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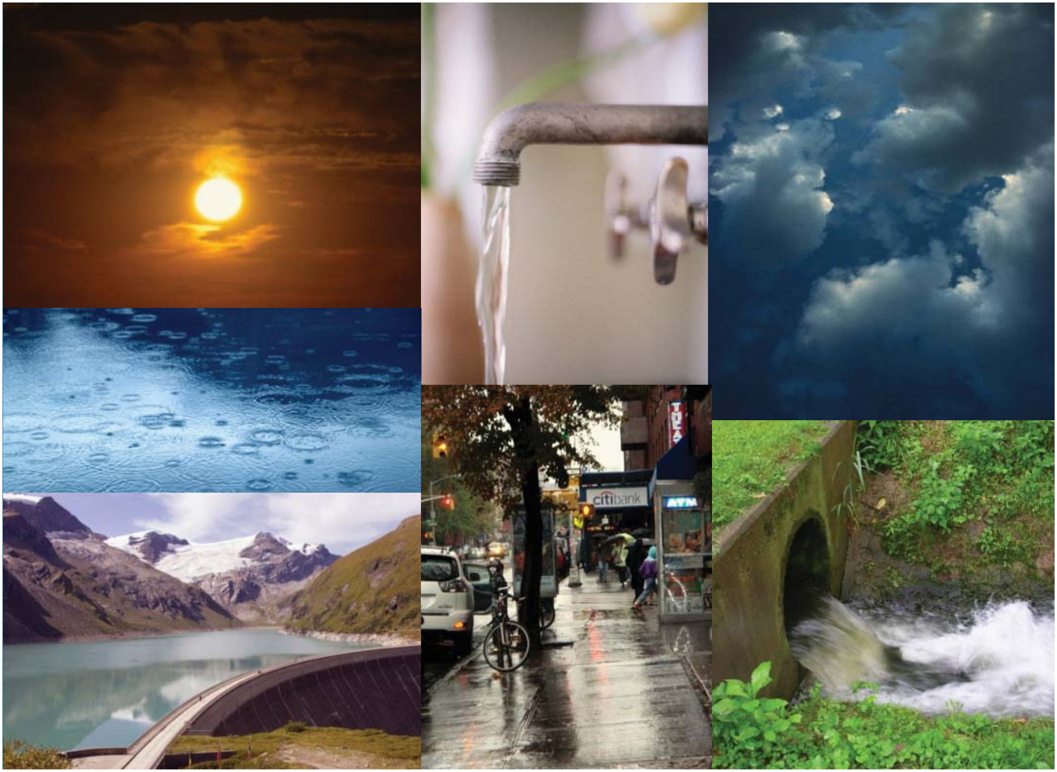
Climate Change Vulnerability Assessments: Four Case Studies of Water Utility Practices



United States Environmental Protection Agency
Office of Research and Development, National Center for Environmental Assessment

EPA/600/R-10/077F
March 2011

Climate Change Vulnerability Assessments: Four Case Studies of Water Utility Practices

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

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Preferred citation:

U.S. Environmental Protection Agency (EPA). (2011) Climate change vulnerability assessments: four case studies of water utility practices. Global Change Research Program, National Center for Environmental Assessment, Washington, DC; EPA/600/R-10/077F. Available from the National Technical Information Service, Springfield, VA, and online at http://www.epa.gov/ncea.

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FOREWORD

Global climate change can have a range of potentially adverse effects on water resources. EPA's Global Change Research Program (GCRP), within the Office of Research and Development (ORD), conducts research to support the development of sustainable solutions for protecting human health and the environment from the effects of air pollution and climate change while sustainably meeting the demands of a growing population and economy. The focus on developing sustainable solutions requires innovative, systems-oriented science that engages end-users from problem-formulation through product application. GCRP research activities addressing the implications of climate change on water quality supports EPA's mission to protect human health and the environment, and is consistent with the goals outlined in the EPA Office of Water's *National Water Program Strategy: Response to Climate Change.*

This report was developed in partnership with the EPA Office of Water (EPA OW). The report is a companion to a report released by EPA OW in 2010 titled *Climate Change Vulnerability Assessments: A Review of Water Utility Practices.* This report can be found at http://water.epa.gov/scitech/climatechange/upload/Climate-Change-Vulnerability-Assessments-Sept-2010.pdf. The 2010 report from the Office of Water describes the range of different approaches being applied by eight U.S. water utilities to assess their vulnerability to climate change. The current report expands on this discussion by presenting a series of case studies that describe in more detail the specific issues, analyses, and actions taken by four U.S. water utilities to assess and respond to climate change. The issue of climate change is complex and will challenge utilities as they strive to meet water quality goals. We hope that the case studies presented in this report will inform, inspire, or otherwise support the efforts of other utilities and water managers to better understand and respond to the challenge of climate change.

We want to thank the authors, reviewers, and entire project team for their effort in preparing this report. Success in producing this report has depended first and foremost on the dedication and enthusiasm of this team. We also want to acknowledge the collaboration of EPA Office of Research and Development and Office of Water in this effort, as well as the cooperation of the utilities examined. While much remains uncertain concerning future climate change, it is clear that our best path forward is through continued research, partnership and collaboration to meet our common goals.

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Preparation of this report was conducted by Abt Associates Inc., Cambridge, Massachusetts, under EPA Contract EP-C-07-023, and Stratus Consulting, Inc., Boulder, Colorado, under subcontract to Abt Associates Inc. Thomas Johnson served as the Technical Project Officer.

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The authors are very grateful for the many thoughtful and constructive comments on an earlier draft of this report provided by Neil Grigg, Paul Kirshen, Simon Pollard, and Len Wright. The authors are also grateful for the many constructive comments received from the public during a public comment period on an earlier draft of this report.

ACKNOWLEDGMENTS

This report could not have been possible without the generous help and support of staff from each of the utilities featured in the report: Alan Cohn, New York City Department of Environmental Protection; Dennis Diemer, East Bay Municipal Utility District; Paul Fleming and Joan Kersnar, Seattle Public Utilities; and Rebecca West, Spartanburg Water. The authors also wish to thank Karen Metchis, Y. Jeffrey Yang, and Meredith Warren at U.S. EPA, and the entire project team at Abt Associates, Stratus Consulting, and U.S. EPA for their help and many thoughtful comments and suggestions that contributed to this report.

EXECUTIVE SUMMARY

Concern about the potential effects of climate change on the quantity, quality, timing, and demand for water is growing. The implications of climate change for long-lived, capital-intensive water infrastructure is a particular concern. In 2009, the U.S. Environmental Protection Agency sponsored the *First National Expert and Stakeholder Workshop on Water Infrastructure Sustainability and Adaptation to Climate Change* (U.S. EPA, 2009a). This workshop highlighted a need for improved information and tools to help water utilities better understand and manage the risk of future impacts due to climate change. Many utilities are already addressing this challenge. One finding of this workshop was that compiling case studies of current water utility activities related to climate change adaptation would be useful to help those in the water sector learn from each other.

This report presents case studies describing the approaches taken by four water utilities in the United States to assess their vulnerability to climate change. The report is not intended to be a comprehensive listing of assessment approaches or utilities conducting vulnerability assessments. Nor does this report represent the full range of potential approaches for assessing and managing climate risk. Rather, the purpose of this report is to illustrate a range of approaches that selected water utilities have taken to understand and respond to climate risk.

Water resources decision making is a complex, multi-factorial process, and determining the impact of a single factor, such as climate change, on decision making is a challenging question. In this report we present the facts from which utility managers, resource planners, climate scientists, and others can draw conclusions and lessons learned. This report is descriptive by design. It does not evaluate the approaches used. Furthermore, because this report is empirical in nature, it might not describe all topics that water utilities need to consider to assess their climate risk.

The following four utilities are featured as case studies in this report:

- East Bay Municipal Utility District (Contra Costa and Alameda Counties, California)
- New York City Department of Environmental Protection (New York, New York)
- Seattle Public Utilities (Seattle, Washington)
- Spartanburg Water (Spartanburg, South Carolina).

The selected utilities differ in terms of their geographic location, size, and the types of impacts they could face from climate change.

EAST BAY MUNICIPAL UTILITY DISTRICT

East Bay Municipal Utility District (EBMUD) used an elaborate policy analysis when designing its Water Supply Management Program (WSMP) 2040 (WSMP 2040; EBMUD, 2009b). The objective of the WSMP 2040 was to identify and recommend a portfolio of projects for meeting dry-year water needs through 2040.[1] The WSMP 2040 process consisted of identifying potential adaptations, bundling them into 14 different portfolios, screening those portfolios based on historic hydrology, and then modeling 5 portfolios under climate change scenarios. EBMUD applied a “bottom-up” approach for the analyses by identifying climate factors most likely to affect the system’s reliability and testing that reliability to changes in those factors that are projected to occur by 2040 (e.g., a 4°F increase in average daily temperatures between 1980 and 2040 or a 20% decrease in precipitation) (EBMUD, 2009a). EBMUD’s analyses reaffirmed the need for a strategy that is flexible and is adaptable to further changes in observed climate and to refinements in climate change projections (EBMUD, 2009b).

NEW YORK CITY DEPARTMENT OF ENVIRONMENTAL PROTECTION

To analyze vulnerability, the New York City Department of Environmental Protection (DEP) examined potential impacts of climate change on the availability of water, turbidity, and eutrophication. The vulnerability analyses identified several potential challenges to New York City’s water supplies and quality, including increased demand, reduced inflows during the spring thaw season, and increased risk of nutrient loadings and eutrophication. Additionally, precipitation changes, sea level rise, and consequent increased salinity levels in the Hudson River could pose challenges to the City’s drainage and wastewater treatment systems. DEP has identified a wide array of initiatives to reduce risks from these potential outcomes. Initiatives include developing a model-based reservoir operation support tool that will allow reservoir operations to be tailored to future climate conditions, relying more on the soon-to-be-filtered Croton water supply during turbidity events, building cost-effective grey infrastructure, making use of natural features such as the wetlands in Staten Island’s Bluebelt, and promoting water conservation. DEP’s extensive vulnerability studies have leveraged momentum for climate change considerations in both strategic and capital planning. For instance, DEP promotes the benefits of green infrastructure for adapting to climate change impacts (e.g., increased heavy precipitation events and intensifying of the urban heat island effect), as part of its broad, citywide effort to better manage stormwater.

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[1] Existing supplies were estimated to be sufficient during normal and wet years.

SEATTLE PUBLIC UTILITIES

Seattle Public Utilities (SPU) has worked closely with the Climate Impacts Group (CIG) at the University of Washington (UW) since 2002 on two studies to assess climate change impacts. In the most recent study, UW-CIG selected global climate models to capture a range of conditions, downscaled them statistically, and ran the outputs through a hydrology model. These results were used in SPU's water supply planning model to examine the effect of climate change on SPU system performance. SPU also used the downscaled data to project changes in demand for water. All climate change scenarios modeled resulted in an estimated decrease in water supplies. The most direct use of the vulnerability assessment by SPU was for water planners to test the effect of different operational assumptions on water supply availability. SPU also identified far-reaching adaptations to use in future decades if demand exceeds water supplies because of either population growth or climate change.

SPARTANBURG WATER

Spartanburg Water is an example of a relatively small utility that did not conduct quantitative vulnerability assessments (e.g., model-based assessments), but was able to use information on climate change together with recent extreme climate events to consider climate change in management decisions. South Carolina has experienced several extreme droughts and hurricanes in recent years and anticipates that climate change will exacerbate these extreme events. With lower low flows in receiving streams during droughts, wastewater treatment plants could be required to upgrade their technology to reduce discharge loads. Also, more intense precipitation could result in greater pollutant loadings from runoff to the receiving streams. In response to these concerns and to plan for projected population increases, Spartanburg Water made several changes in its infrastructure and operations. Recent concerns about water shortages led Spartanburg Water to assert its rights to limit water withdrawals from the reservoir for lawn irrigation during droughts. The utility also launched an aggressive water conservation program and, upon the installation of new pipes, decided to keep the old pipes in place for additional capacity to handle surges from stormwater. These adaptations are consistent with Spartanburg Water's experience with recent extreme events and concerns about population growth and climate change.

OBSERVATIONS ACROSS THE CASE STUDIES

The following summary observations can be made based on these case studies regarding the conduct and use of climate change vulnerability assessments to support adaptation:

- *Conducting climate change vulnerability assessments appears to have increased awareness of climate change risks, informed decision making, and supported adaptation at the utilities featured in this report.* One theme emerging from the case studies is the need to consider climate change in a holistic context, taking into account all factors affecting system performance.

- *Utilities have worked with climate scientists and modelers to obtain data and gain insight into how climate science can be used to inform their decision making.* SPU collaborated with the UW-CIG, DEP collaborated with Columbia University and the City University of New York, and EBMUD used an analysis conducted by the State of California and the California Climate Change Center. In contrast, Spartanburg relied on information gathered from briefings and staff contact with other utilities through participation in the Water Environment Federation and the American Water Works Association but did not formally collaborate with the climate change research community to develop region-specific data on their climate change risks.

- *Uncertainties in vulnerability assessments or climate science need not delay adaptation action.* All four utilities described in this report have taken action to reduce their climate risk despite significant, remaining uncertainties regarding the potential impacts of climate change. Often, these actions also address other concerns, such as managing limited supplies using water conservation or water reuse. Nonetheless, climate change vulnerability analyses can help inform and prioritize among management decisions.

- *The large utilities used a wide array of climate change scenarios to capture some of the uncertainty about future climate change.* EBMUD conducted a “bottom-up” approach by performing sensitivity analyses to improve its understanding about how climate change could affect particular elements of its water resource system. SPU and DEP conducted what are often referred to as “top-down” approaches driven by climate change scenarios and models.[2]

- *Vulnerability analyses to date have focused mainly on water supply and demand.* All four utilities focused their climate change impacts and vulnerability work principally on water supply and demand. Although the utilities expressed concern about the effects of climate change on water quality, urban drainage, wastewater, and other aspects of their systems, these areas have not yet received the same level of attention as water supply.

- *The utilities used system-specific models to understand and manage potential climate impacts on their systems.* All studies except Spartanburg Water used their system hydrology, operations, or planning models to evaluate the effects of potential climate change on their systems. The models were used to assess whether operational changes would be sufficient to cope with the effects of climate change, or whether system changes, such as adding supplies or further reducing demand, also were necessary. These models did not always align with the output of climate models, necessitating tailored use of climate projections for each utility. Spartanburg Water used existing system models to

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[2] For more on the difference between “top-down” and “bottom-up” approaches, see Miller and Yates (2006), Freas et al. (2008), and Stratus Consulting and MWH Global (2009).

understand their system's behavior and qualitatively determine expected climate change impacts.

- *The case studies demonstrate that a variety of methods can be used to understand vulnerability and analyze adaptation options.* Scenario analyses, sensitivity analyses, state-of-the-science literature reviews, and peer information sharing were used in different combinations in the four case studies to understand the potential impacts of climate change. The sensitivity analysis EBMUD performed on their existing system model and the literature review and information gathering from peers Spartanburg Water performed demonstrate two paths that utilities lacking the financial and staff resources to support detailed modeling studies can take to assess their vulnerability to climate change.

- *Utilities expressed an interest in having their needs reflected in future research.* Utilities specifically requested higher resolution climate change projections for the spatial and temporal scales at which they operate, probabilities associated with projected changes, and guidance on appropriate climate change parameters and scenarios to consider and plan for in their regions. One recommendation was to establish a central repository of data to support climate change and adaptation analysis.

- *The results of vulnerability assessments by the four utilities were used in different ways to inform and support adaptation.* SPU responded directly to the results of the vulnerability analysis by evaluating the impact of conservative operational assumptions on reservoir management. The other utilities used their vulnerability assessments to increase knowledge about their climate change risks, integrate information on these risks into decision making, and provide support for adaptation measures.

1. INTRODUCTION

Concern about the potential effects of climate change on the quantity, quality, timing, and demand for water[3] is growing. In particular, decisions about water infrastructure have long-term implications because the infrastructure built today likely will be in place for decades. In 1997, the American Water Works Association (AWWA) issued a statement expressing the need for water utilities to begin planning for consequences of climate change (AWWA, 1997). In 2004, AWWA teamed with the National Center for Atmospheric Research to publish guidance for municipal utilities on how to address climate change (Miller and Yates, 2006). Three years later, eight major municipal water utilities formed the Water Utility Climate Alliance (WUCA) to "provide leadership and collaboration on climate change issues affecting the country's water agencies" (WUCA, 2010).

Vulnerability to climate change, as defined by the Intergovernmental Panel on Climate Change (IPCC), refers to the exposure, sensitivity, and adaptive capacity of systems to climate change (Smit et al., 2001). Exposure consists of the type of change a system experiences. A coastal city might be exposed to a 3-foot sea level rise, while an inland city would not. Sensitivity is the effect that climate change can have on a system assuming no planned adaptation. For example, climate change is projected to reduce the growth of many crops but increase the growth of others. The sensitivity of these crops to climate change differs. Adaptive capacity refers to the potential or ability of a system to adapt to the effects of climate change (Smit et al., 2001). The adaptive capacity of a system is important, for example, in distinguishing the vulnerability of wealthy and poor societies or human systems versus ecosystems. Wealthier societies, in general, have greater adaptive capacity and, thus, on average, are considered less vulnerable to climate change than poorer societies (Parry et al., 2007).

Several water utilities have begun to assess the potential vulnerability of their systems to climate change. Many are considering whether their infrastructures or operations should be changed now or in the future to adapt to climate change. In 2009, the U.S. Environmental Protection Agency (EPA) sponsored the *First National Expert and Stakeholder Workshop on Water Infrastructure Sustainability and Adaptation to Climate Change* (U.S. EPA, 2009a). This workshop highlighted a need for improved information and tools to help water utilities better understand and manage the risk of future impacts due to climate change. One finding of this workshop was that compiling case studies of current water utility activities related to climate change adaptation would help others in the water sector learn from each other.

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[3] For information on climate change and its projected impacts on water resources, see IPCC, 2008 and USGCRP, 2009.

This report presents case studies describing the approaches taken by four water utilities in the United States to assess their vulnerability to climate change. The report is not intended to be a comprehensive listing of assessment approaches or utilities conducting vulnerability assessments (for more detail on these topics, see the companion report, U.S. EPA, 2010). Rather, its purpose is to illustrate a range of issues and current approaches taken by selected utilities that are leaders in climate adaptation to understand and respond to climate risk. Climate change and its effect on water resources is complex and will require ongoing attention and study. We hope the information gleaned from these case studies will be of use to water utilities and other members of the water resources community in illustrating a range of vulnerability studies being applied to guide adaptation decision making. This report is also intended to help identify the types of technical assistance needed to support such assessments.

A companion report is available, *Climate Change Vulnerability Assessments: A Review of Water Utility Practices* (U.S. EPA, 2010). The purpose of that report is to identify and categorize the models and techniques that eight water utilities are using to understand their vulnerability to climate change. The current report provides a more detailed examination of the approaches taken by three of the eight utilities discussed in U.S. EPA (2010). The current report also includes discussion of one utility not included in U.S. EPA (2010).

1.1. SELECTION OF CASE STUDIES

Many water utilities are active in developing climate adaptation strategies and could have been included here. Limiting the scope of this report to just four utilities, however, was necessary for practical reasons. The four utilities featured in this report are (Figure 1)

- East Bay Municipal Utility District (EBMUD) in Contra Costa and Alameda Counties, California
- New York City Department of Environmental Protection (DEP) in New York, New York
- Seattle Public Utilities (SPU) in Seattle, Washington
- Spartanburg Water in Spartanburg, South Carolina.

The selected utilities differ in terms of their geographic location, size, and the types of impacts they could face from climate change (Table 1). Three of the four serve more than a

Figure 1. Location of water utility case studies

Table 1. Key attributes of water utility case studies

Utility	**Location**	**Population served**	**Key climate change risks**
East Bay Municipal Utility District (EBMUD)	Alameda and Contra Costa Counties, California	1.3 million	• Change in timing of runoff • Reduction in water supply • Sea level rise
Department of Environmental Protection (DEP)	New York, New York	9.2 million	• Increases in turbidity, eutrophication, and combined sewer overflows • Sea level rise
Seattle Public Utilities (SPU)	Seattle, Washington	1.4 million	• Change in timing of runoff • Reduction in water supply • Increases in flood risks and combined sewer overflows
Spartanburg Water	Spartanburg, South Carolina	180,000	• Increases in drought and coastal storms

million people. The smaller Spartanburg Water was selected because of its size and because it took a qualitative approach to understanding its vulnerability to climate change. The western utilities are mainly concerned about potential changes in the timing of and reductions in runoff, while the eastern utilities are concerned about changes in extreme events and consequences of these events for water quantity and quality, and the performance of their systems.

Each selected utility has examined or is examining the vulnerability of its system to climate change. The methods used span a range from detailed, quantitative analyses to a more qualitative approach for examining climate change and lessons learned from recent extreme events. All four utilities have also considered or made changes to planning, operations, or infrastructure that, if not driven by the results of their analyses, are at least consistent with adapting to climate change. These four case studies are not necessarily representative of how all utilities are considering climate change. Nor do they represent the full range of potential approaches for assessing and managing climate risk. They do, however, illustrate and provide insight into how information on vulnerability to climate change is being developed and used.

1.2. DATA COLLECTION

The information presented in this report was collected from publically available documents and interviews with utility staff. Specifically, the report focuses on

- Background of the utility—e.g., location, size of utility
- Description of the utility, including the water supply (which includes provision of drinking water) and wastewater system
- Climate change projections and why the utility was interested in vulnerability to climate change
- Approach for conducting vulnerability assessment, including scenarios, assessment methods, and results
- Discussion of application of vulnerability assessment information.

Individual utility case studies are presented in the following four chapters. To the extent possible, the level of detail for the case studies is consistent. The final chapter of this report presents summary observations and insights gained from these four case studies.

2. EAST BAY MUNICIPAL UTILITY DISTRICT

East Bay Municipal Utility District (EBMUD) is a public water utility established in 1923 under the California Municipal Utility District Act. Within the EBMUD service area, Special District Number 1 (SD1) was established in 1944 to treat wastewater.

2.1. BACKGROUND

EBMUD provides water to an estimated 1.3 million people in 35 communities in Alameda and Contra Costa Counties in East San Francisco Bay, as well as industrial and commercial water users (Wallis et al., 2008; EBMUD, 2009b). It produces an average of 220 million gallons per day (mgd) of drinking water in non-drought years. The total service area is approximately 335 mi^2. EBMUD also provides wastewater services for approximately 640,000 customers west of Oakland/Berkeley Hills (EBMUD, 2009b) in an 83-mi^2 component of the EBMUD service area.

Diverse topography and maritime influences in California and the San Francisco Bay area contribute to a varied climate within the EBMUD service area (Figure 2). The Coast Range runs parallel to the coastline from Oregon to north of the Los Angeles Basin and is generally no more than 50 miles wide (WRCC, 2010). A break in the Coast Range at San Francisco Bay allows the inflow of marine air to the interior of the State under specific circulation patterns (WRCC, 2010). The Coast Range merges with the Cascade Range in the northern part of the State creating a 200-mile-wide area of rugged terrain (WRCC, 2010). The Cascades then tend southeast and merge into the Sierra Nevada, which continues to parallel the coast. Between these two ranges is the Central Valley. This flat, 45-mile-wide valley is closed off by the meeting of the Sierra Nevada and Tehachapi Mountains, which tend southwest to meet the Coast Range (WRCC, 2010).

West of these mountain ranges, the climate is predominantly maritime, dominated by the Pacific Ocean. This area experiences warm winters, cool summers, small daily and seasonal temperature ranges, and high relative humidity (WRCC, 2010). East of the mountain ranges, the climate is continental desert, characterized by warmer summers, colder winters, greater daily and seasonal temperature ranges, and generally lower relative humidity (WRCC, 2010). In the transition zone between these two areas, climate depends on how the local topography influences circulation patterns (WRCC, 2010). The difference between Oakland, California, on the San Francisco Bay, and Livermore, California, just 30 miles inland, illustrates the climate variability within the EBMUD service area. The average maximum July temperatures are 72°F and 89°F in Oakland and Livermore, respectively (WRCC, 2010).

Snowmelt from the Sierra Nevada feeds most major streams well into or throughout the arid summer months. Dams serve a dual purpose of providing a water supply throughout the dry part of the year and flood control during the winter and spring. In Oakland, the average total precipitation is 23 inches per year, while in Livermore it is 14 inches per year (NCDC, 2010). All of the precipitation in Oakland falls as rain while Livermore, on average, receives approximately 0.1 inch of snow (NCDC, 2010) annually.

Climate change has been documented in this region. In the second half of the twentieth century, a 3.6°F (2°C) rise in winter temperature was observed in the Sierra Nevada (EBMUD, 2009a). With a 9°F (5°C) rise in temperature, the April 1 snow-covered area could decrease by as much as 50% (California Department of Water Resources [CA DWR] Report).

2.2. DESCRIPTION OF THE WATER SYSTEM

2.2.1. Drinking Water Supply System

2.2.1.1. *Water Sources*

The main water source for EBMUD is the Mokelumne River Watershed, which is located approximately 100 miles northeast of the service area in the Sierra Nevada (Figure 2). Approximately 90% of the water supply originates from this 577-mi^2 area (Wallis et al., 2008). The remaining water supply is from runoff in protected watershed areas of the East Bay into terminal reservoirs. During dry years, evaporation from East Bay terminal reservoirs can exceed runoff, resulting in no net water supply from local runoff in those years (EBMUD, 2009b).

Most of the Mokelumne River Watershed is undeveloped. Approximately 75% of the watershed is forested and located within national forests. Precipitation is highly variable in the watershed; 14 of the past 20 years have had below-normal precipitation or have been critically dry. Precipitation also varies considerably by season, with most precipitation occurring from November to May and the least from June to September. Peak flows take place during winter storms and the spring snowmelt; minimum flows occur in the late summer and fall (EBMUD, 2009b). Approximately 63% of the annual average runoff happens during the spring snowmelt from April to July (EBMUD, 2009a).

Two reservoirs on the Mokelumne River provide water storage, flood protection, recreation, hydropower, and resource management for a downstream fish hatchery. Flow into Pardee Reservoir is regulated by several upstream reservoirs. Pardee Reservoir has a maximum storage capacity of 197,950 acre-feet. The Mokelumne Aqueducts (three closed-pipe aqueducts) stretch 91 miles across the Sacramento/San Joaquin River Delta to convey water from the Pardee Reservoir to the EBMUD service area. The remaining water from the Pardee Reservoir flows to the Camanche Reservoir, which has a maximum storage capacity of 417,120 acre-feet. Water

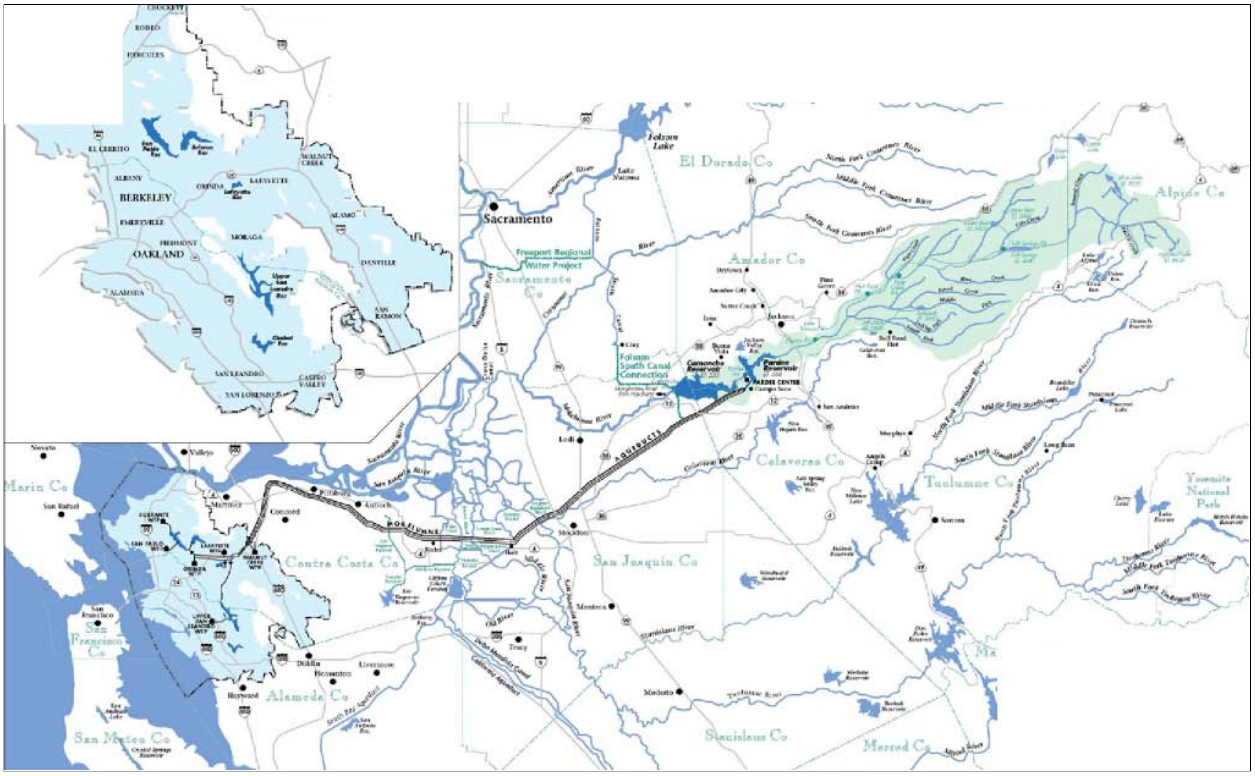

Figure 2. East Bay Municipal Utility District (EBMUD) service area and ultimate service boundary.

Source: EBMUD (2009b).

from the Pardee Reservoir is used to meet the demands of the EBMUD service area, while the Camanche Reservoir is managed to meet EBMUD's obligations to downstream fisheries and senior water rights (EBMUD, 2009b).

EBMUD has water rights and capacity to use or divert to storage up to 325 mgd of water from the Mokelumne River. The actual flow that can be diverted, however, is determined by the amount of runoff and streamflow, upstream and downstream senior water rights, and storage capacities. Additionally, the Camanche Reservoir must also provide releases for fisheries downstream and ensure the availability of up to 200,000 acre-feet of flood control storage during winter months (EBMUD, 2009b). Five terminal reservoirs have a combined capacity of 155,150 acre-feet (EBMUD, 2007). In addition to storing water from the Pardee Reservoir, the terminal reservoirs in the East Bay capture runoff from protected areas of the East Bay Watershed. The terminal reservoirs are operated to maintain 180 days of raw-water supply (EBMUD, 2009b).

Two additional water sources will be available starting mid-2010 to supplement water supplies during dry years (Chan, 2010). Up to 100 mgd of raw surface water will be available from the Sacramento River via the Freeport Regional Water Project. This additional water will meet approximately 22% of the need during dry years. EBMUD estimates that it will use this water source approximately 3 of every 10 years (EBMUD, 2009a). The other new source will be from the first phase of the Bayside Groundwater Project. Treated drinking water from the Mokelumne River will be injected into the south East Bay Plain Basin during wet years and extracted during dry years. The withdrawal permit provides for up to an annual maximum of 1 mgd of water with an extraction rate of 2 mgd for a portion of a "particular drought year" (EBMUD, 2009b).

2.2.1.2. *Water Distribution*

The water distribution system is composed of approximately 120 pressure zones (located at elevations ranging from sea level to 1,450 ft) and approximately 4,100 miles of pipe. About half of the water is distributed by gravity flow. In addition, there are approximately 140 pumping plants and 170 treated water storage tanks (EBMUD, 2007).

Water conveyed to EBMUD either is treated at one of three inline-filtration treatment plants and distributed or is stored in the East Bay terminal reservoirs. Three additional drinking water treatment plants are supplied by two terminal reservoirs. These three plants have full conventional treatment, with two of them also providing ozonation.

2.2.1.3. *Water Use*

Water use in the EBMUD service area is approximately 92% residential, 7% commercial, and 1% industrial and public authority use (EBMUD, 2007). Most water provision services are funded by user fees (approximately 75%) with the remaining revenue coming from capital contributions, investments, taxes, hydropower generation, and other sources (EBMUD, 2009c).

2.2.1.4. *Demand Management*

Programs for managing demand include water rationing, conservation, and reuse. In calculating water availability, EBMUD follows its Water Supply Availability and Deficiency Policy. According to this policy, the maximum rationing (i.e., mandatory water use reduction) during droughts is a 25% reduction in total customer demand, while continuing to provide water to fisheries and other downstream obligations (EBMUD, 2009b). Varying levels of rationing are imposed, depending on the existing and projected extent of the drought and how the levels differ across customer categories. Conservation measures include leak detection and repair in the distribution system, customer incentives for water reduction, and customer education and outreach on water conservation. EBMUD reuses water by providing treated wastewater and untreated raw water from local runoff for irrigation and in-plant processes (EBMUD, 2009b). Approximately 9.3 mgd of water is recycled (Towey, 2010).

2.2.2. Wastewater System

EBMUD provides wastewater treatment in SD1, a subset of the water service area. Nine communities within SD1 have wastewater collection systems that discharge into one of EBMUD's five interceptor sewer trunk lines (EBMUD, 2010). The interceptors have a capacity of 760 mgd of water. On average, the EBMUD wastewater treatment plant (WWTP) in Oakland receives 80 mgd from the interceptors (EBMUD, 2007). The Oakland WWTP has the capacity for 320 mgd of primary treatment, 168 mgd of secondary treatment, a short-term hydraulic peak of 415 mgd during wet weather events, and 11 million gallons of storage (EBMUD, 2007; Cheng, 2010). Treated wastewater is discharged 1 mile off the coast through a deep-water outfall into San Francisco Bay (LAFCO, 2008; EBMUD, 2007).

By-products from WWTP operations are used in two forms: Biosolids are used as a soil amendment or alternative daily cover at landfills, and methane gas provides energy needed for operations (EBMUD, 2007). Additionally, as part of its wastewater source control and pollution prevention activities, EBMUD collects concentrated domestic waste, oil, and grease from restaurants, and other highly organic waste streams to produce methane gas, while decreasing the organic content of the wastewater stream (EBMUD, 2007). Overall, self-produced methane gas provides up to 90% of the Oakland WWTP's power supply (Cheng, 2010).

Since 1979, EBMUD and local communities have addressed rainwater infiltration and inflow in the wastewater collections system resulting from deteriorated pipes and improper storm drain connections. As part of the East Bay Infiltration/Inflow Correction Program, EBMUD constructed three wet-weather treatment plants, two storage basins, 7.5 miles of new interceptor lines, and an expanded Oakland WWTP. Communities have spent more than $460 million on improvements for their wastewater collection systems (EBMUD, 2007).

In 2009, approximately 69% of the revenue for wastewater services came from user fees (53% from wastewater, 16% from wet-weather facilities), and the remaining came from capital contributions, resource recovery, taxes, investments, and other sources (EBMUD, 2009c).

2.3. CLIMATE CHANGE PROJECTIONS AND RISKS

The climate change information EBMUD used to evaluate vulnerability to climate change included the *Fourth Assessment Report of the Intergovernmental Panel on Climate Change* (IPCC, 2007) and two state-level studies that modeled the effects of climate change on water resources (EBMUD, 2009a). Model projections from the IPCC suggest that temperatures in the western United States could rise 3.6−13.5°F (2.0−7.5°C) by the end of this century (IPCC, 2007, as cited in Wallis et al., 2008). In a summary of northern California climate change studies, Dettinger (2004, as cited in EBMUD, 2009a) provides a range of a 3.6−10.8°F (2.0−6.0°C) increase in temperature and either a 20% increase or decrease in precipitation. Rising temperatures are expected to cause precipitation to fall more often as rain, decreasing water storage in snowpack and causing spring runoff to occur earlier. The temperature rise will extend the growing season by about 19–28 days, with more frequent and longer heat waves (Wallis et al., 2008). Sea level is expected to rise another 0.6−1.9 ft by the end of the century (IPCC, 2007, as cited in Wallis et al., 2008). This rise in sea level will affect the frequency and severity of flooding in coastal areas, including the flood-prone Sacramento/San Joaquin River Delta, which three EBMUD water transmission aqueducts cross (Wallis et al., 2008).

EBMUD reviewed two state-level climate change studies—one by the California Energy Commission's Public Interest Energy Research (PIER) and the California Climate Change Center (CCCC), and one by the California Department of Water Resources (CA DWR). A review of both state-level studies by EBMUD concluded that the studies yielded the following similar but uncertain results (EBMUD, 2009a):

- Temperature increases will be significant, but the magnitude of change is uncertain.
- Snowpack volume will decrease.
- Snow will melt earlier.
- The direction and amount of change in total annual precipitation are inconclusive.
- Drought impacts are inconclusive, but some scenarios predict increased frequency and longer duration droughts.
- Climate variability will generally increase.

With a growing awareness of climate change and its potential effects on water resource management, EBMUD started following climate change research, collecting information about projected regional climate change, gathering environmental data, and networking locally and nationally with others in the water community (Wallis et al., 2008; Chan, 2010). EBMUD staff presented these efforts to the Board of Directors and at an annual business forum the Board of Directors and key stakeholders attended (Wallis et al., 2008).

Additionally, EBMUD gauged customer opinion about climate change in an annual customer survey. Of the respondents, almost 75% thought that climate change will be an issue for water suppliers within the next 50 years, and the effect of climate change on water availability was of “highest concern” for 46% (Wallis et al., 2008; Chan, 2010).

In mid-2007, EBMUD established an official utility-wide management approach for addressing climate change and formed a cross-departmental climate change committee. The committee’s primary tasks include keeping up to date on climate change science, evaluating the potential effects of climate change, reviewing Mokelumne River Watershed data to determine changes in trends, assessing water supply and infrastructure vulnerabilities, integrating climate change in planning and budgeting, and developing adaptation and mitigation strategies. By 2008, the EBMUD strategic plan added climate change as one of the strategies for meeting long-term water supply goals (EBMUD, 2008). Strategies included developing and implementing a Climate Change Monitoring and Response Plan and mitigating greenhouse gas emissions across departments (Wallis et al., 2008). While climate change-related activities, such as mitigating greenhouse gas emissions are cross-departmental, vulnerability assessment efforts have focused primarily on the water supply system (Cheng, 2010).

2.4. CLIMATE CHANGE VULNERABILITY ASSESSMENTS

EBMUD identified four key areas of potential vulnerability to climate change: (1) flooding and sea level rise, (2) hydropower generation, (3) water supply and demand, and (4) water quality (Wallis et al., 2008). Since 2006, EBMUD has conducted qualitative assessments and sensitivity analyses to examine these vulnerabilities and their impacts on the drinking water system. The most extensive and quantitative vulnerability analysis was completed as part of the Water Supply Management Program (WSMP) 2040. Vulnerability analyses for the WSMP 2040 focused on water supply, water demand, and the effect of temperature on water quality. Qualitative and less formal assessments have been performed for flooding, sea level rise, and power generation. EMBUD also participates in local and national conferences and workgroups, such as the U.S. Environmental Protection Agency (EPA) Climate Ready Water Utilities Working Group, and currently is working with the U.S. EPA and the Water Research Foundation on developing vulnerability and risk assessment tools to assist other water utilities in conducting climate change analyses (Chan, 2010). For more detailed information on how EBMUD and other utilities organized their vulnerability assessments, see *Climate Change Vulnerability Assessments: A Review of Water Utility Practices* (U.S. EPA, 2010).

2.4.1. Flooding and Sea Level Rise

EBMUD expects that flooding could increase as a result of the more frequent extreme weather events that are predicted with climate change. To assess the effect of more extreme weather events on the potential for flooding in urbanized areas downstream of the Camanche Reservoir, EBMUD modeled the water supply system with a 5.4°F (3°C) rise and 1997 precipitation levels (the wettest year in the past quarter century due to El Niño). The study used the daily operational model for the EBMUD water system (Chan, 2010). Results showed that the peak water release from the Camanche Reservoir would have had to be three times greater than it was in 1997 to prevent riverine flooding (Wallis et al., 2008).

In addition to more extreme weather events, sea level rise could contribute to increased coastal flooding. A 1-foot rise in sea level could cause the 1-in-100-year storm surge flood event to occur once every 10 years (Wallis et al., 2008). The aging levee system in the flood- and earthquake-prone Sacramento/San Joaquin River Delta is an existing vulnerability that would be exacerbated by rising sea levels. Such coastal flooding could disrupt water delivery for months as it did in 2004, when a single levee breach caused flooding that submerged the aqueducts for more than 4 months.

As part of WSMP 2040, EBMUD reviewed the two state-level climate change studies (Section 2.3, above) and found that they sufficiently document current conditions and existing risks, including the susceptibility of the raw-water system to levee failures, earthquakes, and potential failure scenarios. The interactions of vulnerabilities, such as the effects of sea level rise on levee failure, however, have not been characterized. CA DWR is drafting a Delta Risk Management Strategy, and its first report will provide discrete probabilities of levee failure considering several climate change and sea level-rise scenarios. EBMUD plans to use this information to comment on improvement options CA DWR proposes (EBMUD, 2009b).

2.4.2. Hydropower Generation

Although extreme weather events could cause more intense precipitation and flooding, total annual precipitation might decrease. Decreased annual precipitation would not only affect the ability to meet water needs but also would affect hydropower generation. To model the potential range of effects, EBMUDSIM was used. EBMUDSIM is a monthly time-step model of the EBMUD water supply system from the Mokelumne River reservoirs to the five terminal reservoirs in the service area, all of which are modeled as one combined reservoir (Chan, 2010). Results suggested that the projected changes in total precipitation could lead to a 10−30% decrease in hydropower generation (Wallis et al., 2008).

2.4.3. Water Supply

EBMUD has had several ongoing activities related to climate change, but the first extensive, quantitative analyses to assess the effects of climate change on its water supply system were conducted for WSMP 2040. The main objective of WSMP 2040 was to identify and recommend a portfolio of projects for meeting customers' dry-year water needs through 2040.[4] The process consisted of six steps: (1) identifying a list of projects that could provide additional supply, (2) screening the projects, (3) developing portfolios of projects that satisfy water needs through 2040, (4) screening 14 preliminary portfolios under historic hydrologic conditions with existing drought planning sequence, (5) modeling five of these portfolios under the effects of projected climate change, and (6) making a final portfolio selection. Projects included changes in rationing, conservation, water reuse, surface water transfers, groundwater banking/exchange, desalination, and enlargement of reservoir(s) (EBMUD, 2009b). Several uncertainties were identified regarding the proposed projects, including institutional and legal challenges, undefined timelines for project completion, and climate change. To reduce these uncertainties, a reliable portfolio was defined as being (1) robust with respect to an uncertain future, (2) composed of projects that can be pursued simultaneously, and (3) flexible and diverse (EBMUD, 2009c). To inform the selection of a reliable portfolio, a climate change vulnerability analysis was conducted.

EBMUD reviewed 10 other water agencies in California to determine how each was assessing its vulnerabilities to climate change (EBMUD, 2009a). Based on this information, EBMUD considered five approaches for evaluating the effects of climate change on the water supply system: (1) qualitative analysis, (2) perturbing historic hydrology based on perturbation factors from existing studies, (3) hydrologic modeling based on existing climate-derived hydrology by other studies, (4) hydrologic modeling using climate-derived temperature and historic precipitation, and (5) sensitivity analyses using historic hydrology in a hydrologic model (EBMUD, 2009b). A "bottom-up" approach using sensitivity analyses was selected based on a recommendation by Miller and Yates (2006). A bottom-up approach consists of identifying the factors that most affect the system's reliability and testing that sensitivity to and performance under expected changes in those factors (EBMUD, 2009b).

EBMUD identified the three most significant factors that affect the water supply system's reliability in meeting the projected 2040 dry-year water needs: (1) greater-than-expected customer demand, (2) shift in the timing of spring runoff, and (3) decreased volume of precipitation and runoff. EBMUD modeled three sets of scenarios based on these three factors with potential changes in each factor based on the existing regional climate change studies to determine the effect of each factor on the performance of the existing system.[5] Modeling assumptions included using existing conservation and recycled water levels, existing drought planning sequence, and a maximum of 25% rationing. The model was run from 1953 to 2002

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[4] Existing supplies were estimated to be sufficient during normal and wet years.

[5] The existing system was composed of the existing components of the water supply system and projects that were expected to be online by 2010 (i.e., Bayside groundwater and Freeport surface water, see Section 2.2.1).

according to each of the three scenarios (EBMUD, 2009a). Although climate change projections from the IPCC, PIER/CCCC, and CA DWR reports have significant uncertainties, they provided an approximate range of potential changes in climate and hydrology. From this range, EBMUD selected and modeled those changes that are expected to affect the utility's ability to provide sufficient water and meet regulatory obligations for downstream water flow and temperature (e.g., increases in precipitation were not modeled).

2.4.3.1. *Temporal Shift in Runoff*

As a result of increasing temperatures, the volume of runoff between April and July has decreased by approximately 10% over the past century (Wallis et al., 2008). The sensitivity of the water supply system to reductions in spring runoff and increased winter runoff was modeled for 3.6°F, 5.4°F, and 7.2°F (2°C, 3°C, and 4°C) increases in temperature. The analysis estimated the decrease in the volume of runoff from April through June and assumed an increase in the November-to-March runoff by the same volume (EBMUD, 2009a). With 3.6°F, 5.4°F, and 7.2°F (2°C, 3°C, and 4°C) temperature increases, estimated reductions in April through June runoff were 19%, 28%, and 38%, respectively. Carryover storage decreased by an average of 2.5–6% and a maximum of 10–16%. Customer rationing was estimated to increase by a maximum of 7%. Flood control releases increased in 60% of the years between November and May by an average of 66–89%. Between April and July, flood control releases decreased in 35% of the years by 40–80% (EBMUD, 2009a).

The shifts in the timing of runoff had no significant impact on EBMUD's ability to meet water demand because EBMUD's total reservoir storage is larger than the total annual average runoff (EBMUD, 2009a). This capacity enables system operations to be reconfigured for fewer flood control releases (Wallis et al., 2008). When considered in combination with the need to adjust flood releases from the Camanche Reservoir to accommodate extreme precipitation events as predicted above, however, the finding suggests a more delicate balance between flood control and capturing the projected temporal shift in spring runoff.

2.4.3.2. *Decrease in Annual Precipitation*

The effect of reduced precipitation was assessed by assuming that reductions of 10% and 20% in the volumes of annual precipitation directly correspond to 10% and 20% decreases in runoff. Both scenarios were run in the W-E model, a linked combination of the Water Evaluation and Planning and EBMUDSIM models, which resulted in the most significant effects observed among all the scenarios. For the 10% and 20% reductions in precipitation, the average decreases in carryover storage were 12% and 24%, respectively, and the maximum decreases were 47% and 76%, respectively. The magnitude of customer rationing increased on average by

3.8% and 6.4% for the 10% and 20% decreases in precipitation, respectively. The frequency of rationing increased from a baseline of 36% to 44% and 52%, respectively, for the 10% and 20% decreases in precipitation. Average annual flood releases decreased by 43% and 74% for the 10% and 20% decreases in precipitation, respectively (EBMUD, 2009a).

In comparison, the worst drought on record occurred in 1976 and 1977 and resulted in a 75% decrease in average runoff and a 70% reduction in total reservoir capacity (EBMUD, 2009a). A limitation of these sensitivity analyses is that the change in each vulnerability factor was modeled individually, and the synergistic effect of a simultaneous change in all three factors at same time was not considered (EBMUD, 2009b). A final scenario with all three factors would have provided insight into the worst-case scenario.

2.4.3.3. *Increased Demand*

To test the effects of increased water demand, 2040 water demand estimates were recalculated assuming a 7.2°F (4°C) increase in air temperature, resulting in a 3.6% increase in demand.[6] The higher demand estimate accounts for higher consumptive use for drinking and outdoor watering due to higher temperatures alone. A 20% decrease in precipitation had relatively little effect on demands compared to the temperature increase. Therefore, only the demand estimate based on a temperature increase was run in the W-E model. Results showed an average decrease in carryover storage of 3%, with a maximum decrease of 8%. Carryover storage is significant for the EBMUD water supply system, because the reservoirs do not necessarily refill each year, depending on drought conditions. The results also indicate that the magnitude of customer rationing increased to a maximum of 5.6% of demand, but the frequency with which rationing occurred did not change. Flood control releases were not evaluated in this analysis (EBMUD, 2009a).

2.4.4. Water Quality

EBMUD used the Watershed Analysis Risk Management Framework (WARMF) model to assess the effect of increasing air temperatures on water temperatures. The WARMF model was developed by the Upper Mokelumne River Watershed Authority for a different study in which EBMUD participated. This previous analysis was completed to determine the effect of climate change on EBMUD's continued ability to meet its cold-water obligations to the downstream fish hatchery (EBMUD, 2009a).

Six water years were modeled, including two dry years, three below-normal years, and one above-normal year. Each year was modeled for increases of 3.6°F, 5.4°F, and 7.2°F (2°C,

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[6] The 4°C change is based on projected increases from 1980 to 2040 or 2.15°C from 2005 to 2040.

3°C, and 4°C) rise in air temperature projected to occur from 1980 to 2040. Over all scenarios, average annual water temperatures increased by 0.5−6.3°F (0.3−3.5°C) relative to baseline temperatures. In general, the effect of increasing temperatures was found to depend on the type of hydrologic year and the season. In drier years and during the summer months, streamflow is lower and air temperatures have a greater effect on water temperatures (EBMUD, 2009a).

EBMUD studies also identified other water quality effects from climate change, including a greater potential for algal growth with higher water temperatures. In addition, with increasing intensity and frequency of storm events, turbidity levels can increase in water supply sources. Because the EBMUD drinking water treatment plants were designed for treating source water that is low in turbidity, increases in turbidity could decrease the plants' daily outputs and increase treatment costs (Wallis et al., 2008).

2.5. APPLICATION OF VULNERABILITY ASSESSMENT INFORMATION

Several key insights were provided by the climate change analyses described above for the WSMP 2040 decision-making process. The analyses showed a clear distinction between the effects of temporal shifts in precipitation and a decrease in total annual precipitation. The temporal shifts could be managed by adjusting system operations, while decreased precipitation would require additional sources of water outside of the Mokelumne River Watershed. Before conducting these studies, EBMUD believed that diversification of water supply sources was needed. The studies reaffirmed the need for diversifying water supply sources outside of the watershed and selecting projects that can be adapted as climate change effects are observed. For example, instead of relying solely on enlarging existing reservoirs, EBMUD will pursue additional surface water and groundwater sources. Plans also will be drawn up for regional desalination. To meet the 2040 dry-year water needs, conservation, desalination, and the enlargement of reservoirs in combination with groundwater banking and exchange are needed. Pursuing parallel tracks on alternative projects will allow for flexibility, not only with regulatory and logistical challenges, but also with adjusting to future refinements of climate change projections. Although water quality vulnerabilities were not directly addressed, the analyses revealed that the interaction of lower water levels in the reservoirs and increased air temperatures are causal factors for potential water quality concerns.

To support continued climate change vulnerability assessments and adaptation activities, EBMUD identified two main resources that would support these efforts: (1) information on the probabilities of specific projected changes in temperature and precipitation, and (2) a common source for region-specific environmental data to assist in vulnerability analyses (Chan, 2010).

3. NEW YORK CITY DEPARTMENT OF ENVIRONMENTAL PROTECTION

3.1. BACKGROUND

New York City's Department of Environmental Protection (DEP) is responsible for the operation, protection, and maintenance of New York City's drinking water system (DEP, 2010a). DEP supplies 1.1 billion gallons per day (gpd) of drinking water to 8.2 million residents of New York City, and an additional 1 million people in nearby municipalities (DEP, 2008a; see Figure 3). DEP supplies approximately 85% of the water for Westchester County and 5–10% of the water for Orange, Putnam, and Ulster Counties (Rosenzweig et al., 2007). The system also provides legally mandated conservation releases to the Delaware River Basin (DEP, 2008a).

New York State experiences a humid continental climate but with dramatic variations from that climate type due to latitude, general circulation patterns, and topography. Although the region is located along the coast, the area is dominated by drier continental airflow from the prevailing westerly winds. The state's climate is conditioned primarily by cold, dry air masses from the northern continental interior, as well as warm, humid air masses from the south conditioned by the Gulf of Mexico. A third, but relatively less important influence is the air mass from the North Atlantic Ocean, which can produce cool, cloudy, and damp weather. Due to the prevailing winds, however, this maritime influence is secondary to the more prevalent airflow from the continental interior (New York State Climate Office, 2010).

Average annual temperature is approximately 55ºF in New York City but 10–15ºF cooler in the Catskills, which is the major source of water. The distribution of precipitation across New York State is influenced by topography and proximity to the Great Lakes and Atlantic Ocean. Average annual precipitation can exceed 50 inches in the Catskills. In New York City, average annual precipitation is 43–50 inches per year, depending on location within the city. Precipitation is relatively evenly distributed throughout the year, and no distinctly wet or dry seasons occur (NYC Panel on Climate Change, 2009; New York State Climate Office, 2010).

In the mountainous areas of New York State, such as the Catskills, annual average snowfalls range from 70–90 inches, but topography and elevation cause snowfall over even short distances in the state's interior to vary greatly. The bulk of wintertime precipitation in these areas falls as snow. New York City, however, receives only about 25–35 inches of snow per year due to the moderating influence of the Atlantic Ocean. Because of the temperature modulation of the coastal zone, only about one-third of the winter-season precipitation is associated with storms having snow accumulation of at least 1 inch (New York State Climate Office, 2010); the rest falls as rain.

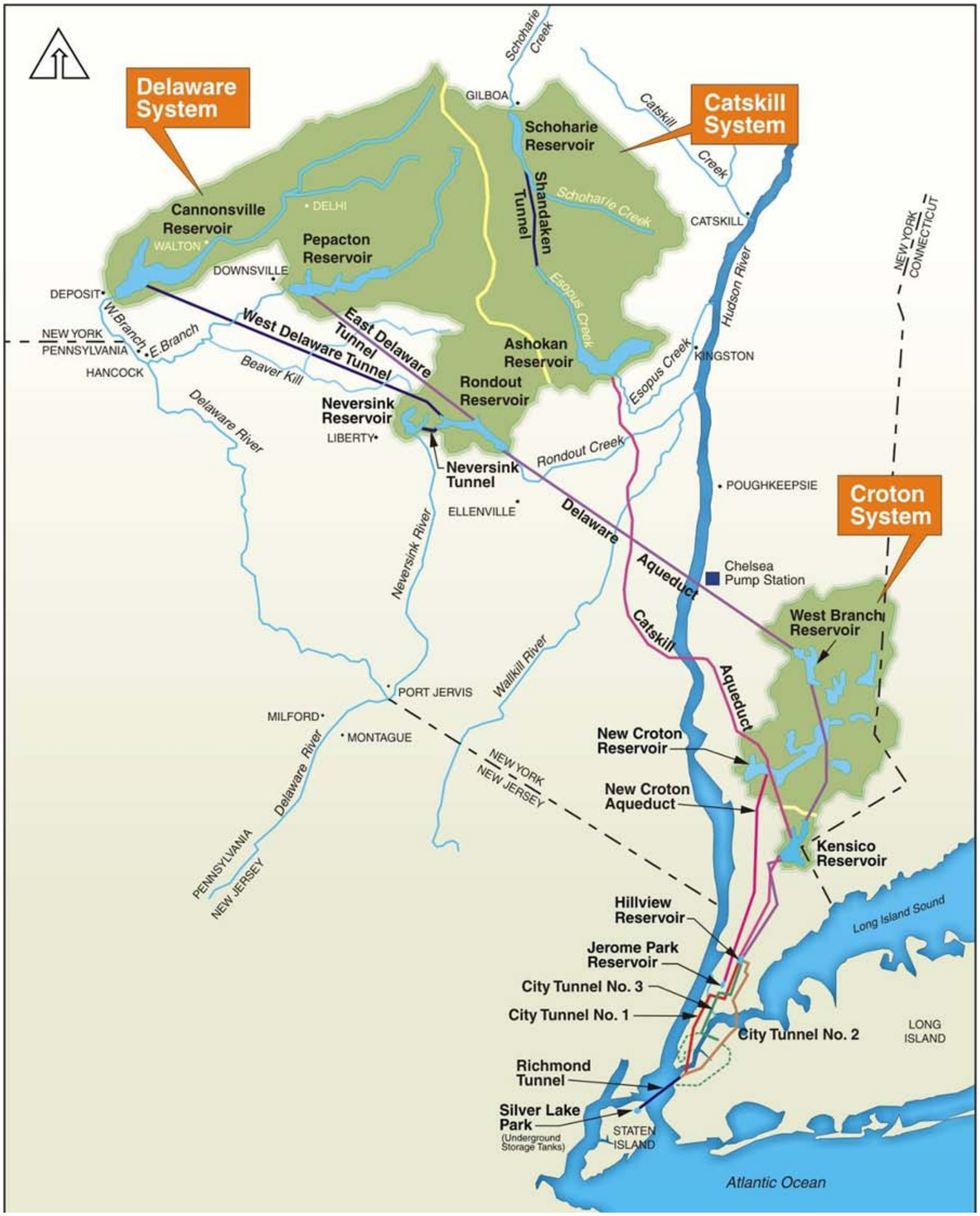

Figure 3. New York City Department of Environmental Protection (DEP) system overview.

Source: DEP (2008b).

Annual mean temperature in New York City has increased 2.5ºF since 1900, although both warming and cooling periods occurred over this time. Mean annual precipitation levels have increased only slightly since 1900, but year-to-year variability in precipitation has increased (NYC Panel on Climate Change, 2009).

3.2. DESCRIPTION OF THE WATER SYSTEM

3.2.1. Water Supply System

New York City's surface water is supplied from a network of 19 reservoirs and three controlled lakes in a region that stretches nearly 2,000 mi^2 and extends 125 mi north of the City (Figure 3). This region is divided into two geographically discrete systems—the Catskill/Delaware reservoir systems, located in upstate New York, well north and west of the City and the Hudson River, and the Croton Reservoir system, which is located north of the City and east of the Hudson River. Some (less than 1%) of New York City's water is obtained from the Brooklyn-Queens Aquifer, located in southeastern Queens (DEP, 2008b).

The Catskill/Delaware reservoir systems provide approximately 90% of New York City's water. The Catskill Water Supply System was completed in 1927, and the Delaware Water Supply System in 1967. Together, these watersheds cover roughly 1,600 mi^2 (U.S. EPA, 2009b). Forests cover approximately 75% of the watersheds. More than 20,000 private landowners own an estimated 75% of the forested land area (Brunette and Germain, 2003).

In 1993, New York City began implementing watershed protection programs to reduce the susceptibility of the surface water supply to contaminants. In 1997, The U.S. Environmental Protection Agency (EPA) partnered with the State of New York, the City of New York, and some 80 watershed municipalities and environmental groups to forge the New York City Watershed Memorandum of Agreement (MOA). This MOA set forth a set of conditions that the City had to meet for U.S. EPA to issue a 5-year Filtration Avoidance Determination (FAD). This FAD allows DEP to avoid filtering its Catskill/Delaware drinking water by establishing a land acquisition program for source water protection, by setting more stringent New York City watershed rules and regulations, and by implementing other watershed protection strategies. U.S. EPA reissued New York City a 5-year FAD in 2002 and a 10-year FAD in 2007. The New York State Department of Health and the U.S. EPA monitor these ongoing source water quality programs. Projects include

- *Land Acquisition*—New York City buys property from willing sellers to buffer the reservoirs and controlled lakes.

- *Land Management*—DEP develops land management programs.

- *Partnership Programs*—DEP partners with many local organizations to help protect source water quality, for example, by improving septic systems.

- *Wastewater Treatment Plant Upgrades*—New York City funds improvements to non-city-owned wastewater treatment plants for communities in the source watersheds.

- *Stream Management Programs*—DEP supports partnerships to stabilize streams in the area.

- *Watershed Agricultural Programs and Forestry Program*—These programs work with farms to help implement best management practices that reduce agricultural pollution and protect water quality (DEP, 2008b).

Glacial clay deposits underlay stream channels and steep topography surrounds the waterways in the Catskill water system. As a result, the system is prone to high turbidity due to intense precipitation events and associated runoff. Maintaining the FAD for the Catskill and Delaware water supplies is a crucial element to future watershed plans. To meet FAD-required standards, DEP has occasionally added alum to the waters entering Kensico Reservoir to reduce turbidity.[7] Periodically, the alum and associated sediment must be dredged from the reservoirs (DEP, 2005).

The Croton Watershed contains three upland reservoirs which supply approximately 10% of the City's water. It covers roughly 375 mi^2 east of the Hudson River in Westchester, Putnam, and Dutchess Counties and a small section of Connecticut. The Croton system began service in the mid-1800s and was completed before World War I (Rosenzweig et al., 2007). Since the 1950s, the Croton Watershed has developed quickly with the construction of 60 wastewater treatment plants, interstate highways, residential developments, and impervious surfaces (New York Water, 2010). On several occasions, the Croton Watershed has been contaminated as a result of stormwater runoff.

For example, 12 of Westchester county's 45 municipalities lie within the boundaries of the Croton Watershed. These municipalities contribute to water supply contamination as a result of lawn-care chemical use, automobile use, combined sewer system overflows, and other human factors, as well as reduced infiltration of precipitation that flows through urban drainage infrastructure. In 1993, the U.S. EPA determined that the Croton system failed to meet the requirements of the Surface Water Treatment Rule, and Croton system raw water would need to be filtered and disinfected. Repeated violations of turbidity and disinfectant by-product rules under the 1996 Safe Drinking Water Act Amendments have caused DEP to periodically remove

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[7] Alum serves as a coagulant, precipitating suspended solids from raw water, reducing objectionable color and turbidity.

the Croton system from service (Water-Technology.net, 2010; DEP, 2010b). After several delays and consent orders resulting in fines, the first phase of construction of the Croton raw-water treatment plant began in 2006 and is expected to be operational by 2012. Treatment will include a pretreatment stage, mixing and coagulation, flocculation, chemical balancing, stacked dissolved air floatation, and ultraviolet and chlorine treatment. The filtration plant is expected to improve water quality by reducing turbidity, decreasing the risk of microbiological contamination, and reducing the levels of disinfection by-products (DEP, 2008b). Communities around the Croton Watershed also signed the 1997 MOA aimed at improving watershed protection. They are participating in land acquisition and other raw water quality projects, as discussed above (DEP, 2008b).

3.2.2. Wastewater System

DEP is also responsible for operating, protecting, and maintaining New York City's wastewater system. The wastewater network includes more than 6,000 mi of wastewater pipes, 135,000 sewer catch basins, 495 permitted outfalls, 95 wastewater pumping stations, and 14 wastewater treatment plants spread across the City's 5 boroughs (DEP Web site). On average, the system treats 1.4 billion gpd of wastewater and has the capacity to treat dry-weather flows of 1.8 billion gpd (DEP, 2006).

New York City's wastewater undergoes five major processes: preliminary treatment, primary treatment, secondary treatment, disinfection, and sludge treatment. Approximately 60% of the City's sewers are combined, making combined sewer overflows (CSOs) a continuing problem for DEP (DEP, 2008a) during intense precipitation events. Violations of New York City's 1988 State Pollutant Discharge Elimination System permit led to a 1992 consent order between New York State's Department of Environmental Conservation and DEP, requiring a CSO abatement program. A 2004 consent order with more detailed guidance includes requirements for more than 30 citywide projects, such as sewer separation, flushing tunnels, off-line retention tanks, and vortex concentrators to improve the efficiency of the wastewater system (NYSDEC, 2010). While continuing to invest in traditional, or grey, infrastructure, the City is implementing measures to maximize the use of green infrastructure and other source controls to reduce stormwater runoff from new and existing development. Unveiled in September 2010 and subject to regulatory negotiations and approvals, the NYC Green Infrastructure Plan marks a departure from conventional and expensive approaches to stormwater management.

3.3. CLIMATE CHANGE PROJECTIONS AND RISKS

DEP expects temperatures in New York City and its watersheds to increase by 1.5–3ºF by the 2020s, 3−5ºF by the 2050s, and 4−7.5ºF by the 2080s (Table 2). The variability in precipitation in the New York City area is large. Most climate model projections indicate small increases in precipitation, but some suggest precipitation decreases, thus reducing confidence in projections of precipitation in this region. The New York City Panel on Climate Change concluded in 2009 that the best estimates at this time indicate approximate increases of 0−5% by the 2020s, 0−10% by the 2050s, and 5–10% by the 2080s. Most models indicate precipitation increases for the winter months and slight decreases during September and October. Furthermore, as temperatures increase, more precipitation is expected to fall as rain instead of snow (NYC Panel on Climate Change, 2009). In short, the observed climate change trends are projected to continue and, in some cases, accelerate.

Table 2. Projected baseline climate and mean annual changes for New York City

Climate indicators	**Baseline 1971−2000**	**2020s**	**2050s**	**2080s**
Air temperature (ºF)	55	+1.5−3	+3−5	+4−7.5
Precipitation	46.5 in	+0−5%	+0−10%	+5−10%
Sea level rise (inches)	N/A	+2−5	+7−12	+12−23
Number of days/year with max temp. above 90ºF	14	23−29	29−45	37−64
Number of days/year with max temp. above 100ºF	0.4	0.6−1	1−4	2−9
Number of heat waves/year	2	3−4	4−6	5−8
Number of days/year with rainfall exceeding 1 inches	13	13−14	13−15	14−16
Number of days/year with rainfall exceeding 2 inches	3	3−4	3−4	4−4
Number of days/year with rainfall exceeding 4 inches	0.3	0.2−0.4	0.3−0.4	0.3−0.5

Source: NYC Panel on Climate Change (2009, pp.17, 20).

New York City has taken a proactive approach to climate change. In 2001, the City joined the Local Governments for Sustainability’s Cities for Climate Protection campaign. In

2004, DEP created a climate change task force to assess the potential impacts of climate change on the City’s water infrastructure. The task force comprises representatives from a variety of DEP’s offices and initially included participants from Columbia University’s Center for Climate Systems Research, the National Aeronautics and Space Administration’s Goddard Institute for Space Studies, HydroQual Environmental Engineers and Scientists, P.C., the New York City Office of Environmental Coordination, the Mayor’s Office of Long-term Planning and Sustainability, and the New York City Law Department. The task force created an action plan, which includes the following tasks (DEP, 2008a):

- Work with climate scientists to improve regional climate change projections
- Enhance DEP’s understanding of the potential impacts of climate change on DEP’s operations
- Determine and implement appropriate adaptations to DEP’s water systems
- Inventory and manage greenhouse gas emissions
- Improve communications and tracking mechanisms.

A sustainability plan for New York City, PlaNYC, was unveiled on Earth Day in 2007. The plan outlines a 25-year vision for the city, focusing on maintaining and improving the City’s infrastructure centering on land, water, transportation, energy, air, and climate change. PlaNYC has set an ambitious target to reduce the City’s greenhouse gas emissions by 30%. New York City’s plan for climate change adaptation includes (1) creating an intergovernmental task force to protect the City’s infrastructure, (2) working with vulnerable neighborhoods to develop site-specific plans, and (3) launching a citywide strategic planning process (PlaNYC, 2007a; PlaNYC, 2007b; PlaNYC, 2008-2010).

To respond to climate change in New York City and to meet the goals established in PlaNYC, the New York City Panel on Climate Change (NPCC) was created in 2008. This panel is composed of climate change scientists and legal, insurance, and risk management experts. With funding from the Rockefeller Foundation, NPCC has been charged with serving as the technical advisory body for the Mayor and the New York City Climate Change Adaptation Task Force. This organization has provided the Climate Change Adaptation Task Force with the most comprehensive set of climate data that has been produced for New York City (NYC Panel on Climate Change, 2009). Several experts engaged to assist DEP in 2004 also were enlisted to assist NPCC in citywide planning efforts. DEP continues to pursue complementary climate change research because it is concerned with climate change in upstate New York (where the Catskill and Delaware reservoir systems are located) and in the City itself.

3.4. CLIMATE CHANGE VULNERABILITY ASSESSMENTS

DEP's vulnerability work is based on three core questions of interest to DEP, including the potential effects of climate change on (1) total water supply, (2) turbidity, and (3) eutrophication (Barsugli et al., 2009). DEP worked with researchers from Columbia University's Center for Climate Systems Research to design its Climate Impact Assessment project (Major et al., 2007). The goal of this integrated modeling project is to estimate the effect of future climate change on the quantity and quality of New York City's water supply. The project will use climate change projections, DEP water quality and water supply models, and analytical measures of system performance to advance DEP's understanding of the potential impacts of climate change on the water supply system. For more detailed information on how DEP and other utilities organized their vulnerability assessments, see the U.S. EPA report, *Climate Change Vulnerability Assessments: A Review of Water Utility Practices* (U.S. EPA, 2010).

The project was planned in two phases. Phase I, now completed under contract with Columbia University and the City University of New York (CUNY), is aimed to provide a first-cut evaluation of the effects of climate change on water quantity and quality in selected portions of the water system, using the existing modeling system and data available from three general circulation models (GCMs). Phase II, now in process with continued support from CUNY, has goals similar to those of Phase I but with upgrades to both models and data sets applied to the entire water supply system, including a greater variety of GCM data and an evaluation and application of differing downscaling methods. The Phase I effort used the Intergovernmental Panel on Climate Change (IPCC) *Third Assessment Report* (DEP, 2008a; McCarthy et al., 2001), but current efforts have upgraded models and data that were used in the IPCC *Fourth Assessment Report* (Parry et al., 2007).

A climate change scenario framework was developed for the New York City water supply system using high temporal resolution data from the Program for Climate Model Diagnosis and Intercomparison (PCMDI) Web site maintained by the Lawrence Livermore National Laboratory in Berkeley, California (Maurer et al., 2007). Data for Phase I were extracted from the single grid box at the center of the watershed region. Baseline data for 1981−2000 came from "hindcast" model runs. Data for 2046−2065 and 2081−2100 came from three GCMs (the Goddard Institute for Space Studies [GISS] Model, the Max Planck Institute [MPI] ECHAM5, and the National Center for Atmospheric Research [NCAR] CCSM3) coupled with three scenarios from the IPCC *Special Report on Emissions Scenarios*: *A1B, A2, and B1*.

The data included mean temperature, maximum temperature, minimum temperature, precipitation, sea level pressure, zonal wind, meridional wind, solar radiation, longwave radiation, and dewpoint temperature.

For Phase I, each scenario was used to calculate delta change coefficients representing mean monthly change in air temperature and precipitation between control and future prediction periods. Monthly delta change factors were applied additively for air temperature and as a ratio for precipitation to historical meteorological period data, generating a future prediction time series. The feasibility of applying the delta change method to the wind and solar radiation data needed for the reservoir models was also investigated.

For Phase II, GCM selection included the entire CMIP3 multi-model data set, the A2, A1B, and B1 emissions scenarios, and seven meteorological variables (precipitation; maximum, minimum, and average temperatures; zonal and meridional winds; and solar radiation). Data from all the GCMs were re-gridded to 2.5º corresponding to the Eastern North America region using bilinear interpolation and the NCAR Command Language (NCL: www.ncl.ucar.edu). The various levels of data processing involved necessitated that some data be eliminated from the study depending on the number of models that contain a given meteorological parameter, the number of runs archived for each GCM, and whether data existed for all points necessary in the re-gridding process. GCM hindcasts were compared to historical data sets at four spatial scales: Eastern North America, the nine grid points surrounding West of Hudson watersheds, the four grid points surrounding New York City, and the single grid point closest to the centroid of New York City watersheds. To develop a skill ranking and probability distribution function for each meteorological variable, spatial scale, season (December to February, March to May, June to August, and September to November), and GCM, the fidelity of hindcast values to observed historical data was calculated.

The system of models that will be used for the integrated modeling project include the General Watershed Loading Function (GWLF) and Soil Water Assessment Tool (SWAT) watershed models, a one-dimensional reservoir eutrophication model, a two-dimensional reservoir turbidity transport model (CEQUAL-W2), and the OASIS system operations model for the entire water supply. These models taken together with the existing and in-process climate scenarios make the proposed integrated assessment possible.

As the project progresses, further model enhancements and integration will be implemented. For the GWLF watershed model, improvements will be made to the following model elements: hydrologic balance, sediment and nutrient generation and transport, ecosystem effects, and land use. For the reservoir models, additional upgrades and calibration and development of response function models keyed on system performance measures will be implemented. For the integrated system, enhanced coupling of the watershed and reservoir models to OASIS will be undertaken. And for model inputs, enhancements will include advanced delta change with historical data morphing, statistical downscaling, and regional climate model (RCM) simulations.

Several performance measures related to water system quantity and quality will be developed and used to estimate climate change effects, including total water quantity, probabilities of refill, probabilities of drawdown, key point turbidity levels, frequency of alum use, reservoir phosphorus and chlorophyll concentrations, and restrictions in water use due to eutrophication. DEP expects the results of this project to provide the basis for recommendations about system operation now and in the future, and, in later phases, recommendations about required infrastructure changes and improvements.

In 2009, the NPCC published its first report, *Climate Risk Information*. This report provides climate change projections for New York City as a whole (not just DEP) and identifies potential risks to the City's critical infrastructure. The projects presented in the model were compiled using model-based probability functions. The NPCC used IPCC methods to calculate changes in temperature, precipitation, and sea level rise from global climate model simulations based on three greenhouse gas emission scenarios (A1B, A2, B1). The NPCC used 16 GCMs to generate possible changes in temperature and precipitation. Only seven GCMs were used for sea level rise, as sea level rise is not a direct output of most GCMs. The generated sea level rise values for the New York City area include both global and local components.

According to the NPCC report, changes in mean climate and climate extremes could affect many aspects of New York City's water infrastructure. The potential wastewater and drinking water impacts of the projected air temperature change include decreased water quality due to biological and chemical impacts; increased water demand due to a longer growing season; decreased snowpack, which could reduce inflows to reservoirs during the spring thawing season; changes in the ecology of streams due to higher stream temperature, which could limit the amount of water that can be extracted; and increased water demand. The biological and chemical reactions in wastewater treatment plants also could be disrupted at higher temperatures (DEP, 2008a).

Impacts related to the potential changes in precipitation include decreased average reservoir storage, increased turbidity, increased nutrient loads, eutrophication, taste and odor problems, and increased loading of pathogenic bacteria and parasites in reservoirs. Impacts of potential precipitation changes on the wastewater system include increased probability of sewer flooding and increased CSO events.

The potential impacts of sea level rise for city water resources include intrusion of the salt front farther up the Hudson River (NASA, 1999), increased probability of seawater entering sewers, reduced ability of wastewater treatment plants to discharge treated water by gravity alone, increased risk of CSO events, and increased coastal flood risk for low-elevation infrastructure and wastewater treatment plants (NYC Panel on Climate Change, 2009; DEP, 2008a).

3.5. APPLICATION OF VULNERABILITY ASSESSMENT INFORMATION

DEP has conducted a suite of modeling studies to understand the vulnerability of its systems to climate change, and has made decisions to reduce that vulnerability. This situation, however, might be a case where analysis and policy, although informing each other, are proceeding in parallel. New York City's climate change work has led to increased consideration of climate change in strategic planning, has altered operations and maintenance practices, and has changed future infrastructure planning and design. Many of these changes are not the direct result of the New York City vulnerability assessments. Rather, they are part of a larger effort to improve the resiliency and redundancy of water infrastructure in the face of existing vulnerabilities that could be exacerbated by climate change. These decisions largely focus on so-called "no-regrets" opportunities, or changes to the water supply system that make sense regardless of whether or how climate changes. Some of these policy choices have been forced by regulatory mandates, such as the development of a filtration plant for the Croton Watershed, but others have significant benefits system wide, such as reducing leakage from aging supply infrastructure.

PlaNYC and DEP's Climate Change Task Force have identified several initiatives that aim to efficiently and effectively upgrade the city's drinking and wastewater systems in the face of a changing climate. Proposed initiatives are discussed in detail below.

3.5.1. Decreasing Turbidity

Turbidity is a significant drinking water concern in the Catskill and Delaware Water Systems. DEP has addressed this issue historically by adding alum as an "end-of-pipe" solution and engaging in source-water protection measures. Projected increases in intense precipitation events under climate change will most likely increase the turbidity of watersheds beyond historic levels. New York City is continuing its historic programs to address this issue. In the future, DEP will address potential turbidity challenges in the Catskill and Delaware Water Systems by relying more heavily on the soon-to-be-filtered Croton system, a proposed interconnection between the Catskill and Delaware Aqueducts, and operational modifications in how DEP uses the Delaware and Catskill Water Systems during heavy precipitation or turbidity events.

3.5.2. Minimizing Flooding

To minimize urban drainage flooding in New York City during the predicted increased severe weather events, the Climate Change Task Force proposed more frequent cleaning of sewers and maintaining catch basins in flood-prone areas. The task force also promoted green roofs and the reuse of stormwater for "ecologically productive purposes." Green infrastructure has become a significant component of DEP's proposed policies, especially for stormwater management to reduce CSOs (PlaNYC, 2008; NYC Green Infrastructure Plan, 2010).

For example, New York City is planning to expand the Staten Island Bluebelt program, which was created as a natural system to prevent coastal and urban drainage flooding and septic tank failure. It functions by diverting water from wastewater treatment to natural systems. Nearly 36% of Staten Island's precipitation is diverted to a 10,000-acre Bluebelt area. The Bluebelt program has saved the city an estimated $80 million in infrastructure development (Rosenzweig et al., 2007). As severe weather events increase, the Bluebelt and further expansions will act as natural buffers, reducing pressure on the wastewater system and reducing flooding issues and CSOs (PlaNYC, 2008).

3.5.3. Minimizing Supply and Demand Imbalances

Higher air temperatures increase peak water demand. Within New York City, annual average demand is approximately 1,069 mgd. During heat waves, demand can increase to more than 2,000 mgd. To minimize supply and demand imbalances, the Climate Change Task Force has stressed the importance of structural improvements, such as reducing water pressure problems and leakage. Small-scale conservation efforts also can reduce water demand (DEP, 2008a).

New York City has reduced water demand since 1985 through a variety of conservation efforts, including education, metering, water-use regulation, leak detection, installation of magnetic-locking hydrants, and rebate programs. These conservation efforts reduced water consumption from 195 gpd per capita in 1991 to 167 gpd per capita in 1998, with coincident substantial cost savings for both DEP and its customers (U.S. EPA, 2002). Reducing water demand also limits the amount of water entering the wastewater system and, thus, stress on the system. With the above conservation measures, the volume of generated wastewater decreased by 200 mgd between 1996 and 2006 (DEP, 2006).

Additionally, to ensure sufficient water quantity even in the face of higher temperatures, DEP is evaluating new water sources throughout New York City and upstream watersheds. These sources include groundwater and new infrastructure, such as potentially increasing the capacity of the Catskill Aqueduct.

3.5.4. Decreasing Combined Sewer Overflows

To decrease CSO events caused by increased precipitation and intense precipitation events, DEP has begun plans to upgrade wastewater treatment capacity, construct additional holding tanks to increase wet-weather holding capacity, and optimize sewer infrastructure to limit releases. New York City is also planning to convert some of the combined sewer systems into high-level sewer systems,[8] which divert a large percentage of the stormwater directly to waterways rather than into treatment plants. This strategy not only decreases the likelihood of CSO events but also reduces costs by avoiding unnecessary water treatment. The Climate Change Task Force also has proposed increasing pipe size to increase flow in areas where possible (PlaNYC, 2008). In September 2010, DEP released the NYC Green Infrastructure Plan, an adaptive management strategy for reducing CSOs using green infrastructure, grey infrastructure, system optimization, and water conservation.

3.5.5. Adapting to Flood Risk

DEP is also considering converting water storage reservoirs for use as both water supply and riverine flood control (DEP, 2005). To prevent critical assets from being disabled during flood events, the DEP Climate Change Task Force has proposed moving key assets above projected flood heights, installing watertight doors around crucial equipment, switching to submersible pumps, and creating protective barriers such as sea walls, dunes, or tidal gates around important assets (DEP, 2008a).

DEP will institute a snowpack-based reservoir management program to provide enhanced riverine flood attenuation downstream. Under this program, Schoharie Reservoir would be sustained below full capacity during the winter months when sufficient snowpack is present in its watershed so that associated runoff produced by spring snowmelt could refill the reservoir to full storage capacity. The capture of inflows associated with spring storm events and snowmelt runoff in the reservoir would provide additional attenuation in downstream sections. The temporary reservoir level targeted during the snowpack-based reservoir management period would be regularly adjusted based on snow-water equivalent estimates of the watershed's regularly monitored snowpack. As the name implies, snow-water equivalent is the water depth equivalent of a given depth of snow and depends on such factors as the water content and density of the snowpack (DEP, 2008c).

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[8] High-level storm sewers alleviate pressure on the combined sewer system by capturing about 50% of the rainfall before it enters combined sewer pipes and diverting it directly into waterways. Because such systems require a separate pipe and outlet to a water body, they are generally cost-effective only near the water's edge.

4. SEATTLE PUBLIC UTILITIES

4.1. BACKGROUND

Seattle Public Utilities (SPU) was formed in 1997 as a combination of the Drainage and Wastewater Utility, Solid Waste Utility, the former Seattle Water Department, and portions of Seattle City Light and the Seattle Engineering Department. This case study focuses on SPU functions related to supplying drinking water to the City of Seattle, Washington. SPU's drainage and wastewater system are mentioned only briefly.

SPU provides drinking water to a population of more than 1.35 million people in Seattle and surrounding suburban areas. SPU provides direct retail water service to about 630,000 people primarily in the City of Seattle, parts of Shoreline, and small areas just south of the city limits. SPU also sells water wholesale to 25 neighboring cities and water districts serving another 720,000 people. SPU supplied 45.1 billion gallons of drinking water in 2008 from two Cascade Mountain watersheds supplemented with groundwater wells.

The Pacific Northwest climate is dominated by large spatial and temporal variations in precipitation due to maritime influences and extreme topographical variation between the coast and the Cascade Mountains. The low-lying valleys west of the Cascades, including the SPU service area, are characterized by mild temperatures year round, wet winters, and dry summers. Average annual precipitation for the Seattle area is about 37 inches, but in the mountains, that total exceeds 100 inches. About 75% of Seattle area precipitation falls between October and March (Miller and Yates, 2006). The SPU water supply system therefore also must be managed for riverine floods. Typically, early winter precipitation fills reservoirs, which are allowed to spill in anticipation of snowmelt combined with normally rainy springs, which refill reservoirs for the dry summer months.

The regional climate fluctuations known as the El Niño Southern Oscillation (ENSO) and the Pacific Decadal Oscillation (PDO) also strongly affect the Pacific Northwest. ENSO, PDO, and the winter and spring climate of the region are highly correlated, enabling predictions of Pacific Northwest precipitation, snowpack, and streamflow. The University of Washington Climate Impacts Group (UW-CIG) has developed annual climate forecasts for regional resource managers, including annual projections of climate variations due to ENSO and PDO. These forecasts help inform SPU managers about projected conditions over the winter and spring months to enable more informed management of the competing objectives of water supply and flood management (UW-CIG, 2010a).

Observed changes in climate include the following: temperatures increased in the Pacific Northwest by 1.5ºF between 1920 and 2003 (Mote, 2003); annual precipitation increased by 14% between 1930 and 1995 (Mote, 2003); April 1 snow-water equivalent has declined dramatically at almost all Pacific Northwest sites (Mote et al., 2003, 2005, 2008; Hamlet et al., 2005); and timing of peak runoff shifted earlier by 0–20 days between 1948 and 2002 (Stewart et al., 2004).

4.2. DESCRIPTION OF THE WATER SYSTEM

4.2.1. Water Supply System

SPU's water supply comes from three sources: the Cedar River Municipal Watershed, the South Fork Tolt Watershed, and the Seattle Well Fields (Figure 4; SPU, 2010a).

In 1895, Seattle residents voted to approve revenue bonds to construct the Cedar River Municipal Watershed. The watershed, almost entirely owned by the City of Seattle, covers 90,638 acres and provides approximately 70% of the city's freshwater supply over the course of the year. Rain and snowmelt are collected and stored in two reservoirs created by the 1914 construction of the Masonry Dam—Chester Morse Lake and Masonry Pool. As water leaves these reservoirs, it powers the Cedar Falls hydroelectric power plant. Twelve miles downstream, at the Landsburg diversion dam, on average, 22% of the river flow is screened to remove debris, chlorinated for microbial control, and fluoridated for dental health. This water is then stored in Lake Youngs, where it is ozonated for odor and taste improvements, ultraviolet-disinfected to disable chlorine-resistant microbes, chlorinated again, and supplemented with lime for pH-adjusted corrosion control to minimize lead leaching in older plumbing systems.

The Cedar River Municipal Watershed is managed to provide an adequate water supply (both for human use and instream conservation flows). The water supply system also provides riverine flood management and hydropower generation. Morse Lake and Masonry Pool hold, on average, just enough water for one water-cycle year. If too little water is released during winter, flooding can occur during heavy rains or when the snowpack melts during the spring wet season. Winter water levels are therefore generally kept low. Conversely, drought conditions in the spring can prevent the reservoir from refilling to the level necessary to provide water during the dry summer months. This situation presents a risk tradeoff that SPU water managers must address every year to meet both riverine flood management and water supply objectives (SPU, 2010b).

The South Fork Tolt Watershed is located on the western slope of the Cascade Range, approximately 35 miles east of Seattle (Figure 4). The City of Seattle purchased water rights to the South Fork Tolt from the Mountain Water Company in 1936, but no infrastructure existed for the diversion, conveyance, or distribution of that water. The South Fork Tolt Dam was

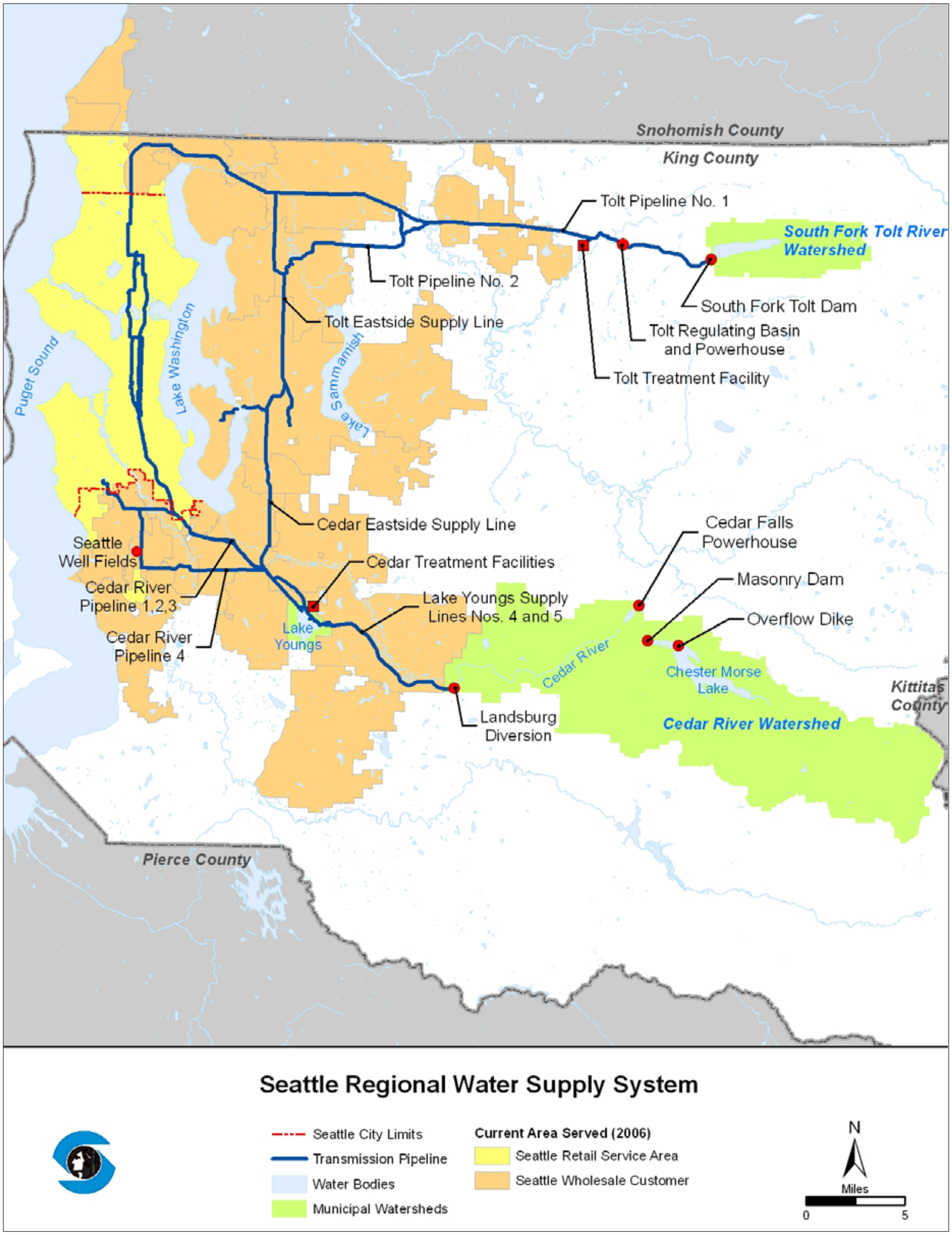

Figure 4. Seattle Public Utilities service area.

Source: SPU (2008).

constructed in 1963, and in 1964, South Fork Tolt Reservoir began supplying water to north Seattle and the Eastside. As water leaves this reservoir, it powers the South Fork Tolt hydroelectric power plant. After a land exchange with Weyerhaeuser Company in 1997, the City of Seattle owned 69% of the 12,107-acre drainage area upstream of the South Fork Tolt Dam. Most of the remaining land lies in the Mt. Baker-Snoqualmie National Forest. The South Fork Tolt Reservoir provides approximately 30% of the city's freshwater supply (SPU, 2008, 2010c). The reservoir is also operated to manage riverine flooding and maintain instream flows.

SPU's Tolt Treatment Facility, the city's first filtration and ozonation facility, began operating in 2000. It provides 120 million gallons per day (mgd) of finished water to customers in Seattle and suburban cities. Although the facility has historically provided very high-quality water, requiring only minimal treatment, it was designed to allow long-range conformity with anticipated regulations, to increase system yield, and to permit continuous supply of Tolt water though periods of high turbidity (SPU, 2010d). Like the Cedar River water supply, the Tolt supply provides fluoridation, chlorination, and adjustment of pH and alkalinity for corrosion control (SPU, 2006a).

In 1987, the first groundwater source was added to the system when two wells in the Highline Well Field began operating. A third well was added in 1990. These wells supply less than 1% of SPU's water from an aquifer to supplement summer demands when necessary. The well field can be pumped for 4 months and becomes available in July (WA DOE, 2001).

Water demand for the SPU system peaked in the 1980s at approximately 170 mgd. A severe drought and mandatory water restrictions in 1992 caused demand to decrease. Subsequently, higher water rates, plumbing code revisions in 1993, conservation efforts, and improved systems operations caused demand to level out around 150 mgd. The economic slowdown in 2000 and continued conservation efforts further reduced demand to approximately 130 mgd. This 24% decrease in demand coincided with a 17% increase in the population of SPU's service area since 1990 (SPU, 2006a). This equates to a 27% decrease in water consumption per capita from 145 gallons per day (gpd) per capita to 105 gpd per capita (SPU, 2010e).

4.2.2. Wastewater System

SPU also conveys wastewater to King County's Wastewater Treatment Division, including associated infrastructure. This drainage infrastructure is partly a combined sewer system, which means that SPU must address the City of Seattle's stormwater quality and urban drainage flooding issues, but often in conjunction with King County Department of Natural Resources and Parks. Because the responsibilities of King County and SPU overlap to some degree, this case study does not present SPU activities related to drainage and wastewater in detail. Of note, however, is that both SPU and King County own conveyance infrastructure within the city, and that combined sewer overflow events are a problem for both entities. SPU has explored the implications of climate change on its stormwater infrastructure and operations. SPU also is pursuing and evaluating adaptation options, engaging in research, and participating in collaborative networks to address stormwater issues—effectively replicating their experience with water supply, but for drainage and wastewater issues.

4.3. CLIMATE CHANGE PROJECTIONS AND RISKS

SPU expects climate in the Seattle area to change in several ways. Global climate models (GCMs) project that temperatures will warm at a rate of 0.5°F per decade, nearly three times the rate experienced over the twentieth century. Most models suggest small changes in annual precipitation compared with year-to-year and decade-to-decade variability observed for the twentieth century. Most models, however, do indicate increased winter precipitation and decreased summer precipitation. The potential future impacts of these changes include decreased mountain snowpack, higher winter and lower spring streamflows, increased sea-surface temperatures, rising sea levels, and increased winter riverine flooding (UW-CIG, 2010b; City of Seattle, 2006). Table 3 provides a summary of projected temperature and precipitation changes in the Pacific Northwest from the Washington State Climate Change Impacts Assessment. Projected changes are based on simulations from 20 climate models and two greenhouse gas emissions scenarios (B1 and A1B; UW-CIG, 2010b).

A series of severe droughts in 1987, 1992, and 1997−1998 increased the sensitivity of SPU managers to the effects of climate on their water supply. A very dry summer in 1987 caused significant declines in raw-water supply quality and forced use curtailments, reduced instream flows for fish, and necessitated the installation of an emergency pumping station to access low water in Chester Morse Lake. In response, the City developed a Water Shortage Contingency Plan (updated in SPU, 2006b) and a state-of-the-art reservoir management and streamflow forecasting model for use in real-time water management and long-range planning. The 1992 water shortage was caused by following standard flood control rules after a below-normal winter snowpack. When the spring season also produced below-normal precipitation, SPU’s mountain reservoir levels did not recover, and mandatory water restrictions were in place by mid-May. Throughout the summer, raw-water quality declined, leading to a decision to invest in an ozone-purification plant. SPU also implemented dynamic flood-control rules, which, in conjunction with enhanced real-time snow, weather, and streamflow monitoring networks, allowed SPU to implement its new reservoir management approach. Finally, in 1997,

Table 3. Projections of changes in annual mean temperature and precipitation for the 2020s, 2040s, and 2080s

Time period	Temperature ºF (ºC)	Precipitation %
2020s		
Low	+1.1 *(0.6)*	−9
Average	+2.0 *(1.1)*	+1
High	+3.3 *(1.8)*	+12
2040s		
Low	+1.5 *(0.8)*	−11
Average	+3.2 *(1.8)*	+2
High	+5.2 *(2.9)*	+12
2080s		
Low	+2.8 *(1.6)*	−10
Average	+5.3 *(3.0)*	+4
High	+9.7 *(5.4)*	+20

new research on ENSO effects on the Pacific Northwest was incorporated into SPU's reservoir management decisions. In anticipation of lower-than-normal snowpack followed by a hot, dry summer, SPU allowed its mountain reservoirs to fill higher than normal and reduced its operational use of water. These proactive decisions allowed the 1997−1998 drought to pass without the public's experiencing any water shortage or restrictions (UW-CIG, 2010c). Another record low snowpack in 2005 threatened water shortages and use restrictions, but, again, careful water management and late spring rains allowed SPU to meet all water supply and instream flow requirements without restrictions.

SPU's predecessor agencies were engaged with the issue of climate change as far back as the 1980s when they helped to develop the American Society of Civil Engineers' policy on global climate change. Informal tracking of climate variability and change issues by SPU staff followed, leading to SPU's formal integration of ENSO into its 1997−1998 reservoir management decisions. In 2002, SPU contracted with UW-CIG to study the potential impacts of climate change and to develop methods for how SPU could incorporate future climate change into its water supply planning (SPU, 2006a). The impacts on water supply projected in the study were reported and incorporated into SPU's 2007 Water System Plan. In a subsequent project, SPU began a new collaboration with UW-CIG to investigate climate change in partnership with the Cascade Water Alliance, Washington State Department of Ecology, and King County Department of Natural Resources and Parks as described below (RWSP, 2010).

Participating agencies formed a Climate Change Technical Committee in spring 2006. The committee included SPU, along with a number of other city, county, state, and tribal government officials managing water resources in the region. The committee met 17 times from March 2006 through December 2007, and drafted a charter in April 2006 containing the following goals:

- Identify the basic building blocks of our understanding of climate change
- Identify what is known about climate change in the Puget Sound region and its potential impacts
- Identify where more information would be useful
- Communicate what is known to other committees in this process
- Document the committee’s findings (Palmer, 2007).

The committee reviewed 10 technical reports written by a University of Washington research team before the reports were publicly released. SPU used information from this work to assess impacts to water supply and demand as described in Section 4.4.

SPU also joined several other major utilities to form the Water Utility Climate Alliance (WUCA) in early 2007. WUCA commissioned two climate change white papers; one of which SPU managed. The first white paper outlines potential improvements to scientific models for projecting the impacts of climate change at spatial and temporal scales relevant to utilities (Barsugli et al., 2009). The second white paper outlines decision-making approaches to address climate change in water resource planning and management in the face of uncertainty about future climate conditions (Means et al., 2010). In addition to WUCA, SPU is involved in several other collaborative efforts to enhance the capacity of the water sector to identify and prepare for the impacts of climate change. A staff member from SPU co-chaired the U.S. Environmental Protection Agency’s (U.S. EPA’s) Climate Ready Water Utilities Working Group, which is developing recommendations on how the U.S. EPA can support a “climate-ready” water sector. SPU is a member of the Water Research Foundation’s Climate Change Strategic Initiative Expert Panel, which is assisting the Foundation in developing a multiyear climate change research agenda for the drinking-water sector. This effort is part of a similar one led by the Water

Environment Research Foundation to develop climate research for the clean-water sector. Finally, SPU is collaborating in a new project initiated in 2010 called Pilot Utilities Modeling Applications (PUMA). PUMA includes five utilities and four National Oceanic and Atmospheric Administration-funded Regional Integrated Sciences and Assessment (RISA) groups that will be collaborating on downscaling climate models and using them to assess climate change effects on water supply.

SPU operates in a political and managerial environment that supports engagement on climate change adaptation. The City of Seattle took early leadership roles in climate change on both the mitigation and adaptation front. On February 16, 2005, for example, Seattle Mayor Greg Nickels launched the U.S. Conference of Mayors Climate Protection Agreement. Mayor Nickels made climate protection a keystone issue of his administration, creating the City of Seattle's Environmental Action Agenda in 2005, including the Seattle Climate Protection Initiative and the Seattle Climate Action Plan. The need to adapt to changes in water supply was highlighted in the Seattle Climate Action Plan (City of Seattle, 2006). According to this plan, "It is vital that the City—and all levels of government—plan and prepare for the climate change that is inevitable. Because Seattle's water and hydroelectricity are so dependent on the hydrology cycle in the Cascade Mountains, the City has focused its planning and adaptation analysis work there." By the time this was written in 2006, SPU had already begun looking at climate change in earnest.

4.4. VULNERABILITY ASSESSMENT

SPU has commissioned or conducted a series of increasingly sophisticated analyses over the course of many years to examine the vulnerability of their water supply and stormwater infrastructure and operations to climate change. The analyses have benefitted from the expertise of UW climate scientists and others associated with the NOAA RISA program's Climate Impacts Group (UW-CIG). Over the course of nearly a decade, SPU and their collaborators refined a model-driven vulnerability analysis that projects changes in global climate, downscaled those changes to Seattle and its watersheds, and ran those projected changes through SPU's system models to determine how climate change might affect SPU's water supply, water infrastructure, and operations. The SPU study methodology represents a scenario-based approach to vulnerability assessment. For more detailed information on how SPU and other utilities organized their vulnerability assessments, see the companion report, *Climate Change Vulnerability Assessments: A Review of Water Utility Practices* (U.S. EPA, 2010).

4.4.1. Water Supply

Downscaled scenarios of future temperature and precipitation change were developed for the Puget Sound region using three combinations of climate model/greenhouse gas emissions (from the IPCC *Special Report on Emissions Scenarios*; SRES) and four time periods (IPCC, 2000). The three climate model/SRES combinations include a "middle-of-the-road" regional climate change scenario (MPI ECHAM5/A2) with moderate warming and precipitation increase, a significantly wetter and warmer scenario (IPSL-CM4/A2), and a slightly drier and warmer scenario (GISS-ER/B1).[9] The four time periods were a 2000 hindcast and projected future conditions for 2025, 2050, and 2075. Climate models were selected because they performed well in other studies replicating temperature and precipitation trends of the Pacific Northwest during the twentieth century (Mote et al., 2005). A statistical downscaling approach was used to translate GCM grid-scale output to a quasi-steady-state daily time series of temperature or precipitation for a specific location at a specific future time that preserves the historic variability of climate (Polebitski et al., 2007a; Polebitski et al., 2007b).

SPU's water supply planning model is the Conjunctive Use Evaluation (CUE) systems model—a weekly time-step simulation model of the Cedar and Tolt River systems. Because it uses observed inflow data for both river systems as input, however, CUE cannot directly incorporate climate model output (temperature and precipitation). Consequently, UW-CIG ran the downscaled meteorological data sets through its Distributed Hydrology Soils and Vegetation Model (DHSVM) to produce climate-altered hydrologic data sets for use in CUE. CUE is used for calculating the firm yield[10] and reliability of Seattle's water supply system and potential future water supply projects. CUE results indicated that yield decreased under all climate change scenarios for all time periods. SPU also ran several planning scenarios through CUE to determine whether available supply could be increased to compensate for anticipated supply shortfalls.

4.4.2. Water Demand

SPU examined the effect of climate change on water demand using a dual approach of regression analysis and forecast modeling. First, SPU performed a regression analysis of peak-season consumption for 1982–2007 using monthly consumption data, maximum temperature, and rainfall at SeaTac Airport for May through September. This relationship was assumed to hold in the future. SPU had also already developed a demand forecasting model for

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[9] Note that the A2 emission scenario is relatively high by the second half of the twenty-first century, while the B1 scenario has the lowest level of greenhouse gas emissions of the SRES family.

[10] Firm yield is a calculation of how much water can be guaranteed from a water system, in this case, based on a 98% reliability standard.

its *2007 Water System Plan* and used this model to forecast non-climate-related changes in demand (SPU, 2006a). In this study, demand was forecast to decrease below historic levels through 2050, but to increase above historic levels by 2075. Applying the results of the regression analysis to these forecasts adjusts demand slightly upward due to the climate change scenarios in 2025 and 2050. In 2075, a larger climate-induced increase in conjunction with significant increases in baseline demand led to 2075 demands increasing to above historic levels.

4.4.3. Storms and Runoff

SPU also engaged a consultant to use the University of Washington's Weather Research and Forecasting (WRF) regional climate model to examine projected precipitation changes in the Thornton Creek Watershed (Northwest Hydraulic Consultants, 2009). This study was focused on storms and runoff, and is distinct from the statistical downscaling study of water supply described previously. Northwest Hydraulic Consultants used the WRF model to dynamically downscale temperature and precipitation data from two GCM-scale simulations (CCSM3 model with A2 SRES, and ECHAM5 model with the A1B SRES) for two 31-year periods (1970−2000 and 2020−2050) to grid sizes of 20 and 36 km^2. These data were used in the rainfall/runoff model Hydrologic Simulation Program-Fortran (HSPF) to model changes in several creek parameters for the entire Thornton Creek Watershed. The results of the study indicated that runoff would increase, except at one sub-basin where modeling results diverged, although the magnitude of the increases varied by a factor of two at times. This work, however, was deemed too uncertain for SPU's planning purposes. According to the study's conclusions, "Additional work is needed to improve confidence in future projections before applying dynamically downscaled data to stormwater planning, policy, or design standards" (Northwest Hydraulic Consultants, 2009). SPU currently is not using modeled climate projections for stormwater planning purposes.

4.5. APPLICATION OF VULNERABILITY ASSESSMENT INFORMATION

SPU arguably has undertaken the most sophisticated vulnerability assessment of any of the utilities discussed in this report, and is the only one of the four utilities that directly used the results to make an adaptation decision. SPU has also identified a more far-reaching set of adaptation options for use in future decades in the event that demand exceeds available water supplies. Prior to this analysis, SPU was already considering how to make the most effective use of usable storage, including the use of dynamic rule curves that use current watershed state conditions instead of relying on past hydrologic records. SPU also had a conservation program that had led to significant reductions in demand since the mid-1980s and more recently, has committed to an additional 15 mgd of conservation by 2030. This analysis demonstrated what

SPU already knew, that demand could exceed supplies in 2075 even without climate change, with no new conservation programs past 2030.

4.5.1. Water Supply

Based on the information generated by its water supply vulnerability assessments, SPU determined that available water supply decreased under all scenarios for all time periods. Projections for 2025 indicated Seattle's water supply would decrease by 6–10%, projections for 2050 indicated a decrease of 6–21%, and projections for 2075 indicated a decrease of 13−25%. Demand was projected to decrease in 2025 and 2050 to around 83% of historic supply but increase in 2075 to approximately 106% of historic supply.

Based on these projections, SPU analyzed "Tier 1" low- or no-cost intrasystem modifications that effectively increased the usable storage capacity for water with no new supply infrastructure.[11] This approach primarily consisted of eliminating conservative operating assumptions from SPU's water system supply calculations.[12] These low-cost modifications were estimated to compensate for supply shortfalls in all three scenarios in 2025, in two of three scenarios in 2050, and in none of the three scenarios in 2075.

"Tier 2" alternatives were identified that could compensate for the remaining projected shortfalls in 2050 and 2075. These included additional use of Lake Youngs storage, modified/optimized conjunctive use operations, and additional conservation programs after 2030. Even more expensive or complex alternatives were identified for "Tier 3," "Tier 4," and "Tier 5" spanning from reservoir operational changes to new supply alternatives, but these higher cost modifications were deemed unnecessary through 2075.

All of these policy options were directly informed by the quantitative results of the SPU vulnerability analysis. SPU has decided that its vulnerability analysis indicates no need for near-term operational changes or new infrastructure. In one sense, SPU has not changed its water supply planning and management decisions because, although significant, the projected climate impacts are not imminent. On the other hand, the changes to conservative operating assumptions represent an important class of "no-regrets" adaptations. Even the Tier 2 adaptations, such as increased water conservation efforts, represent policy options that provide benefits in terms of supply reliability, regardless of the magnitude of climate change. In SPU's current estimation, no adaptations beyond Tier 2 will be needed through 2075.

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[11] Tier 1 did include one structural adjustment—the raising of one overflow dike.

[12] Changes include, among others (1) allowing Chester Morse Lake to refill to 1,563 ft (versus 1,560 ft), increasing Cedar River watershed storage by 12%; and (2) allowing South Fork Tolt Reservoir drawdown to 1,690 ft (versus 1,710 ft), increasing Tolt watershed storage by 18%.

4.5.2. Storms and Runoff

The results of SPU’s dynamical downscaling and urban drainage study provided insufficient certainty to be useful for planning purposes. Consequently, SPU is relying on a qualitative understanding that intense precipitation events are likely to increase and is exploring changes in peak storm events as a proxy for changes in precipitation due to climate change. This approach represents an important hedging strategy. In the absence of reliable projections of future climate conditions, SPU decided to apply a safety factor to new infrastructure construction to ensure that new investments would perform their intended function over their useful lives based on a general understanding of the climate trends and a reasonable estimate of the magnitude of that change.

5. SPARTANBURG WATER

Spartanburg Water is a public water and wastewater utility that is composed of two distinct legal entities: Spartanburg Water System (SWS) and Spartanburg Sanitary Sewer District (SSSD). The two entities function as one company (West, 2010). SSSD was formed as a special-purpose district for wastewater services. SWS is a political subdivision of the City of Spartanburg and is overseen by three Commissioners of Public Works. SSSD is overseen by the seven-member Sewer Commission, which includes the three Commissioners of Public Works (Spartanburg Water, 2010a; West, 2010).

5.1. BACKGROUND

Spartanburg Water serves a population of approximately 180,000 people in Spartanburg County and portions of Greenville, Cherokee, and Union Counties in South Carolina (Spartanburg Water, 2010a). The SWS service area includes a contiguous retail service area of approximately 259 mi^2, a noncontiguous retail service area of approximately 15 mi^2, and a wholesale service area of approximately 605 mi^2(Spartanburg Water, 2010a). The SSSD wastewater service area is defined by the Spartanburg city limits—a contiguous service area covering approximately 196 mi^2, and a noncontiguous service area of eight locations serving approximately 22 mi^2 (Spartanburg Water, 2010a).

From 1971 to 2000, Spartanburg County received on average 61 inches of rain per year (SRCC, 2010). Precipitation is somewhat consistent throughout the year, ranging on average from 3.44 to 6.86 inches per month (SRCC, 2010). The average minimum and maximum temperatures are 48.6°F and 71.3°F, respectively (SRCC, 2010). Over the past 10 years, however, the southeastern region of the United States has experienced prolonged droughts that have lasted several years. The Spartanburg Water service area experienced droughts in 2002 and 2003, and a drought has persisted since 2005, with the lowest recorded streamflow occurring in 2009 (West, 2010).

5.2. DESCRIPTION OF THE WATER SYSTEM

5.2.1. Water Supply System

Spartanburg Water provides approximately 30 million gallons of water to its customers each day. Approximately 60% of the water use is residential (West, 2010). Industrial water use has significantly declined in the past decade from 110 to 52 industrial accounts (West, 2010). Although there are commercial and other small business accounts, these sectors are not significant water users.

Three reservoirs on the Pacolet River provide the vast majority of the Spartanburg water supply (Figure 5). Bowen Reservoir, the most northern reservoir, is on the south fork of the Pacolet River. Built in 1960, it covers 1,534 acres and has a total capacity of 17,115 acre-feet (Spartanburg Water, 2010b; West, 2010). Water from Bowen Reservoir flows downstream to Municipal Reservoir Number 1 (MR1), which is located just above the confluence of the North and South Pacolet Rivers. Built in 1926, MR1 serves mainly as a pass-through reservoir with a capacity to store approximately 1 day's worth of water. MR1 improves water quality through sedimentation as the water flows through it (West, 2010). Blalock Reservoir is downstream from the confluence of the North and South Pacolet Rivers and receives inflow from MR1 and the North Pacolet River. Built in 1983, Blalock Reservoir covers 1,105 acres and has a total capacity of 16,894 acre-feet (Spartanburg Water, 2010b; West, 2010). Spartanburg Water expanded Blalock Reservoir in 2006 by raising the height of dam to meet projected future water demand (Spartanburg Water, 2009).

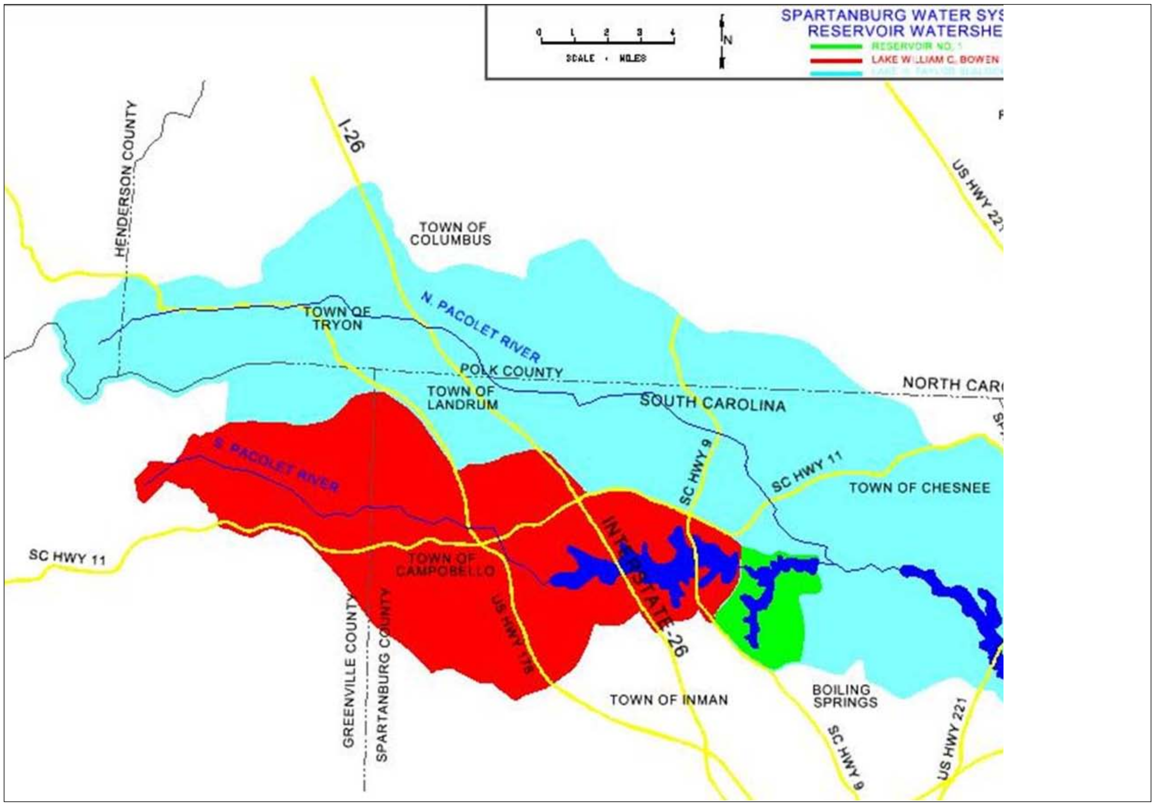

Figure 5. Reservoirs and watersheds of the Spartanburg water system.

Source: Spartanburg Water (2009).

Two smaller water sources supplement the reservoir system: Vaughn Creek and an unnamed stream off Hogback Mountain provide approximately 800,000–900,000 gallons per day (gpd) of water. These sources supply the Landrum Water Treatment Plant (WTP), which has a capacity of 1 million gallons per day (mgd). Landrum WTP also has a groundwater backup source with a pumping capacity of 50,000 gpd (West, 2010).

In addition to Landrum WTP, two other plants provide drinking water treatment. R.B. Simms WTP, located at Bowen Reservoir, has a capacity of 64 mgd, and Blalock WTP, located at Blalock Reservoir, has a capacity of 22.5 mgd. Spartanburg's three water treatment plants provide full conventional treatment, including sedimentation, filtration, and chlorination (West, 2010).

The distribution system is composed of 1,308 miles of pipes (West, 2010). Hydroelectricity produced at R.B. Simms WTP is used to support the water treatment operations. Hydroelectricity is not generated, however, when Spartanburg Water operates in full conservation mode during droughts. Operating in conservation mode can have a significant effect on the utility's energy costs, especially during peak hours, because peak usage can set the pricing for the month for all of its electricity use (West, 2010).

Discharges from Blalock Reservoir are managed to meet instream flow requirements based on a combination of factors, including the water level in Blalock Reservoir, the time of year, and flow into the reservoir system. Because of spawning of fish downstream, the South Carolina Department of Health and Environmental Control (SC DHEC) issued Spartanburg Water a permit that set the downstream flow requirements and determined the 7Q10 for Pacolet River[13]. In the event of a persistent drought, Spartanburg Water may request permission for reduced releases, provided it conducts additional monitoring to ensure fish health and water quality (West, 2010).

5.2.2. Wastewater System

Spartanburg Water has 10 wastewater treatment plants (WWTPs) that range in capacity from 50,000 gpd to 25 mgd. The largest of the 10 plants, Fairforest WWTP, is located just downstream of Blalock Reservoir. All 10 WWTPs provide secondary treatment. Discharge permits for the WWTPs are calculated based on the 7Q10, which is determined in part by releases from the reservoirs; therefore, there is a relationship between Spartanburg Water's ability to withdraw water and discharge wastewater. In total, approximately 13 mgd of wastewater is collected, treated, and discharged into the Pacolet River (West, 2010).

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[13] The 7Q10 is the lowest streamflow for 7 consecutive days that is expected to occur once every 10 years.

Spartanburg Water owns, operates, and maintains 940 miles of wastewater collection pipes throughout the service area (West, 2010). Some infiltration and inflow occur during storm events. A separate storm sewer system is maintained by the city and county and does not fall under Spartanburg Water's jurisdiction (West, 2010).

5.3. CLIMATE CHANGE PROJECTIONS AND RISKS

Spartanburg Water is aware that projected climate change could affect its water and wastewater systems. The utility expects droughts in the region to increase in frequency and severity with greater variability in precipitation. Spartanburg Water also expects severe storm events, such as hurricanes and tropical storms, to increase in frequency and severity.

Spartanburg Water identified these projected climate changes and their potential effects on its water and wastewater systems and operations in a variety of ways. One staff member attends meetings of the South Carolina State Drought Response Committee, whose chair is the State Climatologist and where projected climate change for the area is often discussed (Spartanburg Water, 2010c). Networking within the water utility community has provided information on approaches other utilities are using to examine and address climate change. For example, Spartanburg Water's Deputy General Manager of Engineering and Technical Services served as the President of Water Environment Federation. This provided her the opportunity to visit other domestic water utilities, including those in Las Vegas, East Bay in California, and Seattle, in addition to water utilities in Europe, South Africa, and Tanzania. Also, she and other Spartanburg Water staff often attend conferences to follow the activities of and consult with other utilities (West, 2010).

Mainly because of the prolonged and repeated droughts in recent years, Spartanburg Water is considering the effects of climate change on its infrastructure and operations. The droughts of the past decade have exacerbated many of the existing vulnerabilities of the Spartanburg Water system, including increased water demand from population growth, changes in land use patterns affecting water quantity and quality, and increasing frequency of droughts and extreme storm events affecting quality and flooding (West, 2010).

Most of the expected effects of climate change will require increased management of existing vulnerabilities, rather than addressing completely new challenges (West, 2010). For example, one of Spartanburg's water conservation efforts for drought management is a pricing structure with increasing block rates, which discourages water use beyond a certain minimum level and generally serves to discourage outdoor water use. With potential for more frequent or more severe droughts with climate change, Spartanburg Water might implement this pricing structure along with other enhanced drought management approaches to conserve additional water.

5.4. CLIMATE CHANGE VULNERABILITY ASSESSMENTS

Spartanburg Water assessed their potential vulnerability to climate change using existing information on climate change projections, experience from recent extreme events in their region, and experiences of other utilities. Based on this assessment, Spartanburg Water believes the effects of climate change will exacerbate existing vulnerabilities. As a result, rather than undertaking completely new activities or management approaches, the utility is incorporating climate change into many of its existing management activities. Climate change is now a consideration in all utility planning processes and incorporating climate change is part of the utility's culture (West, 2010). To better consider climate change in its decisions, Spartanburg Water attempts to stay current on regional climate change projection data. It also collects and tracks a variety of data relevant to climate change, including rainfall, temperature, streamflow, reservoir levels, groundwater levels, water usage, revenue streams, public perception, and Web sites (West, 2010).

Spartanburg Water's consideration of climate change takes into account the potential effects of climate change throughout its entire system—from providing sufficient water supplies to ensuring an uninterrupted supply chain for treatment chemicals during extreme weather events (West, 2010). This holistic approach to the system and operations—the result of Spartanburg Water's past experiences (such as having an interrupted supply of treatment chemicals following Hurricane Katrina) or lessons learned from other utilities—is essential because many aspects of the system are interconnected. For example, the release of water from Blalock Reservoir for the water system affects the 7Q10 determination for wastewater discharge permitting. Another example of Spartanburg's system-wide thinking is its understanding of the potential effect of water conservation programs on its revenue.

Spartanburg Water has a reservoir management model to support its management and water use decisions throughout the supply system. It also is currently developing a hydraulic model for the wastewater system. Combined with information on projected climate change, Spartanburg Water believes these models of their existing systems will enable them to assess the potential consequences of climate change on the system and allow the utility to consider adaptation actions accordingly.

5.4.1. Water Quantity

One of the primary considerations for the water supply system is sufficient water quantity. In the past 10 years, population growth has increased water demand in the Spartanburg Water service area and in six other water districts in the county downstream of Spartanburg

Water. Additionally, continued development has led to more impervious surfaces, which in some cases have redirected runoff outside of the reservoirs' watersheds, thereby reducing supply.

The recent prolonged drought experienced in the region has affected not only surface water but groundwater resources as well. Although the main water source for the Spartanburg Water system is surface water, groundwater contributes to baseflow and, therefore, surface water supplies. Multiple and prolonged years of drought impact groundwater supplies, which can take several years to recover. This results in a continued risk to surface water supply sources beyond the length of the drought (West, 2010). Also, during these drought periods, people living within Spartanburg County who obtain their drinking water from groundwater sources and are not serviced by Spartanburg Water request to be added as a customer because groundwater sources are insufficient. Often these requests originate from areas where water distribution systems do not already exist. This issue can be a challenging to manage because often public expectations are for the utility to provide access to water (West, 2010).

Change in water quantity can also affect wastewater system operations. Several of Spartanburg Water's WWTPs discharge to small streams, where wastewater discharges can constitute up to 80% of streamflow (West, 2010). With prolonged drought, Spartanburg Water anticipates that the future permit limits for these facilities will change if the 7Q10 changes for the receiving streams. In an adjacent county, similar conditions resulted in the wastewater utility upgrading to tertiary treatment. Some of the 7Q10 determinations are expected to undergo review in 2012. The result of these reviews could require additional capital planning and "creative treatment strategies in the interim" (West, 2010).

5.4.2. Water Quality

In addition to drought conditions, the Spartanburg Water service area has experienced extreme rain events, including tropical storms and hurricanes. These events caused flooding throughout the area and damaged components of Spartanburg Water's facilities (West, 2010). With the increased frequency and severity of such storms projected to happen because of climate change, preventive and restorative efforts will require additional planning and financing. Additionally, when combined with continued land development, water quality problems resulting from impervious surface runoff will be exacerbated. Impervious surfaces are a significant water quality concern because runoff of sediments, contaminants, oil, and grease is increased. Because Spartanburg County has no zoning laws, land use changes (and accompanying development and impervious surface increases) can be unpredictable in some areas (West, 2010).

Extreme storm events and droughts, especially in combination, have been associated with taste and odor problems in Bowen Reservoir and MR1. The problems are caused by high levels of geosim, which is a naturally occurring compound produced by certain soil bacteria and blue-green algae, depending on environmental conditions, including water temperatures, nutrient enrichment, and turbidity (USGS, 2009). SC DHEC determined that both reservoirs were fully supportive of all uses based on established criteria. An investigation by Spartanburg Water and the U.S. Geological Survey found that nutrient enrichment was not the contributing cause of the elevated geosim levels but that streamflow and the resulting hydraulics within the reservoir system affect the production and release of geosim by blue-green algae (West, 2010). Hydraulics affects sedimentation or re-suspension of sediment, which, in turn, affects the penetration of sunlight and the temperature of the water—both factors in the release of geosim. Today, Spartanburg Water has a monitoring system in place that helps predict when geosim events might occur.

The two main weather events that can trigger geosim release are (1) droughts, when water clarity is greatly increased by lower reservoir levels and slower streamflow; and (2) major storm events, when hydraulic surges stir up sediment in the system, releasing phosphorus and resulting in an increased abundance of blue-green algae. The highest levels of geosim were observed in 2003−2005 when tropical storms followed droughts in 2002 and 2003(West, 2010). Because these two main contributing factors are both predicted to increase in severity and frequency, Spartanburg Water expects that climate change will exacerbate the geosim water quality problem and could require additional management.

5.4.3. Infiltration/Inflow

With projected increases in the intensity of storm events, Spartanburg expects infiltration and inflow into the wastewater collection system to increase. Increased infiltration and inflow could threaten the capacity of the system to handle wastewater flow during these events.

5.5. APPLICATION OF VULNERABILITY ASSESSMENT INFORMATION

Spartanburg Water does not expect climate change to introduce new challenges but rather to exacerbate existing vulnerabilities. Given both its climate experiences of the past 10 years in the form of increased frequency and duration of drought and its information about projected climate change, Spartanburg Water has initiated a utility-wide effort to incorporate climate change into its planning processes. Spartanburg Water has combined its environmental, operational, and financial data with its understanding of the water system to qualitatively assess the potential effects of projected climate change on its infrastructure, operations, and customer needs. It has also changed its planning and management, particularly by increasing the flexibility of its system and operations.

As part of long-term water supply planning, in 2006, Spartanburg Water doubled the capacity of Blalock Reservoir, based on a study conducted in the 1990s. When this project was completed, Spartanburg Water rethought its management strategy for the reservoir system as a result of extended droughts in the Southeast. Based on a set of indicators, including streamflow and long-term weather forecasts, reservoir releases are managed for maximum water storage when signs of prolonged drought are present and hydroelectric power generation might be suspended[14]. Also, because Bowen and Blalock Reservoirs support recreational activities and adjoining properties are permitted to directly withdraw water from the reservoirs for lawn irrigation, recreational activities were limited, and water conservation requirements were instituted. Spartanburg Water asserted its right to discontinue all withdrawals for lawn irrigation from the reservoirs during droughts (West, 2010).

Spartanburg Water also revised its Water Demand Management Plans and became a WaterSense® Partner and Charter Sponsor of The Alliance for Water Efficiency. Aggressive water conservation campaigns were launched throughout the community, including placing educational kiosks and rotating them through public areas. Spartanburg Water promotes water conservation year round, regardless of drought conditions.

As a result of the conservation program and decreased industrial water use, Spartanburg Water has realized a reduction of 10 mgd in water use, and the summer peak demand has been reduced by 5 mgd. Because of this decreased demand, the time that water resides in the distribution system has increased, so Spartanburg Water is considering taking some ground storage offline or retrofitting lines to minimize this time or both. These lines and storage options, however, will be maintained in place for future use. This plan could prove useful, with potential increases in water demand from new customers or increased demand with climate change. In the next 4 years, Spartanburg Water plans to spend $3 million on its water distribution system (Spartanburg Water, 2010d).

The combination of Spartanburg Water's water conservation program and loss of many industrial accounts has resulted in a sustained loss of approximately 13% of the utility's typical revenues in the past 2 years. Spartanburg Water is now re-evaluating its revenue streams and management strategies to ensure not only environmental but also financial sustainability (West, 2010).

On the wastewater side of the system, Spartanburg Water has plans to evaluate the feasibility of modifying future treatment at 3 of the 10 WWTPs (Spartanburg Water, 2010e). The three benefits cited for the projects include the assurance of the effectiveness of ultraviolet light disinfection at these plants, potential future reuse of water, and continued compliance with discharge permits by providing "additional treatment that may be needed with fluctuations in stream flows from climate impacts" (Spartanburg Water, 2010e).

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[14] Hydroelectric power is used to pump water into the distribution or storage system.

To address the potential increase in infiltration and inflow into the wastewater collection system, Spartanburg Water adopted a new strategy when upgrading pipes in the wastewater collection system. Instead of closing off the old pipes, they were left in place to provide additional capacity during storm events and additional flexibility in managing the projected effects of climate change.

Spartanburg Water has been able to gather information on climate change impacts and adaptation by attending state-level drought committee meetings and networking with other water utilities. It does not, however, have the benefit of a state-level water program that assesses available water resources or provides guidance on projected climate change. Not having a state-level water program limits Spartanburg Water’s long-term planning and modeling. Spartanburg Water notes that the most helpful resources for continuing to address climate change would be the availability of more environmental data, descriptions of best practices and management tools, and case studies of other utilities’ actions. Addressing overlapping regulations and coordinating regulations on a watershed basis among surface water, groundwater, wastewater, stormwater, and other water resource-related programs also would facilitate Spartanburg Water’s efforts to manage its water resources efficiently and sustainably in the face of continued climate change (West, 2010).

6. SUMMARY

Each utility featured in this report is faced with a unique set of issues and challenges related to climate change. Although the issues and challenges vary, several summary observations can be made that might be useful to other utilities and members of the water resources community regarding the conduct and use of climate change vulnerability assessments to support adaptation.

- *Conducting climate change vulnerability assessments appears to have increased awareness of climate change risks, informed decision making, and supported adaptation at the utilities featured in this report.* One theme emerging from the case studies is the need to consider climate change in a holistic context, taking into account all factors affecting system performance.

- *Utilities have worked with climate scientists and modelers to obtain data and gain insight into how climate science can be used to inform their decision making.* SPU collaborated with the UW-CIG, DEP collaborated with Columbia University and the City University of New York, and EBMUD used an analysis conducted by the State of California and the California Climate Change Center. In contrast, Spartanburg relied on information gathered from briefings and staff contact with other utilities through participation in the Water Environment Federation and the American Water Works Association but did not formally collaborate with the climate change research community to develop region-specific data on their climate change risks.

- *Uncertainties in vulnerability assessments or climate science need not delay adaptation action.* All four utilities described in this report have taken action to reduce their climate risk despite significant, remaining uncertainties regarding the potential impacts of climate change. Often, these actions also address other concerns, such as managing limited supplies using water conservation or water reuse. Nonetheless, climate change vulnerability analyses can help inform and prioritize among management decisions.

- *The large utilities used a wide array of climate change scenarios to capture some of the uncertainty about future climate change.* EBMUD conducted a "bottom-up" approach by performing sensitivity analyses to improve its understanding about how climate change could affect particular elements of its water resource system. SPU and DEP conducted what are often referred to as "top-down" approaches driven by climate change scenarios and models.[15]

- *Vulnerability analyses to date have focused mainly on water supply and demand.* All four utilities focused their climate change impacts and vulnerability work principally on water supply and demand. Although the utilities expressed concern about the effects of

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[15] For more on the difference between "top-down" and "bottom-up" approaches, see Miller and Yates (2006), Freas et al. (2008), and Stratus Consulting and MWH Global (2009).

climate change on water quality, urban drainage, wastewater, and other aspects of their systems, these areas have not yet received the same level of attention as water supply.

- *The utilities used system-specific models to understand and manage potential climate impacts on their systems.* All case studies except Spartanburg Water used their system hydrology, operations, or planning models to evaluate the effects of potential climate change on their systems. The models were used to assess whether operational changes would be sufficient to cope with the effects of climate change, or whether system changes, such as adding supplies or further reducing demand, also were necessary. These models did not always align with the output of climate models, necessitating tailored use of climate projections for each utility. Spartanburg Water used existing system models to understand their system's behavior and qualitatively determine expected climate change impacts.

- *The case studies demonstrate that a variety of methods can be used to understand vulnerability and analyze adaptation options.* Scenario analyses, sensitivity analyses, state-of-the-science literature reviews, and peer information sharing were used in different combinations in the four case studies to understand the potential impacts of climate change. The sensitivity analysis EBMUD performed on their existing system model and the literature review and information gathering from peers Spartanburg Water performed demonstrate two paths that utilities lacking the financial and staff resources to support detailed modeling studies can take to assess their vulnerability to climate change.

- *Utilities expressed an interest in having their needs reflected in future research.* Utilities specifically requested higher resolution climate change projections at the spatial and temporal scales at which they operate, probabilities associated with projected changes, and guidance on appropriate climate change parameters and scenarios to consider and plan for in their regions. One recommendation was to establish a central repository of data to support climate change and adaptation analysis.

- *The results of vulnerability assessments by the four utilities were used in different ways to inform and support adaptation.* SPU responded directly to the results of the vulnerability analysis by evaluating the impact of conservative operational assumptions on reservoir management. The other utilities used their vulnerability assessments to increase knowledge about their climate change risks, integrate information on these risks into decision making, and provide support for adaptation measures.

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EPA/600/R-10/077F/March 2011/www.epa.gov

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