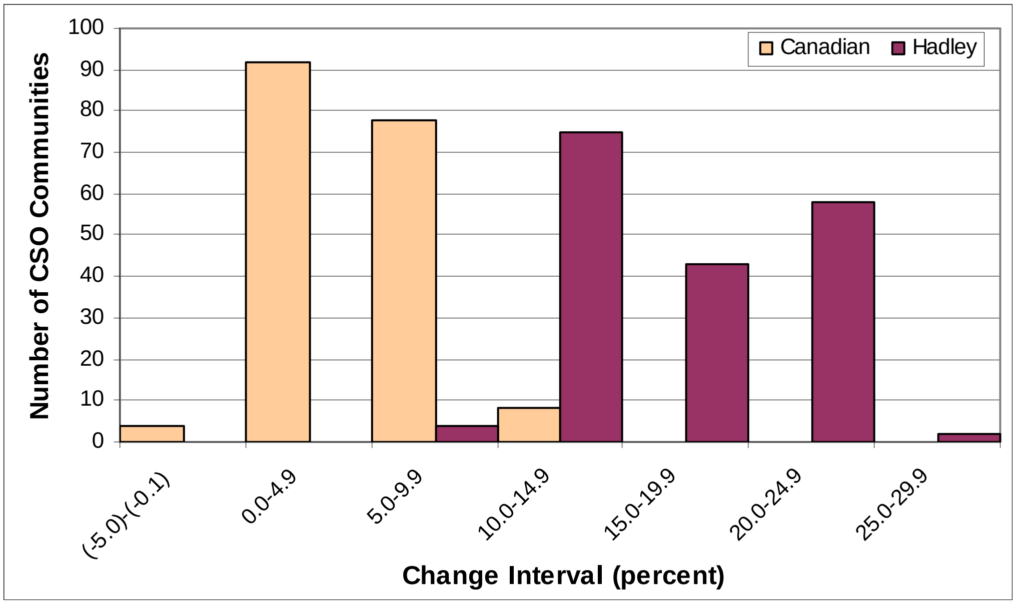

Figure 8. Percent change in the four-event benchmark daily total precipitation in the Great Lakes region relative to historical values based on Canadian (CCCM) and Hadley (HADCM2) Model climate projections for the future period 2060–2099 (1-day averaging period).

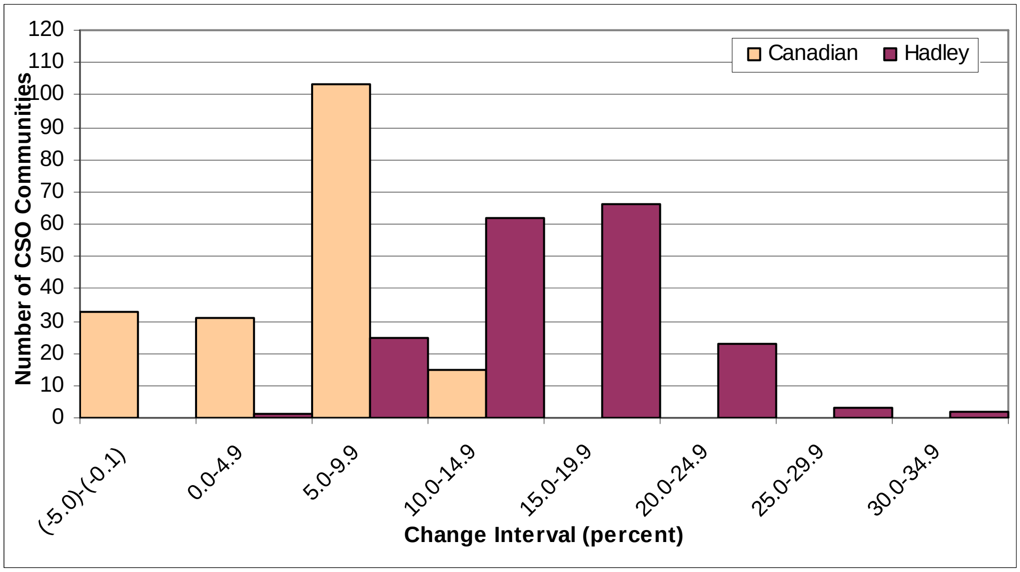

Figure 9. Percent change in the four-event benchmark daily total precipitation in the Great Lakes region relative to historical values based on Canadian (CCCM) and Hadley (HADCM2) Model climate projections for the future period 2060–2099 (4-day averaging period).

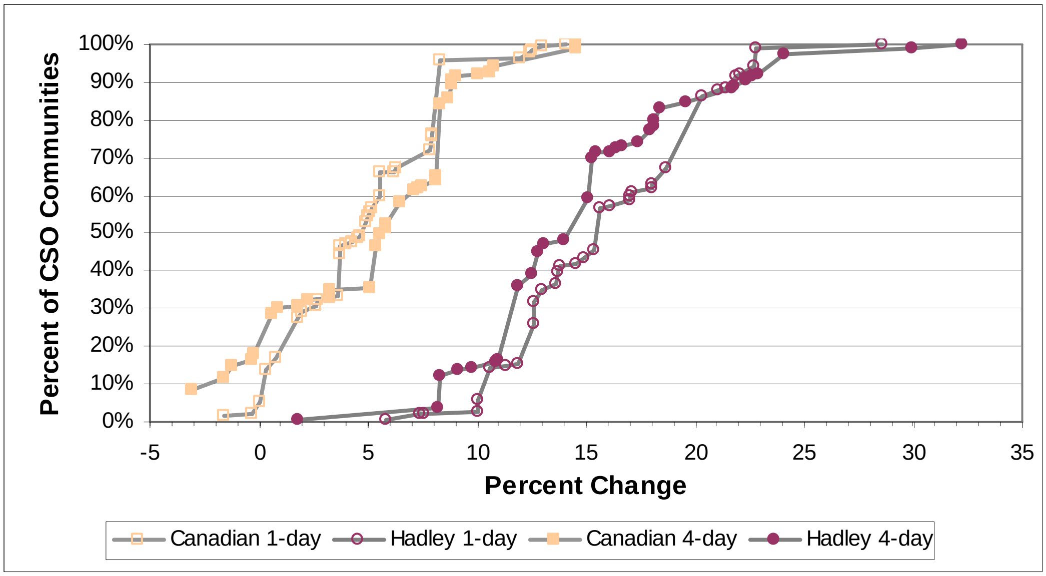

Figure 10. Cumulative distribution of percent change in four-event benchmark daily total precipitation in the Great Lakes region relative to historical values based on future climate projections for the period 2060–2099.

4.2.1.2. *New England Region*

In the New England Region, the regional average daily total precipitation corresponding to a recurrence interval of four events per year during the future period from 2025–2050 is projected to change from -6% to 3% relative to historical values (Table 6). The regional-average change based on the different AOGCM models disagree in sign, with the CCCM model predominantly suggesting decreases in average intensity, and the HADCM2 model predominantly suggesting increases. This inconsistency in the direction of change complicates interpretation of results in the context of necessary changes in system capacity to adapt to climate change. Nonetheless, results do provide information on the potential magnitude of change relative to historical values in this region.

Table 6. Regional average percent change in the benchmark daily total precipitation in the New England region during the future period 2025–2050. Changes are expressed relative to historical values.

Moving Average	CCCM	HADCM2
1-Day	-3.2%	2.8%
4-Day	-5.7%	3.1%

Figure 11 shows the distributions of projected changes in the benchmark daily precipitation event in the New England Region based on a 1-day moving average of daily precipitation. Projections based on the CCCM model suggest three communities may experience an increase in benchmark daily event exceeding 10%, whereas projections based on the HADCM2 model suggest 21 communities may experience increases in the benchmark daily event exceeding 10%. Figure 12 shows the distributions of projected changes in the four-event benchmark event intensity for the 4-day averaging period. In each case, the projected changes in event magnitude based on the CCCM model are shifted slightly to the left, indicating a decrease relative to projections based on the HADCM2 Model. Figure 13 shows the cumulative distributions of projected changes in benchmark daily precipitation from the HADCM2 and CCCM models for the 1- and 4-day averaging periods.

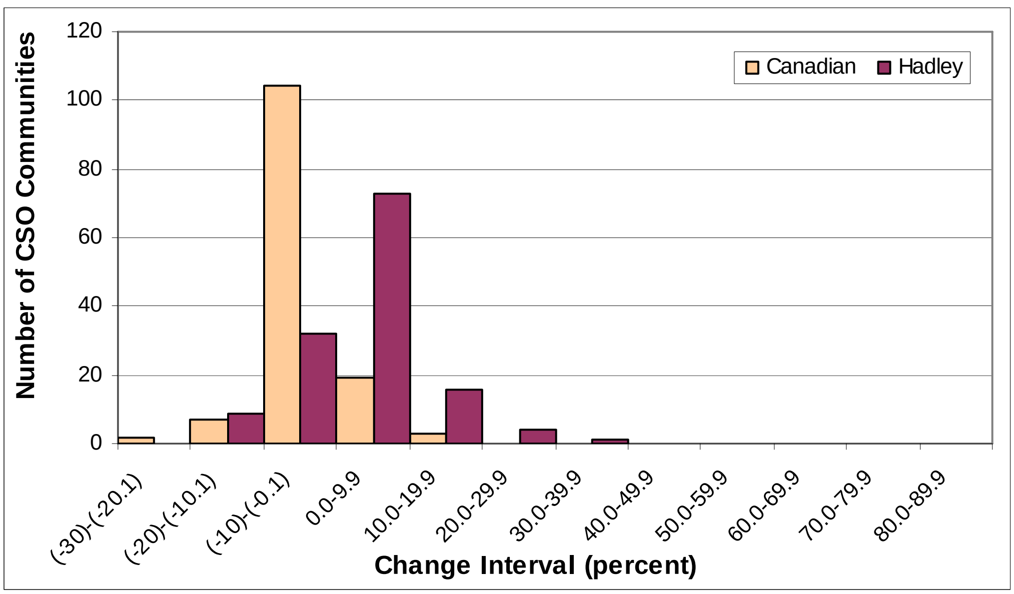

Figure 11. Percent change in the four-event benchmark daily total precipitation in the New England region relative to historical values based on Canadian (CCCM) and Hadley (HADCM2) Model climate projections for the future period 2025–2050 (1-day averaging period).

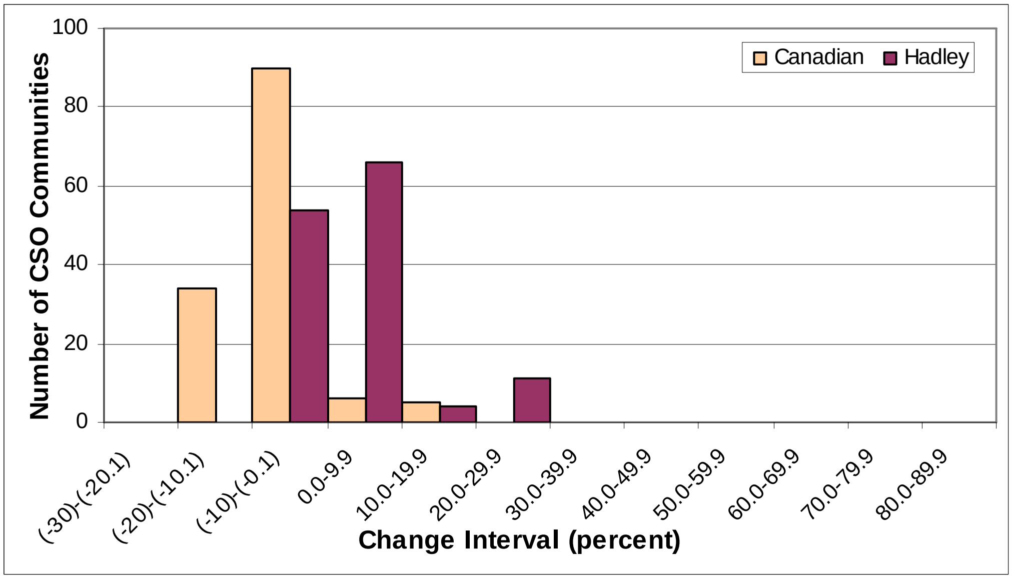

Figure 12. Percent change in the four-event benchmark daily total precipitation in the New England region relative to historical values based on Canadian (CCCM) and Hadley (HADCM2) model climate projections for the future period 2025–2050 (4-day averaging period).

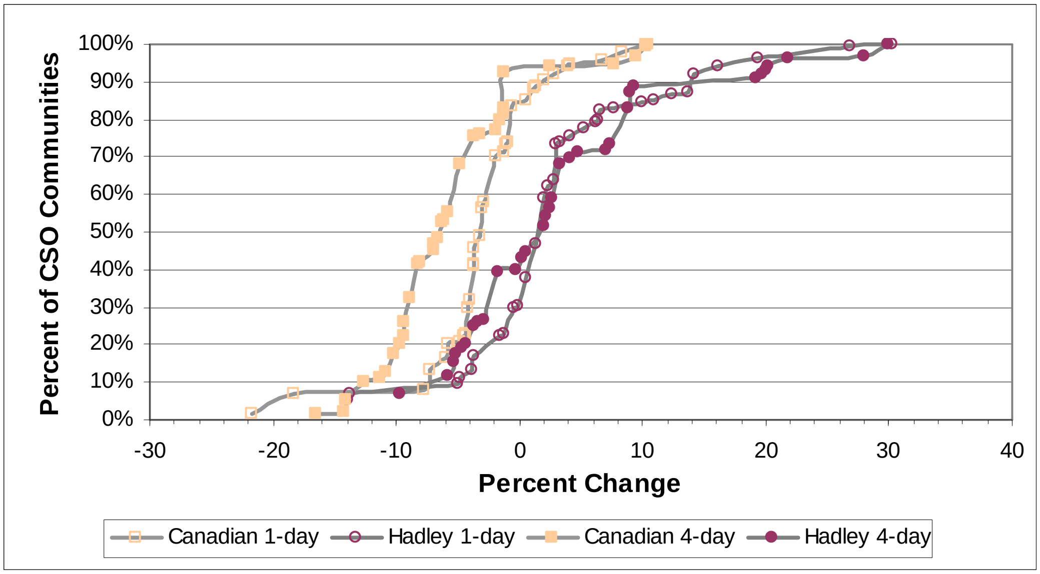

Figure 13. Cumulative distribution of percent change in four-event benchmark daily total precipitation in the New England region relative to historical values based on future climate projections for the period 2025–2050.

4.2.2. Potential Changes in System Capacity

Future changes in precipitation are an important indicator of the potential impacts of climate change on CSOs, particularly in the context of precipitation design criteria upon which CSO mitigation strategies are based. In addition to precipitation, however, CSO events are influenced by specific watershed and sewershed attributes affecting the generation and routing of stormwater entering the system, and attributes of the CSS including the conveyance, storage capacity, and wastewater treatment plant capacity. Detailed modeling of individual systems is required to properly account for these factors, but was beyond the scope of this study. Rather, coarse, order-of-magnitude estimates of the potential changes in stormwater runoff needing to be accommodated by CSSs in each region were made by applying a high- and low-range scaling factor to projected future changes in precipitation.

Chiew et al. (1995) suggest that the percent change in runoff is about twice the percent change in precipitation in wet and temperate areas. The United Nations Food and Agriculture Organization (FAO) suggests that the percent change in runoff increases at half the rate of the increase in precipitation (Critchley and Siegert, 1991). In the United Kingdom, an assessment based on climate change projections for the year 2080 suggests that increases in rainfall of 40% would approximately double the frequency and volume of flooding (Wilkinson and Balmforth, 2004). The range of these estimates reflects changes in the hydrologic response associated with changes in climate in different regions and watersheds. Future changes in watershed (and sewershed) landuse, infrastructure, and urban stormwater management practices will also influence the hydrologic response to changes in climate.

To capture a broad range of potential changes in hydrologic response, the estimates of the FAO and Chiew et al. (1995) were used as lower and upper bounds on the change in runoff per unit change in precipitation. Table 7 shows the estimated regional average changes in runoff resulting from application of FAO and Chiew et al. scaling factors to projected changes in benchmark event intensity in the Great Lakes Region. Table 8 shows the same estimates for the New England Region.

Table 7. Estimated regional average percent change in runoff volume for the Great Lakes region for the future period 2060–2099. Changes are expressed relative to historical values.

	CCCM Model			HADCM2 Model		
Averaging Period	% Change Precipitation	% Change Runoff (0.5x scaling)	% Change Runoff (2x scaling)	% Change Precipitation	% Change Runoff (0.5x scaling)	% Change Runoff (2x scaling)
1-Day	4.8	2.4	9.6	16.2	8.1	32.4
4-Day	5.1	2.6	10.2	14.9	7.5	29.8

Table 8. Estimated regional average percent change in runoff volume for the New England region for the future period 2025–2050. Changes are expressed relative to historical values.

	CCCM Model			HADCM2 Model		
Averaging Period	% Change Precipitation	% Change Runoff (0.5x scaling)	% Change Runoff (2x scaling)	% Change Precipitation	% Change Runoff (0.5x scaling)	% Change Runoff (2x scaling)
1-Day	-3.2	-1.6	-6.4	2.8	1.4	5.6
4-Day	-5.7	-2.9	-11.4	3.1	1.6	6.2

4.3. LIMITATIONS AND FUTURE RESEARCH

This screening-level report assesses the potential order of magnitude of climate change impacts on CSO mitigation in the New England and Great Lakes Regions. The purpose is to assess whether the potential implications of climate change on CSOs in these regions warrant further consideration and study in these regions. Accordingly, a methodology was used that involved a number of simplifying assumptions and other limitations. This section outlines some key limitations of the approach that must be considered when interpreting results and presents several suggestions for future research.

4.3.1. Limitations

Presumption Approach–The CSO Control Policy Presumption approach standard of no more than four events per year is assumed to be the main objective of CSS managers, and increasing system storage is assumed to be the primary mitigation measure used to meet this standard. In practice, there are many site-specific issues that make development of long-term control plans very complicated, and not all planners choose to increase storage as their primary mitigation measure. Moreover, the CSO Control Policy also allows use of a Demonstration approach based on levels of effluent treatment and water quality standards of the receiving waterbody. Thus, the analysis takes a relatively simple approach to a very complex and heterogeneous system; the approach lacks the technical robustness that would result from the use of sewer system models such as the Storm Water Management Model (SWMM). Modeling and analysis that captures the effects of changes in rainfall, snowfall, snowmelt, and rain-on-snow runoff events and system design would be particularly helpful.

Benchmarking–This analysis is based on a benchmarking comparison of historical and future daily precipitation totals based on weather observations and AOGCM projections. A simple ranking technique was used in this study to identify benchmark events rather than more sophisticated statistical techniques. The use of statistical techniques for identifying benchmark events may yield slightly different results. Moreover, the historical data sets used to establish storm intensity, duration, and frequency may go back further in time than the 25-year period used for the New England Region or the 40-year period used for the Great Lakes Region. To the extent that there are underlying trends in precipitation[3] toward increasing intensity of storm events, use of a short (more recent) time period from the historical data set as the baseline may bias estimates of future change relative baseline values based on other historical periods.

General Circulation Models–Use of the four-event-per-year standard from the Presumption Approach as a standard benchmark required a focus on values at the high end of the precipitation distribution–the 100th largest out of 9,130 values (25 years) for the New England Region and the 160th largest out of 14,600 values (40 years) for the Great Lakes Region. The validity of these values is a function both of the validity of the AOGCM projections and the validity of the downscaling approach used to manipulate those projections. The VEMAP precipitation data used in this study is based on AOGCM projections (CCCM and HADCM2 models) at a monthly time step. Monthly average values were converted to daily projections based on the stochastic weather generator, WGEN. The initial AOGCM outputs and the use of a weather generator to generate daily data incorporate many limitations and a considerable degree

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[3] For example, the observed 20th century values for annual precipitation were up to 25% greater than pre-20th century records for the eastern coastline of the New England Region, where many of the CSS communities are located (U.S. Department of State, 2002).

of uncertainty, as described earlier in this report and in the VEMAP documentation. All of those limitations and uncertainties apply directly to these results. Moreover, most models are more valid in their estimation of central tendencies than in the tails of the output distribution, and to the extent that we are concerned here with the high-end tail, the results should be used with caution.

Averaging Period–The VEMAP data used in this study was at a daily time step. Although the analysis uses 1- and 4-day averaging periods to bracket the effects of short, intense storms versus longer or multiple precipitation events in sequence, it is possible that by choosing shorter or longer periods the results could change. For example, the approach does not distinguish between intense precipitation "pop-up" events (e.g., a thunderstorm yielding 2 inches of rain in 1 hour) versus a steady rain that accumulates 2 inches over a full 24-hour period. These short, but intense, events can quickly overwhelm a CSS and result in an overflow or surcharged sewer condition. More sophisticated ways for addressing sub-daily event characteristics would improve the results of this study. Higher temporal resolution evaluation of hydrologic effects (e.g., an hourly time-step) will require additional precipitation data sets and/or methods for disaggregating daily precipitation to finer time scales. In either case, the use of hydrologic models such as SWMM would likely be required.

Snowmelt–Analysis of total daily precipitation data from the VEMAP data set does not distinguish between rain and snow. All precipitation is treated as rainfall. Snowfall is less likely than rainfall to result in elevated peak flows in a CSS at the time of the precipitation event, but snowmelt at a later date can have significant impacts on sewer flows, especially if the snowmelt occurs during a rain event. Moreover, rain on snow events can result in significant runoff, with virtually all of the rainfall converted to runoff, supplemented by melting snow. This is a significant limitation for our analyses of the New England and Great Lakes Regions, given the generally cold temperatures throughout these regions during the winter months.

Future Time Period of Concern–This analysis is strongly influenced by variability in climate change projections in time and space. In the case of the long-term (2060–2099) projections for the Great Lakes Region, the CCCM and HADCM2 AOGCMs each predict an increase in CSO event frequency (with respect to a historical benchmark) and the intensity of the four-events-per-year benchmark storm event. In the New England Region, however, more near-term (2025–2050) projections disagree in the direction of change; the HADCM2 model projected increases and the CCCM model projected decreases in the frequency of CSO events and intensity of the four-events-per-year benchmark event. The methodology is, thus, not able to determine if the differences in AOGCM behavior are due to differences in the two time periods or to differences in the two geographic regions. This is a limitation of this study that requires additional investigation.

This inconsistency does, however, highlight an important consideration for assessing the future implications of climate change. On one hand, it is desirable to focus on a more distant future when changes in climate, if present, are more likely to be detectable. One the other hand, a focus on the near-term provides information more useful and relevant to current decision making. Finding the right balance is important to the overall value of an assessment activity. The work in the New England and Great Lakes Regions described in this report was conducted as two separate projects. Work in the New England Region was done subsequent to that in the Great Lakes Region, and the more near-term focus was selected to be more relevant to current decision making. Unfortunately, despite the inconclusive near-term results in the New England Region, resource limitations did not allow analysis of additional future time periods (e.g., 2060–2099) in this region.

4.3.2. Future Research

This study is only a first step towards understanding a very complex issue, the implications of which will vary significantly depending on location and system. The following are suggested areas of follow-up research to this study.

Utilize More Recent Climate Models–Newer AOGCM runs have become available since the VEMAP Phase II data set was created in the mid 1990s. There are also additional approaches for obtaining daily, time-step projections through updated weather generators or AOGCMs that generate daily precipitation data. More up-to-date AOGCM results would reflect advances in the state of the science, and regional models (e.g., the UK Hadley Centre's PRECIS model) can provide better resolution on a regional basis.

Case Studies–A smaller scale case study approach looking in detail at a few communities would provide more accurate data on system responses on an hourly basis. These case studies would likely involve the use of detailed sewershed runoff models such as SWMM. These models typically utilize continuous precipitation data, so a method for applying AOGCM outputs to modify historical continuous precipitation data would need to be created. This would provide a more robust analysis as event intensity on an hourly (or shorter time-step) basis for predicting CSO events would provide a more accurate basis than the daily precipitation data utilized in this screening-level analysis. The use of hydrologic models for more detailed case study assessments would also allow for better handling of the complex hydrologic responses to climate change including the effects of changes in snow, snowmelt, and temperature.

Determine Best Practices for Characterizing Design Storms–One opportunity to provide useful guidance would be to establish a straightforward approach for modifying the Intensity-Duration-Frequency (IDF) curves and design storms commonly utilized for water resource engineering design and planning. To develop guidance, it would be useful to review (1) the current practices associated with creating IDF curves (e.g., how far back in the historical record, what statistical techniques are used) and (2) the extent to which recent trends in increasing storm intensity are already embedded in the IDF curves. One possible approach for modifying the way that design storms are calculated would be to utilize research examining trends in precipitation intensity over the last century. For example, research by Groisman et al. (2005) evaluated historical precipitation data for the United States and determined that there were statistically significant trends which indicated an increase in the intensity of the heavy (upper 5% of precipitation) events. Specifically, their research has found a 4.6% increase in event intensity per decade for the largest 5% of precipitation events; a 7.2% increase in event intensity per decade for the largest 1% of precipitation events; and a 14.1% increase in event intensity per decade for the largest 0.1% of precipitation events. Relationships like these could be used, along with assumptions on the design lifetime of CSSs, to provide adjustment factors for characterizing future storm intensity.

Effectiveness of Best Management Practices in CSO mitigation– The threat of increased future precipitation variability could provide additional motivation for rigorous inflow and infiltration (I&I) mitigation programs that maximize the capacity of the existing CSS. By eliminating flow in sewers due to groundwater infiltration and runoff from gutter downspouts and sump pumps, additional capacity can be made available to reduce the frequency and severity of CSOs. Many municipalities already have aggressive I&I programs in place, and the potential for increased precipitation intensity in the future under climate change makes this mitigation option even more important. Moreover, a variety of stormwater best management practices (BMPs) and low-impact design strategies can be implemented to reduce runoff peaks entering CSSs including rain gardens, rain barrels, green roofs, and other practices. Assessment of the design, implementation, and effectiveness of I&I programs for adapting to climate change is an important area requiring additional study.

5. CONCLUSIONS

This screening-level analysis assesses the potential order of magnitude of climate change impacts on CSO mitigation in the New England and Great Lakes Regions. The purpose is to determine whether the potential implications of climate change on CSOs in these regions warrant further consideration and study, and secondly, to evaluate the need for decision support tools and information enabling CSS managers to better incorporate consideration of climate change into their decision making processes. As such, this assessment and report is only a first step towards understanding a complex issue, the implications of which will vary significantly in different locations and for different systems.

In the Great Lakes Region, projected long-term (2060–2099) changes in precipitation suggest that if CSO mitigation efforts are designed based on historical precipitation values, many systems could experience increases in the frequency of CSO events beyond their design capacity, resulting in increases in overflow volume discharged to receiving waters. In the New England Region, projected near-term (2025–2050) changes in precipitation are inconsistent, with projections based on the CCCM and HADCM2 AOGCM models disagreeing on the direction of change. This difference in direction complicates interpretation of the results and highlights uncertainties associated with the AOGCM climate projections. The near-term results for the New England Region are best considered inconclusive, however, neither confirming nor refuting the likelihood of future impacts due to climate change. This analysis did not consider long-term (2060–2099) projections of change in the New England Region—a limitation that precludes any direct comparison of impacts in the two study regions. Future study is required to address this issue in the New England Region.

It must be noted that the methodology used in this study involves a number of simplifying assumptions and other limitations. Key limitations include the inherent uncertainty in AOGCM projections, use of a weather generator to downscale to daily data, lack of consideration of snow and snowmelt, and the use of simple scaling factors to estimate stormwater runoff rather than detailed modeling of individual CSSs. Results are thus not intended, nor the methods appropriate, to provide site-specific information on the potential impacts or mitigation requirements for any individual system or facility.

Investments in water infrastructure tend to be long-term, capital-intensive, and, in many cases, irreversible in the short- to medium-term. It is thus prudent to consider that today's decisions could influence the ability of treatment facilities to accommodate changes in climate for decades into the future. As indicated in this report, knowledge of future climate change at the local scales required by CSS managers is still subject to uncertainty, particularly with respect to changes in precipitation. Throughout much of the United States, however, there is empirical evidence for a trend toward increasing precipitation intensity during the last century (Karl and Knight, 1998). Irrespective of the uncertainties in the AOGCM projections, consideration of these changes may be warranted. Moreover, uncertainty regarding future climate change should be considered in context. CSS managers already include other factors with similar uncertainty and long-term effects in their design such as total impervious area, sewered area, population served, and per capita water demand.

Faced with the prospect of future climate change, opportunities may exist where current CSO mitigation efforts can be upgraded at little additional cost to provide an added margin of safety to account both for near-term extreme events and the potential future effects of climate change. No-regrets opportunities may also exist where actions taken today to address current, other water quality concerns can provide additional benefits in the context of adapting to climate change.

Finally, it is important to recognize that each CSS and CSS community has a unique set of attributes, existing challenges, constraints, and other factors that must be considered in determining what reasonable and appropriate actions should be taken to manage any increase in risk associated with climate change. The focus of this report, CSOs, is not meant to imply that CSOs are the single or even the greatest source of water quality impairment in these areas. Other sources of impairment including non-point loading from agriculture, urban development, and other sources also occur in the study regions. Moreover, CSS managers are also faced with a range of regulatory and other challenges not related to climate change. Accordingly, responding to climate change will require a holistic approach that considers climate change in the context of other impacts on CSSs and regional water quality to determine what reasonable and appropriate actions can be taken.

Although limited in scope, this screening-level analysis provides a first step towards a better understanding of climate change impacts on CSOs in the New England and Great Lakes Regions. Results suggest that certain systems may be vulnerable to future climate change, and that there is a need for more detailed, site-specific analyses including the development of decision support tools and information. Regardless of whether or not CSS managers choose to include climate change in their long-term planning, it is preferable that the decision be intentional and not due to lack of awareness of the problem.

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