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

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PREFACE

The U.S. Environmental Protection Agency's (EPA's) Global Change Research Program (GCRP), located within the Office of Research and Development, works to define critical issues and information needs, and to provide information and tools to build the capacity of EPA program and regional offices, water managers, and other decision-makers to assess and respond to global change. The GCRP has four focus areas: air quality, water quality, aquatic ecosystems, and human health. The Program's focus on water quality is consistent with the Research Strategy of the U.S. GCRP, the federal umbrella organization for climate change science in the U.S. government, and is responsive to EPA's mission and responsibilities as defined by the Clean Water Act, Safe Drinking Water Act, and other federal laws.

This report presents a series of 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. 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. The issue of climate change is complex and will require ongoing attention and study. The authors hope that the examples presented in this report can in some way inform or otherwise support other utilities and water managers faced with this challenge.

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EXECUTIVE SUMMARY

There is growing concern about the potential effects of climate change on the quantity, quality, timing, and demand for water. 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, 2009b). One outcome of this workshop was that it would be useful to develop case studies of successful adaptation projects and activities to help individual utilities learn from each other.

This report presents a series of 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. Rather, its purpose is to illustrate a range of issues and current approaches taken by leading water utilities to understand and respond to climate risk.

The following four utilities are featured 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 four case studies presented in this report were selected not because they are typical of how climate change is being addressed by water utilities in the United States but, rather, because they are among the leaders in adaptation. The selected case studies also differ in terms of their geographic location, size, and the types of impacts from climate change they may face.

EAST BAY MUNICIPAL UTILITY DISTRICT

East Bay Municipal Utility District (EBMUD) used an elaborate policy analysis when designing its Water Supply Management Program 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 five portfolios under climate change scenarios. EBMUD applied a “bottom-up” approach for the analyses by identifying climate factors most likely to

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

affect the system's reliability and testing the system's 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 2004 or a 20% decrease in precipitation) (EBMUD, 2009a). EBMUD's analyses reaffirmed the need for a strategy that is flexible and adaptable to observations in further changes in climate and to refinements in climate change projections (EBMUD, 2009b).

NEW YORK CITY DEPARTMENT OF ENVIRONMENTAL PROTECTION

To analyze vulnerability, New York City Department of Environmental Protection (DEP) examined potential impacts on the availability of water, turbidity, and eutrophication. The vulnerability analyses identified a number of potential risks to New York City's water supplies and quality, including increased demand, reduced inflows during the spring thaw season, and increased risk of combined sewer overflows, nutrient loadings, and eutrophication. In addition, sea level rise and consequent increased salinity levels in the Hudson River may pose risks to the city's drainage and wastewater treatment systems. DEP has identified a wide array of initiatives to reduce risks from these potential outcomes, including developing a modeling-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 reservoir during turbidity events, more frequently cleaning and maintaining sewers and catch basins, expanding 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, such as increased heavy precipitation events and urban heat island effect, as part of its broad, city-wide effort to better manage stormwater.

SEATTLE PUBLIC UTILITIES

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

SPARTANBURG WATER

Spartanburg Water is an example of a relatively small utility that was unable to conduct quantitative vulnerability assessments (e.g., model-based assessments) but nonetheless was able to use information on climate change and recent extreme climate events to inform and allow for the consideration of climate change in management decisions. Recent extreme weather events perhaps had the greatest influence on Spartanburg Water's consideration of climate change risks. South Carolina has experienced several extreme droughts and hurricanes in recent years and anticipates that climate change will exacerbate these extreme events. In addition, with lower low flows in receiving streams, the wastewater treatment plants may be required to upgrade to reduce their discharge loads. More intense precipitation could result in greater pollutant loadings to the receiving streams.

In response to all of these concerns and planning for increases in population, Spartanburg Water made a number of changes in its infrastructure and operations. Recent concerns about droughts 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 when installing new pipes, kept the old ones for additional capacity. These adaptations are consistent with Spartanburg Water's experience with recent extreme events and concerns about population growth, and climate change provides additional justification for these measures.

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:

- *For the four utilities researched for this report, conducting climate change vulnerability assessments appears to have increased awareness of climate change risks, informed decision making, and provided support for adaptation measures.* These case studies illustrate the wide range of issues and constraints faced by utilities and approaches for considering adaptation to climate change in a holistic context, taking into account all factors affecting system performance.

- *Utilities have benefitted by working with climate change researchers.* SPU collaborated with the Climate Impacts Group at the University of Washington, 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 information on climate change risks.

- *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 particular elements of its water resource system could be affected by climate change. SPU and DEP conducted what are often referred to as "top-down" approaches driven by climate change scenarios and models.

- *The utilities used models to manage and understand the dynamics of their systems.* All of the case studies except Spartanburg used their 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, were also necessary.

- *A review of literature on climate change and understanding of how recent extreme events could become worse in the future informed Spartanburg's consideration of climate change in its decision making.* This suggests that while modeling the potential effects of climate change on a system appears to be useful in providing insights about vulnerability, it is not necessary. The Spartanburg case study demonstrates that utilities lacking the financial and staff resources to support detailed modeling studies can still considerably reduce their vulnerability to the potential impacts of climate change by increasing their knowledge of projected climate change and associated risks.

- *Utilities expressed an interest in obtaining better information on climate change, and that their needs are reflected in future research.* They particularly requested information on projections at the spatial and temporal scales in which they operate, the probability of specific changes in climate, and guidance on appropriate climate change parameters and scenarios to consider and plan for in their regions. It was recommended that a central repository of data be created to support climate change and adaptation analysis. Utilities need transparent information on how data are collected and what their appropriate uses are.

- *Overall, the case studies presented in this report suggest that while there is uncertainty about how climate will change in different regions of the country, through analysis and study, utilities are able to improve their understanding of the risks they will likely face from climate change.* This will help them make informed decisions about how to best adapt to climate change so as to minimize their potential losses.

- *The results of vulnerability assessments by the four utilities presented in this report were used in different ways to inform and support adaptation.* Seattle responded specifically to the results of the vulnerability analysis by evaluating the impact that conservative assumptions have on reservoir management. Vulnerability assessments conducted by the other utilities appeared to have increased awareness of climate change risks, informed decision making, and provided support for adaptation measures.

1. INTRODUCTION

There is growing concern about the potential effects of climate change on the quantity, quality, timing, and demand for water. In particular, decisions about water infrastructure have long-term implications because the infrastructure we build today will likely 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 to address climate change (Miller and Yates, 2006). Three years later, eight major municipal water utilities formed the Water Utilities 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 experienced by a system. A coastal city may be exposed to a 3-foot sea level rise, while an inland city will 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).

A number of water utilities have begun to assess the potential vulnerability of their systems to climate change. Many are considering whether their infrastructure 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, 2009b). This workshop examined how to provide useful information to water and wastewater utility managers on adapting to the impacts of climate change. One outcome of the workshop was that it would be useful to develop case studies of successful adaptation projects and activities to help individual utilities learn from each other.

This report presents a series of 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. 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. The issue of climate change 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 most needed to support such assessments.

A companion report has been prepared for the EPA Offices of Water and Research and Development, *Climate Change Vulnerability Assessments: A Review of Water Utility Practices* (Stratus Consulting, 2010). The purpose of that report is to identify and categorize the models and techniques being used by eight water utilities to understand their vulnerability to climate change. This report provides an in-depth examination of three of the eight utilities discussed in the previous report, plus one that was not.

1.1. SELECTION OF CASE STUDIES

Many water utilities are active in climate adaptation and could have been included in this report. It was necessary for practical reasons, however, to limit the scope of this report to just four utilities. 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; and
- Spartanburg Water (Spartanburg, South Carolina).

These utilities were selected because they appear to be leaders in climate adaptation and because they differ in terms of their geographic location, size, and the types of impacts from climate change they may face (Table 1). Case studies are located in the northwestern, southwestern, northeastern, and southeastern United States. Three of the four serve over a

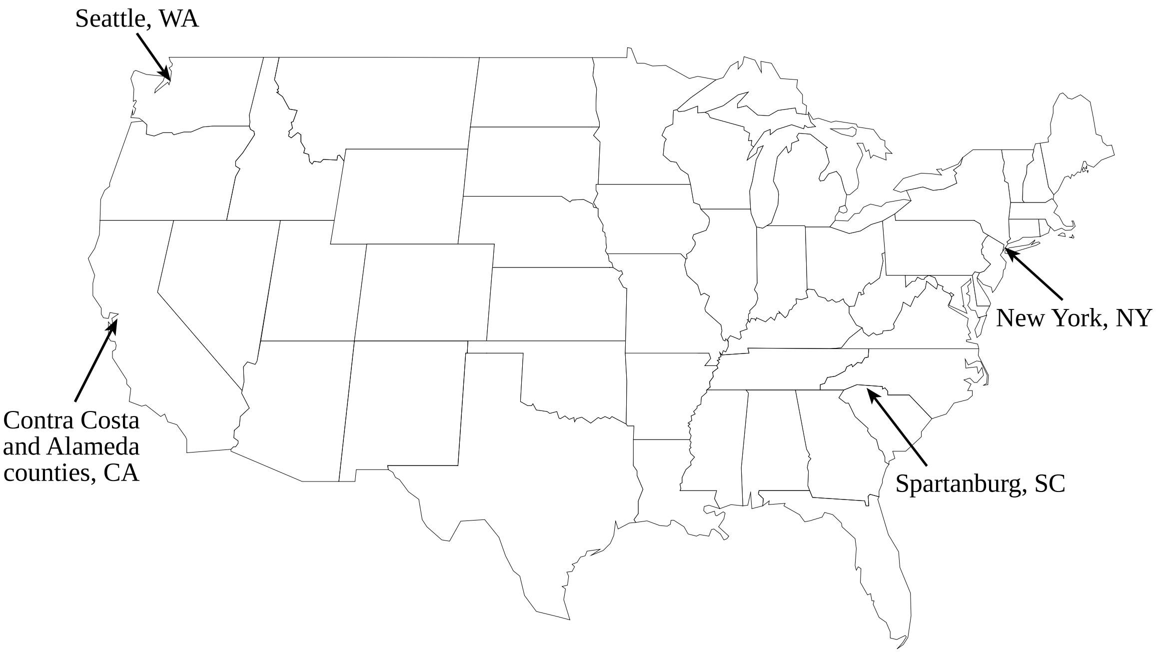

Figure 1. Location of water utilities for case studies.

Table 1. Key attributes of water utility case studies

Utility	Location	Population served	Key climate change risks
EBMUD	Alameda and Contra Costa Counties, California	1.3 million	• Change in timing of runoff • Reduction in water supply • Sea level rise
DEP	New York, New York	9.2 million	• Increases in turbidity, eutrophication, and combined sewer overflows • Sea level rise
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. 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, quality, and the performance of their systems.

Each of the selected utilities has examined or is examining the vulnerability of their system to climate change. The methods used span a range from detailed, quantitative analyses to a more qualitative approach for examining climate change and learned lessons from recent extreme events. All four utilities have also 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. While these four case studies should not be considered representative of how all utilities are considering climate change, they can 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, we focused 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; and
- Discussion of application of vulnerability assessment information.

Individual utility case studies are presented in the following four chapters. To the extent possible, we have attempted to present each case study in a consistent level of detail. 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 the 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 nondrought 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. 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 reach southeast and merge into the Sierra Nevada, which continues to parallel the coast. Between these two ranges, there is the Central Valley. This flat, 45-mile-wide valley is closed off by the meeting of the Sierra Nevada and Tehachapi Mountains, which reach southwest to meet the Coast Range (WRCC, 2010).

West of these mountain ranges, there is a predominantly maritime climate dominated by the Pacific Ocean. This area experiences warm winters, cool summers, small daily and seasonal temperature ranges, and high relative humidities (WRCC, 2010). East of the mountain ranges, there is a continental desert climate with warmer summers, colder winters, greater daily and seasonal temperature ranges, and generally lower relative humidities (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).

Snow melt 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 through the dry part of the year and flood control during the winter and spring. In Oakland, the average total precipitation is 23 inches while in Livermore it is 14 inches (NCDC, 2010). All of the precipitation in Oakland falls as rain while Livermore, on average, receives approximately 0.1 inch of snow (NCDC, 2010).

Climate change has been documented in this region. In the second half of the twentieth century, a 2°C rise in winter temperature was observed in the Sierra Nevada (EBMUD, 2009a). With a 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 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. During dry years, evaporation can exceed runoff, resulting in no net water supply in those years (EBMUD, 2009b).

Most of the Mokelumne River Watershed is undeveloped (approximately 75% of its land is forested) and is located within national forests. Precipitation is highly variable in the watershed, with 14 of the last 20 years having below-normal precipitation to being critically dry. Precipitation also varies considerably by season, with the most precipitation from November to May and the least precipitation from June to September. Peak flows are during winter storms and the spring snowmelt; minimum flows are in the late summer and fall (EBMUD, 2009b). Approximately 63% of the annual average runoff occurs 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 a number of 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

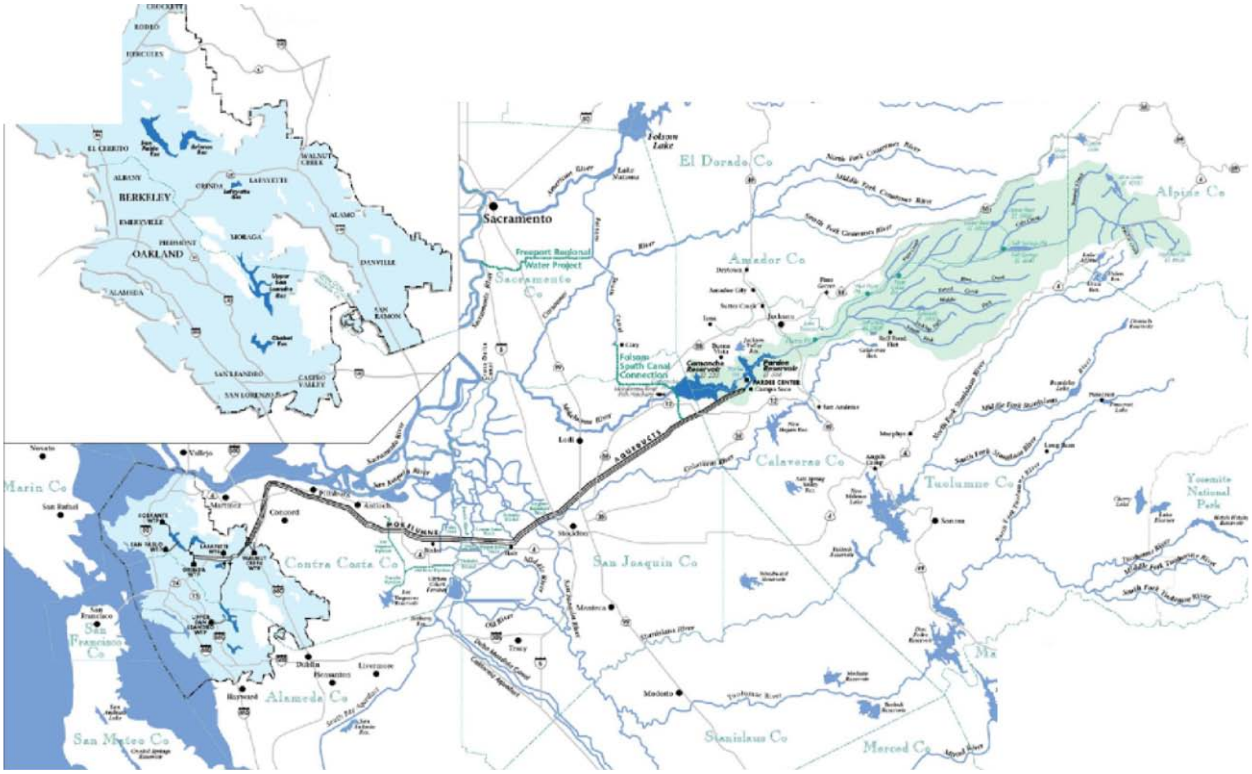

Figure 2. East Bay Municipal Utility District (EBMUD) service area and ultimate service boundary.

Source: EBMUD (2009b).

417,120 acre-feet. Water 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 and/or divert to storage up to 325 mgd of water from the Mokelumne River. However, the actual flow that can be diverted is determined by the amount of runoff and streamflow, upstream and downstream senior water rights, and storage capacities. In addition, 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). There are five terminal reservoirs that 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 will meet approximately 22% of water needs during dry years. EBMUD estimates that it will use this water source approximately 3 out of every 10 years (EBMUD, 2009a). The other new source will be from the first phase of the Bayside Groundwater Project. Treated drinking water 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***

The water use in the EBMUD service area is approximately 92% residential, 7% commercial, and 1% industrial and public authority use (EBMUD, 2007). The majority of water provision services are funded by user fees (approximately 75%) with the remaining revenue coming from capital contributions, investment, 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 are recycled (Towey, 2010).

2.2.2. Wastewater System

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 up to 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). In addition, 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

Climate change information used by EBMUD to evaluate vulnerability to climate change included the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) 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 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 2.0−6.0°C increase in temperature and either a 20% increase <u>or</u> decrease in precipitation. In addition, rising temperatures are expected to cause precipitation to fall more often as rain, decreasing water storage in snowpacks 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 will affect the frequency and severity of flooding in coastal areas, including the flood-prone Sacramento/San Joaquin River Delta, where 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 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 is inconclusive.
- Drought impacts are also inconclusive, but some scenarios predict increased frequency and longer-duration droughts.
- There will be a general increase in climate variability.

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 attended by the Board of Directors and key stakeholders (Wallis et al., 2008).

In addition, EBMUD gauged customer opinion about climate change in an annual customer survey. The survey showed that almost 75% of respondents 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% of the respondents (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 incorporated climate change as one of the strategies for meeting long-term water supply goals. 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 done 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 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).

2.4.1. Flooding and Sea Level Rise

EBMUD expects that flooding may 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 3°C rise and 1997 precipitation levels (the wettest year in the last 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 as much as it was in 1997 to prevent flooding (Wallis et al., 2008).

In addition to more extreme weather events, sea level rise may 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 of the flood-prone and earthquake-prone Sacramento/San Joaquin River Delta is an existing vulnerability that will be exacerbated by rising sea levels. The 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. However, the interactions of vulnerabilities, such as the effects of sea level rise on levee failure, 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 proposed by CA DWR (EBMUD, 2009b).

2.4.2. Hydropower Generation

While extreme weather events may cause more intense precipitation and flooding, total annual precipitation may 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 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 may lead to a 10−30% decrease in hydropower generation (Wallis et al., 2008).

2.4.3. Water Supply

EBMUD 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.[2] The process consisted of six steps: (1) identifying a list of projects for providing additional supply, (2) screening the projects, (3) developing portfolios of projects that satisfy water needs through 2040, (4) screening 14 preliminary portfolios under historic hydrology 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). In order to inform the selection of a reliable portfolio, a climate change 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 the system's 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

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

determine the effect of each factor on the performance of the existing system.[3] 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 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. *Increased Demand*

To test the effects of increased water demand, 2040 water demand estimates were recalculated assuming a 4°C increase in air temperature, resulting in a 3.6% increase in demand.[4] 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 extent of customer rationing increased to a maximum of 5.6%, but the frequency with which rationing occurred did not change. Flood control releases were not analyzed (EBMUD, 2009a).

2.4.3.2. *Temporal Shift in Runoff*

As a result of increasing temperatures, the volume of runoff between April and July 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 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 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

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[3] 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 of this chapter).

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

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 did not have a significant impact on EBMUD's ability to meet water demand because EBMUD's total reservoir storage is larger that the total annual average runoff (EBMUD, 2009a). This provides the ability to reconfigure system operations for fewer flood control releases (Wallis et al., 2008). However, when considered in combination with the need to adjust flood releases from the Camanche Reservoir to accommodate extreme precipitation events as predicted above, it suggests that there will be a more delicate balance between flood control and capturing the projected temporal shift in spring runoff.

2.4.3.3. ***Decrease in Annual Precipitation***

The effect of reduced precipitation was assessed by assuming that reductions of 10% and 20% in the volume of annual precipitation directly correspond to 10% and 20% decreases in runoff. Both scenarios were run in the W-E model, with 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).

The magnitude of these results may be evaluated relative to the worst drought on record, which 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 the 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.

2.4.4. 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 had been developed by the Upper Mokelumne River Watershed Authority for a different study in which EBMUD participated. This 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 2°C, 3°C, and 4°C. Over all scenarios, average annual water temperatures increased by 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 the drier years and during 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 algae growth with higher water temperatures. In addition, with increasing intensity and frequency of storm events, turbidity levels may 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 may decrease the plants' daily output and increase treatment costs (Wallis et al., 2008).

2.5. APPLICATION OF VULNERABILITY ASSESSMENT INFORMATION

Of the four case studies discussed in this report, EBMUD may have used the most elaborate policy analysis as part of its WSMP 2040 initiative. Several key insights were provided by the climate change analyses for the WSMP decision-making process. Although EBMUD staff already knew before conducting these studies that diversification of water supply sources was needed, the vulnerability studies provided further support for the recommended adaptation measures.

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, and the climate change vulnerability studies provided further support for the recommended adaptation measures.

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 only relying on enlarging existing reservoirs, EBMUD will pursue additional surface water and groundwater sources. Plans will also be drawn up for regional desalination. To meet the 2040 dry-year water needs, conservation, desalination, and the enlargement of reservoirs in combination with some 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. While water quality vulnerabilities were not directly addressed, the vulnerability analyses revealed that the interaction of lower water levels in the reservoirs and increased air temperatures are the causal factors; addressing water quantity will mediate water quality concerns. However, this was not explicitly addressed.

To support continued climate change vulnerability assessments and adaptation activities, EBMUD has 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, 2008b). DEP supplies approximately 85% of the water for Westchester County and 5−10% of the water needs of Orange, Putnam, and Ulster Counties (Rosenzweig et al., 2007). Additionally, the system provides legally mandated conservation releases to the Delaware River Basin (DEP, 2008b).

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 prevalent 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 air mass is the maritime influence of 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. The distribution of precipitation across New York State is influenced by topography and proximity to the Great Lakes and Atlantic Ocean. Average annual precipitation amounts 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 evenly distributed throughout the year, and there are no distinctly wet or dry seasons repeated on an annual basis, although minimum precipitation tends to occur in the winter and maximum precipitation in the summer (NYC Panel on Climate Change, 2009; New York State Climate Office, 2010).

In the mountainous areas of New York State, such as the Catskills, average snowfalls range from 70−90 inches, but topography and elevation produce great variation in snowfall over even short distances in the state's interior. The bulk of wintertime precipitation in these areas falls as snow. New York City, however, receives only some 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 falls in storms that include snow accumulation of at least 1 inch (New York State Climate Office, 2010).

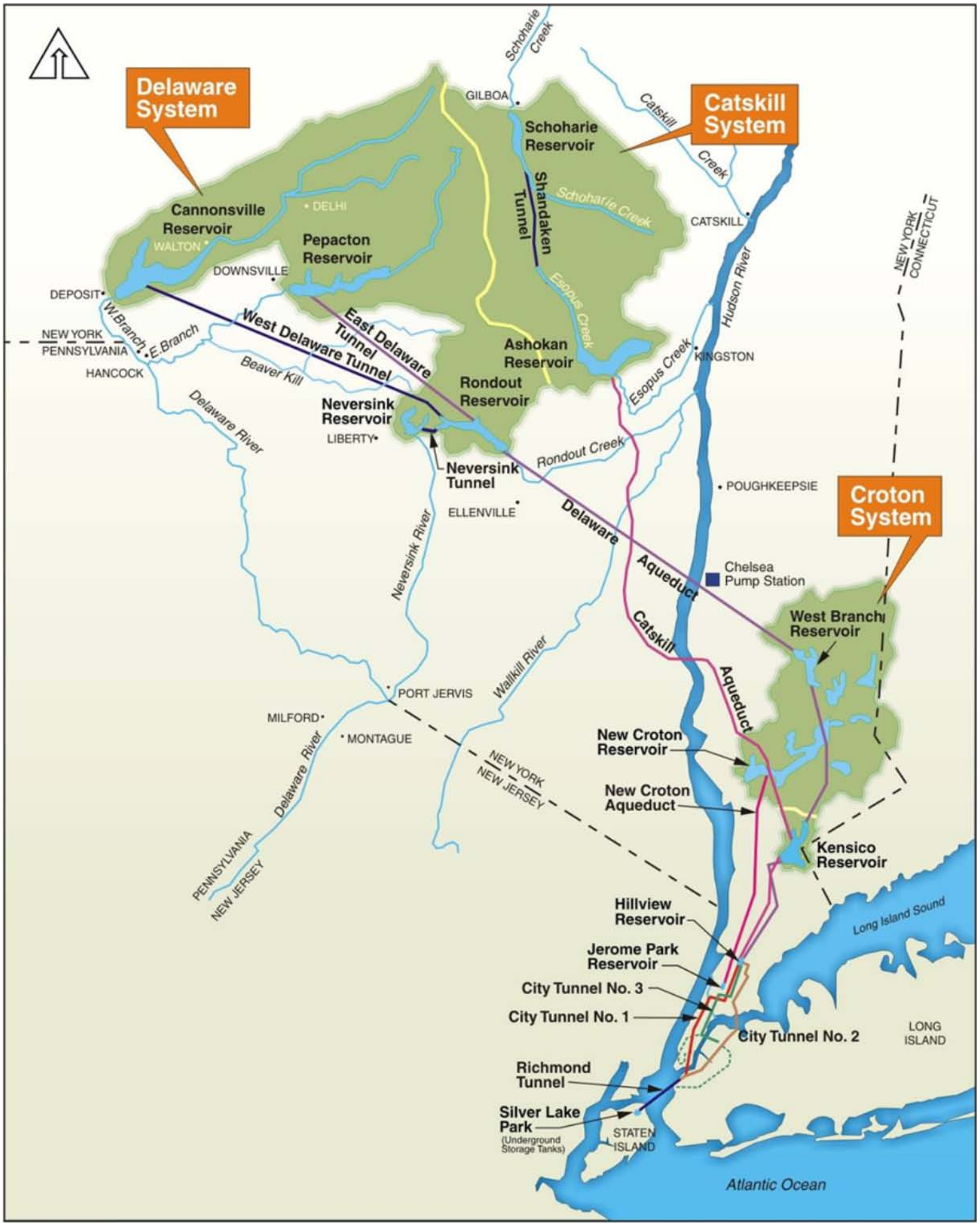

Figure 3. New York City Department of Environmental Protection (DEP) system overview.

Source: DEP (2008a).

Instrumental measurements indicate that 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 interannual 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 watershed that stretches nearly 2,000 mi^2 and extends 125 mi north of New York City (Figure 3). The watershed is divided into two geographically discrete regions—the Croton Reservoir system, which is located north of the city and east of the Hudson River, and the Catskill/Delaware Reservoir system, located in upstate New York, well north and west of the city and the Hudson River. Additionally, less than 1% of New York City's water is obtained from the Brooklyn-Queens Aquifer, located in southeastern Queens (DEP, 2008a).

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, 2009a). Forests cover approximately 75% of the watersheds. An estimated 75% of the forested land area is owned by more than 20,000 private landowners (Brunette and Germain, 2003).

In 1993, New York City began implementing watershed protection programs to reduce the susceptibility of the surface water supply to a number of 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, environmental groups, and agricultural organizations 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 EPA to issue a 5-year Filtration Avoidance Determination (FAD), which 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. EPA reissued New York City a 5-year FAD in 2002 and a 10-year FAD in 2007. These ongoing source water quality programs are monitored by the New York State Department of Health and EPA. 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 for source water quality, for example, by improving septic systems.

- *Wastewater Treatment Plant Upgrades*—New York City funds improvements to non-NYC-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*—The Program works with farms to help implement best management practices that reduce agricultural pollution and protect water quality (DEP, 2008a).

Because of glacial clay deposits underlying stream channels and steep topography surrounding the waterways, in the Catskill water system there are risks of high turbidity due to intense precipitation events and associated runoff. Maintaining the FAD on the Catskill and Delaware water supplies is a crucial element to future watershed plans. In order to meet FAD-required standards, DEP has occasionally added alum to the waters entering Kensico Reservoir to reduce turbidity.[5] However, periodically the alum and associated sediment must be dredged from the reservoirs (DEP, 2005).

The Croton Watershed system covers approximately 375 mi^2 east of the Hudson River in Westchester, Putnam, and Dutchess Counties and a small section of Connecticut. It includes three upland reservoir systems and supplies approximately 10% of the city's freshwater supply. The system began service in the mid-1800s and was completed prior to 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, DEP provides water to some 800,000 residents of Westchester County. But 12 of the County's 45 municipalities lie within the boundaries of the Croton Watershed, contributing to water supply contamination from lawn care chemicals, 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, EPA determined that the Croton system failed to meet the requirements of the Surface Water Treatment Rule, and

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

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 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, 2008a). Communities around the Croton Watershed were also signatories of the 1997 MOA aimed at improving watershed protection. They are participating in land acquisition and other raw water quality projects, as discussed above (DEP, 2008a).

3.2.2. Wastewater System

DEP is also responsible for the operation, protection, and maintenance of New York City's wastewater system. The wastewater network includes over 6,000 mi of wastewater pipes, 135,000 sewer catch basins, 494 permitted outfalls, 93 wastewater pumping stations, and 14 wastewater treatment plants spread across the city's five boroughs (Rosenzweig et al., 2007). 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. New York has approximately 60% combined sewers, making combined sewer overflows (CSOs) during intense precipitation events a continuing problem for DEP (DEP, 2008b). 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 over 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).

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). Natural precipitation variability in this area is large. While most climate model projections indicate small increases in precipitation, some models 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 approximately a 0−5% increase by the 2020s, a 0−10% increase by the 2050s, and a 5−10% increase by the 2080s. Most models indicate precipitation increases for the winter months and slight decreases during September and October. Furthermore, as temperatures increase, it is expected that more precipitation will 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, p.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 is composed of 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, 2008b):

- 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 focusing 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).

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, as well as 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 of the experts engaged to assist DEP in 2004 were also engaged 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 watersheds are located) as well as 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 combine the use of 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.

The project is 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 continued support from CUNY, has similar goals as 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, 2008b; 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, while 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 possibility 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 multimodel 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 regridded 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 some data to be eliminated from the study dependent 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 regridding 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, seasons (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-progress 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, this includes improvements to the following model elements: hydrologic balance, sediment and nutrient generation and transport, ecosystem effects, and land use. For the reservoir models, this includes additional upgrades and calibration and development of response function models keyed on system performance measures. For the integrated system, this includes enhanced coupling of the watershed and reservoir models to OASIS. And for model inputs, this includes advanced delta change with historical data morphing, statistical downscaling, and regional climate model (RCM) simulations.

A number of 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 probabilities for temperature, precipitation, and sea level rise from global climate models simulations based on three greenhouse gas emission scenarios (A1B, A2, B1). The NPCC used 16 GCMs to generate possible changes in temperature and precipitation. It used only seven GCMs 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 region include both global and local components.

According to the NPCC report, changes in mean climate and climate extremes may 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 may reduce inflows to reservoirs during the spring thawing season; changes in the ecology of streams due to higher stream temperature, which may limit the amount of water that can be extracted; and increased water demand. The biological and chemical reactions in wastewater treatment plants could also be disrupted at higher temperatures (DEP, 2008b).

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

The impacts of potential sea level rise for city water resources include an increase of the salt front 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 flood risk for low-elevation infrastructure and wastewater treatment plants (NYC Panel on Climate Change, 2009; DEP, 2008b).

3.5. APPLICATION OF VULNERABILITY ASSESSMENT INFORMATION

Like East Bay Municipal Utility District, DEP also conducted a suite of model studies to understand vulnerability and has made decisions to reduce the vulnerability of its systems to climate change. However, this may be a case where policy and analysis, although informing each other, are also proceeding in parallel. New York City's climate change work has led to increased incorporation 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 a direct result of any 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 exacerbated by climate change. These decisions largely focus on so-called no regret adaptations, or changes to the water supply system that make sense regardless of whether 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 a number of 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 un how DEP uses the Delaware and Catskill water systems during heavy precipitation or turbidity events.

3.5.2. Minimizing Flooding

To minimize 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. Additionally, the task force 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 (PlaNYC, 2008).

For example, New York City is planning to expand the Staten Island Bluebelt program, which was created as a natural system to prevent flooding and septic tank failure. It functions by diverting water from wastewater treatment to natural systems. Nearly 36% of State Island's precipitation is diverted to a 10,000-acre Bluebelt. 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 of the concept will act as a natural buffer, reducing pressure on the wastewater system and reducing flooding issues and CSOs (PlaNYC, 2008).

3.5.3. Minimizing Supply and Demand Imbalances

Higher temperatures increase peak water demand. Within New York City, annual average demand is approximately 1,069 mgd. During heat waves, demand can increase to over 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. Additionally, small-scale conservation efforts can reduce water demand (DEP, 2008b).

New York City has successfully reduced water demand since 1985 with 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 include groundwater sources and new infrastructure, including potentially increasing the capacity of the Catskill Aqueduct.

3.5.4. Combating Combined Sewer Overflows

To combat CSOs 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.

Additionally, New York City is planning to convert some of the combined sewer systems into high-level sewer systems,[6] which divert a large percentage of the stormwater directly to waterways rather than into treatment plants. This not only decreases the likelihood of CSO events but additionally reduces costs by avoiding unnecessary water treatment. The Climate Change Task Force has also proposed increasing pipe size to increase flow in areas where this is possible (PlaNYC, 2008). In mid-2010, DEP will release 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 to be used for both water supply and 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 around important assets, such as sea walls, dunes, or tidal gates (DEP, 2008b).

DEP has decided to institute a snowpack-based reservoir management program to provide enhanced 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 such 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 strived for during the snowpack-based reservoir management period would be regularly adjusted based on snow water equivalent (SWE) estimates of the watershed's regularly monitored snowpack. As the name implies, SWE is the water depth equivalent of a given depth of snow and is dependent upon such factors as the snowpack's water content and density. (Source: http://www.nyc.gov/html/dep/pdf/gilboa/gilboa_proj_desc.pdf).

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[6] High-level storm sewers alleviate pressure on the combined sewer system by capturing some 50% of 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 only cost-effective 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. In this report, we focus on SPU functions related to the provision of Seattle's drinking water supply and we touch briefly on vulnerability assessments of changes in urban hydrology on SPU's drainage and wastewater system.

SPU provides drinking water to a population of more than 1.35 million people in the City of Seattle and suburban areas. SPU provides direct retail water service to about 630,000 people mostly 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 SPU's 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). This means that the SPU water supply system is also managed for 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 Pacific Northwest is also strongly affected by the regional climate fluctuations known as the El Niño Southern Oscillation (ENSO) and the Pacific Decadal Oscillation (PDO). The relationship between ENSO, PDO, and the winter and spring climate of the region is highly correlated, enabling predictions of Pacific Northwest precipitation, snowpack, and streamflow. The University of Washington Climate Impacts Group (UW-CIG) develops 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 1st 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).

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 gathered and stored in two reservoirs created by the 1914 construction of the Masonry Dam—Chester Morse Lake and the 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 flood management and hydropower generation Morse Lake and the Masonry Pool hold, on average, just enough water for one water cycle year. If too little water is released during winter, there could be flooding in heavy rains or when the snowpack melts during the spring wet season, so winter water levels are generally kept low. However, drought conditions in the spring could prevent the reservoir from refilling to the level necessary to provide water during the dry summer months. This implies a risk tradeoff that SPU water managers must address every year to meet both 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 5). 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 constructed in 1963, and in 1964, South Fork Tolt Reservoir began supplying water to north Seattle and the

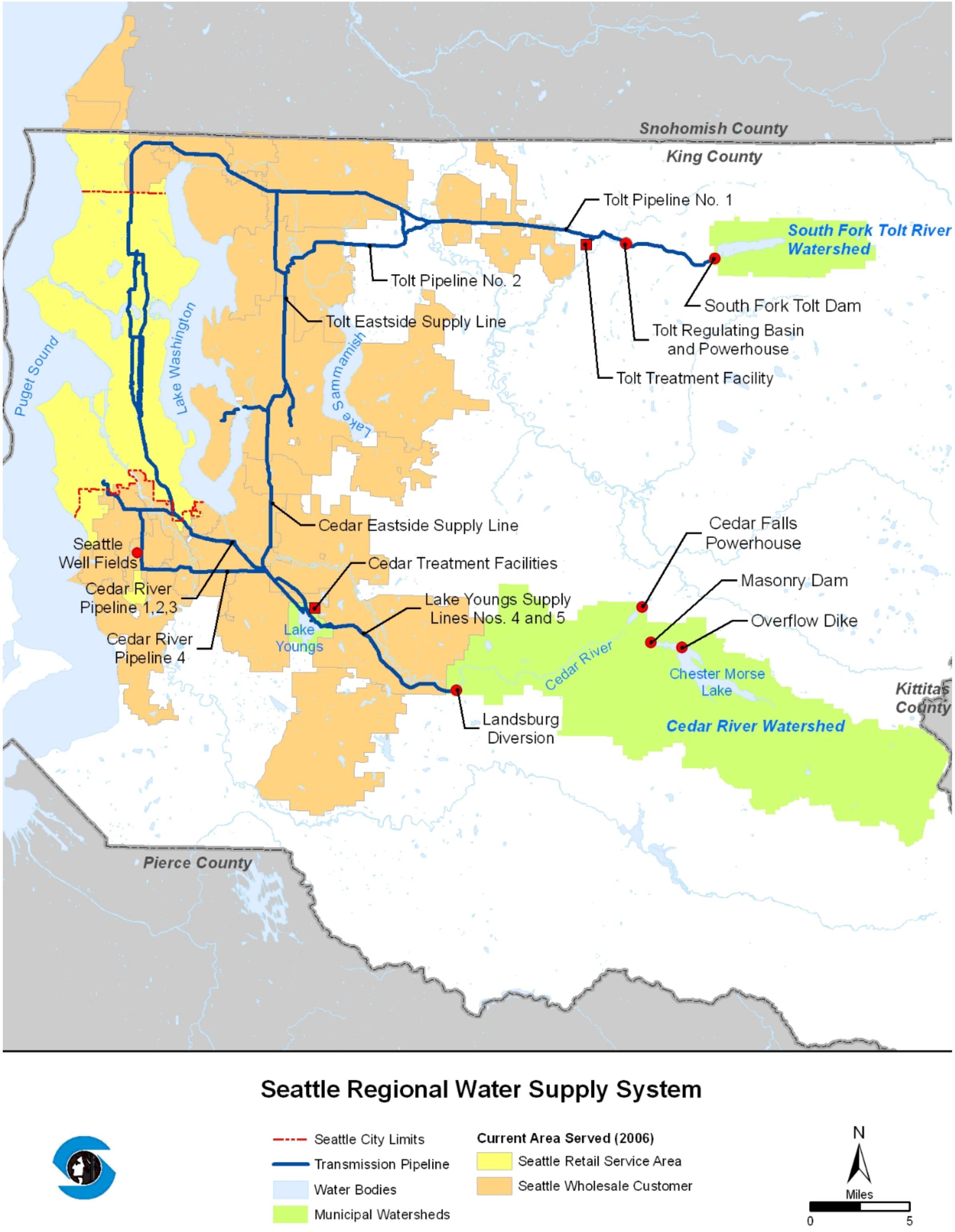

Figure 4. Seattle public utilities service area.

Source: SPU (2008).

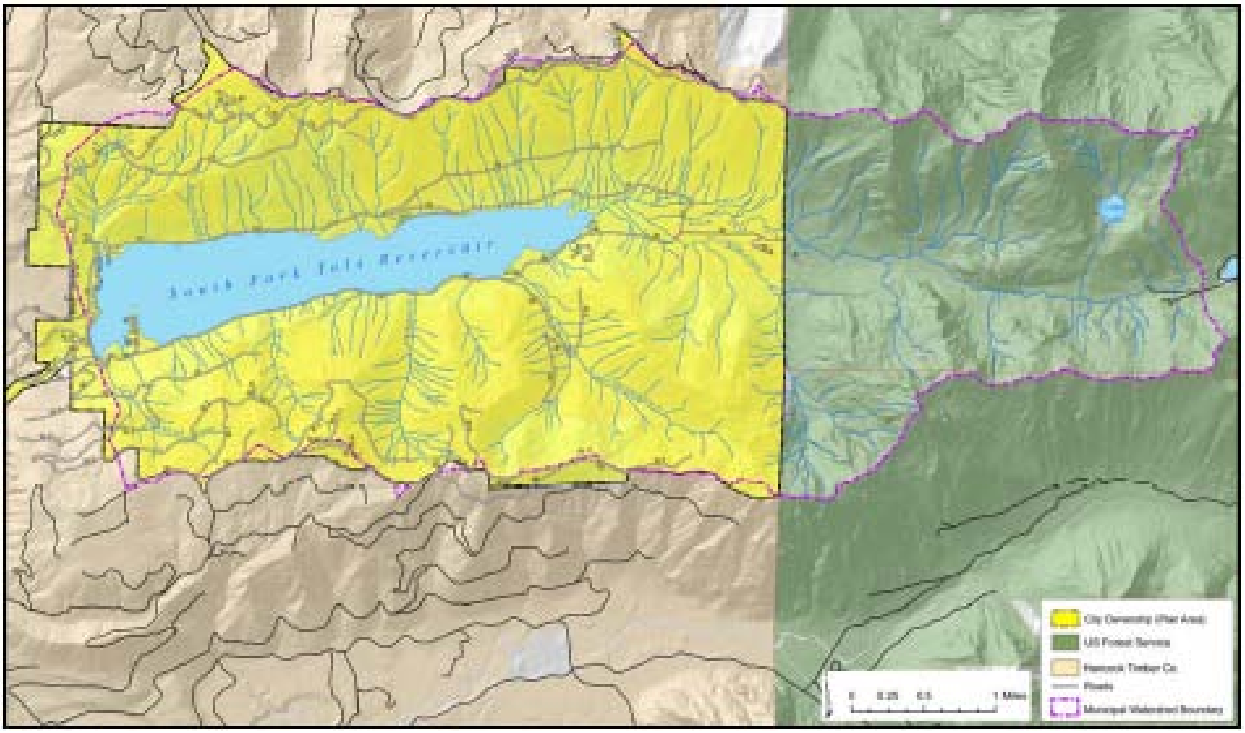

Figure 5. South Fork Tolt watershed.

Source: SPU (2008).

Eastside. As water leaves the 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 flood flows and maintain instream flows.

SPU's Tolt Treatment Facility, the city's first filtration and ozonation facility, began operation in 2000. It provides 120 million gallons per day (mgd) of finished water to customers in Seattle and suburban cities. While 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, 2006b).

In 1987, the first groundwater source was added to the system when two wells in the Highline Well Field began operation. A third well was added in 1990. These wells supply less than 1% of SPU's water from an underground 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, 2006b). 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, 2010a).

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 addresses the City of Seattle's stormwater quality and flooding issues, but often in conjunction with King County Department of Natural Resources and Parks. Because the relative responsibilities of King County and SPU overlap to some degree, this case study does not delve deeply into this aspect of the SPU system. It is worth noting, however, 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. In addition, SPU 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 0.5ºF/decade, nearly three times the rate experienced over the 20th century, and the majority of models indicate small changes in precipitation compared with 20th century observed interannual and decadal variability. Most models, however, indicate increased winter precipitation and decreased summer precipitation. Potential impacts of these changes include decreased mountain snowpack, higher winter and lower spring streamflows, increased sea-surface temperatures, rising sea-levels, and increased winter flooding in the future (UW-CIG, 2010c; City of Seattle, 2006). Table 3 provides a summary of temperature and precipitation projections, including average changes in Pacific Northwest climate from 20 climate models[7] and two greenhouse gas emissions scenarios[8] (B1 and A1B).[9] (UW-CIG, 2010c).

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

Time period	Temperature °F (*°C*)	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

A series of bad 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, 2006a) 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

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[7] http://cses.washington.edu/cig/fpt/climatemodels08.shtml#models

[8] http://cses.washington.edu/cig/fpt/climatemodels08.shtml#ghgscenarios

[9] All changes are benchmarked to average temperature and precipitation for 1970−1999. Model values are weighted to produce the "average." http://cses.washington.edu/cig/fpt/climatemodels08.shtml#rea

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 successfully implement its new reservoir management approach. Finally, in 1997, 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 experiencing any water shortage or restrictions (UW-CIG, 2010b). Another record low snowpack in 2005 threatened water shortages and use restrictions, but, again, careful water management and late spring rains allowed SPU to successfully meet all water supply and instream flow requirements without restrictions.

SPU's predecessor agencies were involved with climate change as far back as the 1980s when they helped to develop the American Society of Civil Engineers' policy on global climate change. That was followed by informal tracking of the climate variability and change issues by SPU staff, until SPU formally integrated 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, 2006b). While a final report was never completed, 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, which was proposed in October 2005 by a collaborative planning process for water resource management planning; 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; and
- Document the committee's findings (Palmer, 2007).

Ten technical reports authored by a research team from the University of Washington were reviewed by the committee prior to public release. Information from this work was used by SPU to assess impacts to water supply and demand, which is described below (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 was managed by SPU. 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 is cochairing U.S. Environmental Protection Agency's (EPA's) Climate Ready Water Utilities Working Group, which is developing recommendations on how EPA can support a "climate ready" water sector. SPU is also 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, and is part of a similar effort lead by the Water Environment Research Foundation to develop climate research for the clean water sector.

SPU operates in a political and managerial environment that supports engagement on climate change adaptation. 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 the Seattle Climate

Action 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 personnel at National Oceanic and Atmospheric Administration’s Regional Integrated Sciences and Assessment (RISA) program, known as the 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 approach to vulnerability assessment.

4.4.1. Water Supply

Downscaled temperature and precipitation data were developed for the Puget Sound region using three climate model/Special Report on Emissions Scenarios (SRES) combinations and four time periods (IPCC, 2000). The 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).[10] The four time periods include 2000 (hindcast), 2025, 2050, and 2075. These models were selected because they performed well in other studies replicating temperature and precipitation trends of the Pacific Northwest during the 20th 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).

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[10] Note that the A2 emission scenario is relatively high by the second half of the 21st century, while the B1 scenario has the lowest level of greenhouse gas emissions of the SRES family.

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. However, because CUE uses observed inflow data for both river systems as input, it cannot directly incorporate climate model output (temperature and precipitation). Consequently, 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[11] 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 already developed a demand forecasting model for its *2007 Water System Plan*, which forecasted nonclimate-altered demand change over time (SPU, 2006b). Under this model, demand was forecasted to decrease below historic levels through 2050 but 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. But, in 2075, the climate-induced increase accelerates in conjunction with significant increases in baseline demand.

4.4.3. Storms and Runoff

SPU also engaged a consultant to use UW's Weather Research and Forecasting (WRF) regional climate model to examine projected precipitation changes in the Thornton Creek Watershed (Northwest Hydraulic Consultants, 2009). Note that this is a separate study from the statistical downscaling study of water supply above but was deemed too uncertain for SPU's planning purposes. This study focused on urban drainage, but it represents an advance over previous water supply and climate change studies because of its use of dynamical instead of statistical downscaling techniques. Northwest Hydraulic Consultants used output generated by

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[11] 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.

two GCM/scenario combinations (CCSM3/A2 and ECHAM5/A1B) for two 31-year time periods (1970−2000 and 2020−2050). This output was used in the WRF regional climate model to calculate temperature and precipitation data sets for two 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 a number of creek parameters for the entire Thornton Creek basin. The results of the study indicated that there would be increases in runoff, except at one sub-basin where modeling results diverged, although the magnitude of the increases varied by factors of two at times. 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 is not currently using modeled climate projections for stormwater planning purposes.

4.5. APPLICATION OF VULNERABILITY ASSESSMENT INFORMATION

SPU may have 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 also identified more far-reaching adaptations to use in future decades in case demand exceeds water supplies. Even prior to this analysis, SPU was 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 successful 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. The analysis also 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.[12] This primarily consisted of eliminating conservative assumptions from SPU's water system supply calculations.[13] These low-cost modifications were estimated to compensate for supply shortfalls in all three scenarios in 2025, in two out of three scenarios in 2050, and in none of the three scenarios in 2075.

Other "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 though significant, the projected climate impacts are not imminent. On the other hand, the changes to conservative supply planning 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.

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 a 1−15% increase 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 reasonably high-certainty 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.

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

[13] 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%.

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, and SSSD is overseen by the seven-member Sewer Commission, which includes the three Commissioners of Public Works (Spartanburg Water, 2010a; West, 2010). Spartanburg Water can be defined as a medium-sized utility.

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 water service area includes a contiguous retail service area of approximately 259 mi^2, a noncontiguous retail service area of approximately 15 mi^2 (Spartanburg Water, 2010a), and a wholesale service area of approximately 605 mi^2. 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 in 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). In the last 10 years, however, the Southeast region of the United States experienced prolonged droughts that lasted several years. Spartanburg Water experienced droughts in 2002 and 2003, and there has been a persistent drought 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

Each day, Spartanburg Water provides approximately 30 million gallons of water to its customers. 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 6). 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 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).

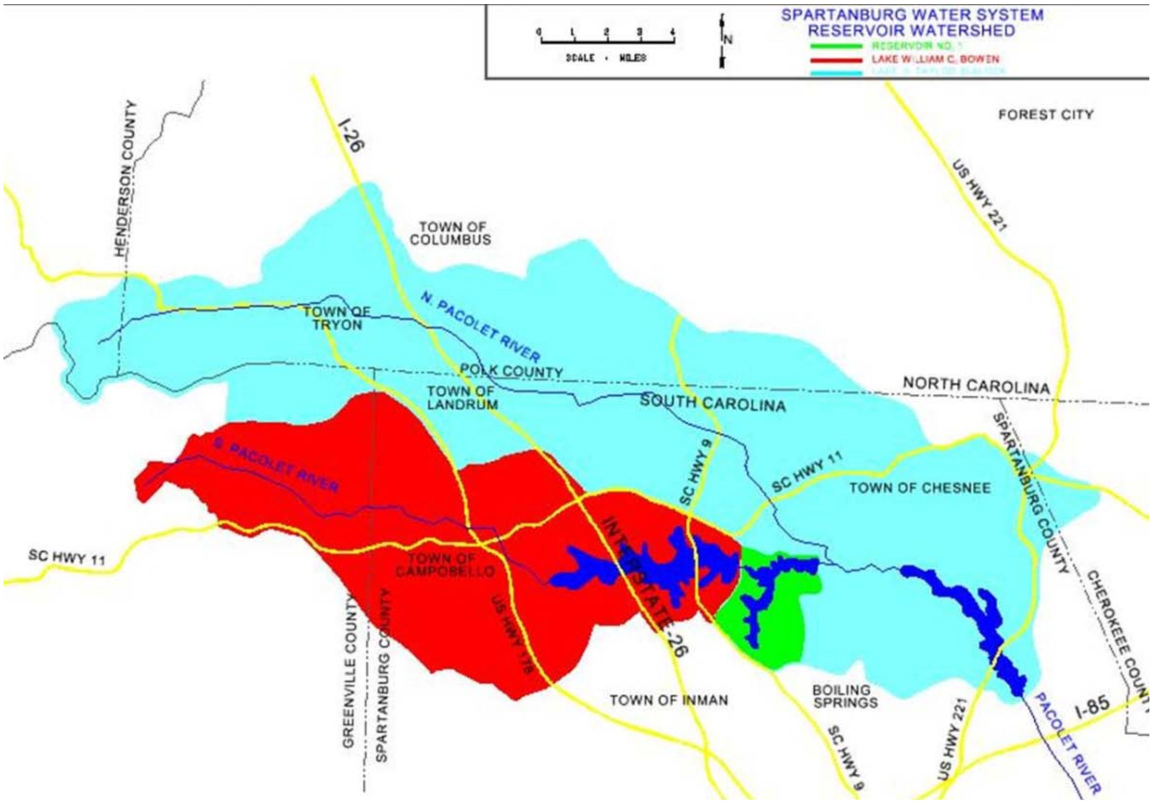

Figure 6. Reservoirs and watersheds of the Spartanburg water system.

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). In addition, Landrum WTP 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. However, hydroelectricity is not generated when Spartanburg Water operates in full conservation mode during droughts. This 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 based on instream flow requirements and the time of year. Releases are regulated based on a combination of factors, including the water level in Blalock Reservoir, the time of year, and instream 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[14] for Pacolet River. 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 of the 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 are collected, treated, and discharged into the Pacolet River (West, 2010).

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[14] 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. Although there is a separate storm sewer system, it 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 may affect its water and wastewater systems. The utility expects droughts in the region to increase in frequency and severity with greater variability in precipitation. On the other hand, Spartanburg expects severe storm events, such as hurricanes and tropical storms, to increase in frequency and severity as well.

Spartanburg Water identified projected climate changes and their potential effects on its water and wastewater systems and operations in a variety of ways. Networking within the water utility community 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 (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). Also, 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).

Largely 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 may implement this pricing structure along with other enhanced drought management approaches to conserve additional water.

5.4. CLIMATE CHANGE VULNERABILITY ASSESSMENTS

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 in 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. In addition, it 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 site visits (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 is also 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 allow 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 last 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. In addition, continued development has led to more impervious surfaces, which 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. While 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 can be a challenging issue to manage, because often public expectations are for the utility to provide access to water (West, 2010).

Change in water quantity may also affect wastewater system operations. Several of Spartanburg Water's WWTPs discharge to small streams, where wastewater discharges may 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 may 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. In addition, 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 there is more runoff of sediments, contaminants, oil, and grease. Because there are no zoning laws in Spartanburg County, land use changes 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). The hydraulics affect sedimentation or re-suspension of sediment, which, in turn, affect 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 may 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 droughts in 2002 and 2003 were followed by tropical storms (West, 2010). Because these two main contributing factors are both predicted to increase in severity and frequency, Spartanburg Water expects that climate change may exacerbate the geosim water quality problem and may 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. This may 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 system, its 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 may be suspended. (Hydroelectric power is used to pump water into the distribution or storage system.) 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 also asserted its right to discontinue all withdrawals for lawn irrigation from the reservoirs during droughts (West, 2010).

In addition, Spartanburg Water 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 educational kiosks that rotated through public areas. Spartanburg Water promotes water conservation year-round activities, 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 and/or retrofitting lines to minimize this time. These lines and storage options, however, will be maintained in place for future use. This may 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 successful water conservation program and loss of many industrial accounts has resulted in a sustained loss of approximately 13% of the utility's usual revenues in the last 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 in the CIP 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).

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. This 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. In addition, addressing overlapping regulations and coordinating regulations on a watershed basis among surface water, groundwater, wastewater, stormwater, and other water resource-related programs 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 of the utilities featured in this report is faced with a unique set of issues and challenges related to climate change. While the issues and challenges vary, a number of summary observations can be made that may 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.

- *For the four utilities researched for this report, conducting climate change vulnerability assessments appears to have increased awareness of climate change risks, informed decision making, and provided support for adaptation measures.* These case studies illustrate the wide range of issues and constraints faced by utilities and approaches for considering adaptation to climate change in a holistic context, taking into account all factors affecting system performance.

- *Utilities have benefitted by working with climate change researchers.* Seattle Public Utilities (SPU) collaborated with the Climate Impacts Group at the University of Washington, New York City Department of Environmental Protection (DEP) collaborated with Columbia University and the City University of New York, and East Bay Municipal District (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 information on climate change risks.

- *The large utilities used a wide array of climate change scenarios to capture some of the uncertainty about future climate change.* However, EBMUD also conducted a sensitivity analysis to improve its understanding about how particular elements of its water resource system could be affected by climate change. SPU and DEP conducted what is often referred to as “top-down” approaches driven by climate change scenarios and models.

- *The utilities used models to manage and understand the dynamics of their systems.* All of the case studies except Spartanburg used their 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, were also necessary.

- *A review of literature on climate change and understanding of how recent extreme events could become worse in the future informed Spartanburg’s adaptation analysis.* This suggests that while modeling appears to be useful to provide insights into vulnerability, it is not necessary. Education on climate change risks can be a substitute. To be sure, quantitative analysis can provide more detailed results and can identify possible surprises arising from climate change. Nevertheless, the Spartanburg example demonstrates that utilities lacking the financial and staff resources to support detailed modeling studies can still considerably reduce their vulnerability to the potential impacts of climate change by increasing their knowledge of potential risks.

- *Utilities expressed an interest in obtaining better information on climate change, and that their needs are reflected in future research.* They particularly requested information on projections at the spatial and temporal scales in which they operate, the probability of specific changes in climate, and guidance on appropriate climate change parameters and scenarios to consider and plan for in their regions. It was recommended that a central repository of data be created to support climate change and adaptation analysis. Utilities need transparent information on how data are collected and what their appropriate uses are.

- *Overall, the case studies presented in this report suggest that while there is uncertainty about how climate will change in different regions of the country, through analysis and detailed study, utilities are able to improve their understanding of the risks they will likely face from climate change, and make informed decisions about how to best adapt to climate change so as to minimize their potential losses.* This will help them make informed decisions about how to best adapt to climate change so as to minimize their potential losses.

- *The results of vulnerability assessments by the four utilities presented in this report were used in different ways to inform and support adaptation.* Seattle responded specifically to the results of the vulnerability analysis by evaluating the impact that conservative assumptions have on reservoir management. Vulnerability assessments conducted by the other utilities appeared to have increased awareness of climate change risks, informed decision making, and provided support for adaptation measures.

REFERENCES

AWWA (American Water Works Association). (1997) Climate change and water resources. Committee report of the AWWA public advisory forum. J Am Water Works Assoc 89(11):107–110.

Barsugli, J; Anderson, C; Smith, JB; et al. (2009) Options for improving climate modeling to assist water utility planning for climate change. Prepared for Water Utility Climate Alliance. December. Available online at http://www.wucaonline.org/assets/pdf/actions_whitepaper_120909.pdf.

Brunette, V; Germain, R. (2003) Forest management in the New York City watershed. World Forestry Conference, Quebec City. Available online at http://www.fao.org/docrep/article/wfc/xii/0649-b3.htm.

Chan, C. (2010) Personal communication from Clifford Chan, Manager of Water Treatment and Distribution, EBMUD on April 2, 2010.

Cheng, S. (2010) Personal communication from Stephanie Cheng, Associate Engineer in Resource Recovery Program, EBMUD on April 5 and 7, 2010.

City of Seattle. (2006) Seattle, a climate of change: meeting the Kyoto challenge. Climate Action Plan. September. Available online at http://www.cityofseattle.net/climate/docs/SeaCAP_plan.pdf.

DEP (New York City Department of Environmental Protection). (2005) Adapting New York City’s water supply and wastewater treatment center to climate change. U.S. Climate Change Science Workshop. November 15. Available online at http://www.climatescience.gov/workshop2005/presentations/WA2.5_Lloyd.pdf.

DEP (New York City Department of Environmental Protection). (2006) New York City’s wastewater treatment system. Available online at http://www.nyc.gov/html/dep/pdf/wwsystem.pdf.

DEP (New York City Department of Environmental Protection). (2008a) New York City 2008 drinking water supply and quality report. Available online at http://www.nyc.gov/html/dep/pdf/wsstate08.pdf.

DEP (New York City Department of Environmental Protection). (2008b). Assessment and action plan: a report based on the ongoing work of the DEP climate change task force. Climate change program. Available online at http://www.nyc.gov/html/dep/pdf/climate/climate_complete.pdf.

DEP (New York City Department of Environmental Protection). (2009) Implicit climate change adaptation: modifying system operations for turbidity control. First national expert and stakeholder workshop on water infrastructure sustainability and adaptation to climate change. January 6–7, Washington, DC. Available online at http://www.epa.gov/nrmrl/wswrd/wqm/wrap/pdf/workshop/A4_Rush.pdf.

DEP (New York City Department of Environmental Protection). (2010a). History of New York City’s water supply system. Available online at http://www.nyc.gov/html/dep/html/drinking_water/history.shtml.

DEP (New York City Department of Environmental Protection). (2010b). The Croton water filtration plant project. Available online at http://www.nyc.gov/html/dep/html/news/croton.shtml.

Dettinger, MD. (2004) From climate-change spaghetti to climate-change distribution. In: Climate scenarios and projections: the known, the unknown and the unknowable as applied to California. Aspen Global Change Institute Workshop held March 11−14, 2004, San Francisco, CA. Available online at http://www.agci.org/programs/past_scientist_workshops/about_the_workshop/sciSess_details.php?recordID=88 (as cited in EBMUD 2009a).

EBMUD (East Bay Municipal Utility District). (2007) All about EBMUD. Available online at http://ebmud.com/sites/default/files/pdfs/current_allaboutebmud[1].pdf.

EBMUD (East Bay Municipal Utility District). (2008) Strategic plan. July. Available online at http://ebmud.com/sites/default/files/pdfs/Strategic_Plan_July_2008[1].pdf.

EBMUD (East Bay Municipal Utility District). (2009a). Climate change analysis. In: WSMP 2040—water supply management program 2040 plan, Appendix C TM-9, October. Available online at http://www.ebmud.com/sites/default/files/pdfs/WSMP-2040-Appendices-October-2009.pdf,

EBMUD (East Bay Municipal Utility District). (2009b) WSMP 2040—water supply management program 2040 plan. Final program environmental impact report response to comments. SCH #2008052006. October. Available online at http://www.ebmud.com/sites/default/files/pdfs/WSMP-2040-Main-Document-October-2009.pdf.

EBMUD (East Bay Municipal Utility District). (2009c) Water visions: a clear path to the future. Available online at http://www.ebmud.com/sites/default/files/pdfs/FY09annual10_0.pdf.

EBMUD (East Bay Municipal Utility District). (2010) Sewer system management plan. Part E8—capacity management. Available online at http://ebmud.com/sites/default/files/pdfs/New_Construction/E8-Capacity-Management.pdf.

Fleming, Paul. 2010. Personal communication, March 24, 2010.

Hamlet, AF; Mote, PW; Clark, M; et al. (2005) Effects of temperature and precipitation variability on snowpack trends in the western United States. J Climate 18(21):4545−4561.

IPCC (Intergovernmental Panel on Climate Change). (2000): Emissions scenarios: summary for policymakers. a special report of IPCC Working Group III of the Intergovernmental Panel on Climate Change. Available online at www.ipcc.ch/pdf/special-reports/spm/sres-en.pdf.

LAFCO (Local Agency Formation Commission). (2008) Water and wastewater services: municipal services review for west Contra Costa County. August. Available online at http://www.contracostalafco.org/municipal_service_reviews/west_county_water_wastewater/9.0%20EBMUD%20Final.pdf.

Major, DC; Horton, R; Rosenzweig, C. (2007) Integrated modeling project for water quantity and quality: guidelines for project final report. Climate impact assessment of environmental infrastructure systems. New York City Department of Environmental Protection. June 29.

Maurer, P; Brekke, L; Pruitt, Y; et al. (2007) Fine-resolution climate projections enhance regional climate change impact studies. Eos Trans AGU 88(47):504.

McCarthy, JJ; Canziani, OV; Leary, NA et al; eds. (2001) Climate change 2001: impacts, adaptation, and vulnerability. contribution of Working Group II to the third assessment report of the Intergovernmental Panel on Climate Change. Cambridge, UK, and New York, NY: Cambridge University Press. Available online at http://www.grida.no/publications/other/ipcc_tar/.

Means III, EG; Laugier, MC; Daw, JA. (2010) Decision support planning methods: incorporating climate change uncertainties into water planning. Final report. Prepared for Water Utility Climate Alliance. January. Available online at www.wucaonline.org/assets/pdf/actions_whitepaper_012110.pdf.

Miller, K; Yates, D. (2006) Climate change and water resources: a primer for municipal water providers. Denver, CO: Water Research Foundation and University Corporation for Atmospheric Research. Available online at http://www.waterresearchfoundation.org/research/TopicsAndProjects/projectProfile.aspx?pn=2973.

Mote, PW. (2003) Trends in temperature and precipitation in the Pacific Northwest during the twentieth century. Northwest Sci 77(4):271−282.

Mote, PW; Parson, EA; Hamlet, AF; et al. (2003) Preparing for climatic change: the water, salmon, and forests of the Pacific Northwest. Climatic Change 61(1−2):45−88.

Mote, PW; Hamlet, AF; Clark, M; et al. (2005) Declining mountain snowpack in western North America. Bull Am Meteorol Soc 86(1):39−49. Available online at http://www.livingrivers.org/pdfs/LRlibrary/ClimateDocs/MoteHamletClarkLettenmaier.pdf .

Mote, PW; Hamlet, AF; Salathé, EP. (2008) Has spring snowpack declined in the Washington Cascades? Hydrol Earth Syst Sci 12:193−206. Available online at www.hydrol-earth-syst-sci.net/12/.../hess-12-193-2008.html.

NASA (National Aeronautics and Atmospheric Administration). (1999). Scientists prepare New York City for future climate change. Goddard Institute for Space Studies. Research news June 4, 1999. Available online at http://www.giss.nasa.gov/research/news/19990604/.

NCDC (National Climatic Data Center). (2010) Climate of California. Climates of the States, Climatography of the United States No. 60. Available online at http://cdo.ncdc.noaa.gov/climatenormals/clim60/states/Clim_CA_01.pdf.

New York State Climate Office. (2010) The climate of New York. Available online at http://nysc.eas.cornell.edu/climate_of_ny.html.

New York Water. (2010) The threat to NYC's drinking water from phosphorus pollution. Available online at http://www.newyorkwater.org/pdf/phosporousPollutionmar2010_2.pdf.

Northwest Hydraulic Consultants. (2009) Application of dynamically downscaled climate model data to analysis of hydrologic change in Seattle's Urban Creeks: The Thornton Creek Case Study. Prepared for Seattle Public Utilities.

NYC (New York City) Panel on Climate Change. (2009). Climate risk information. Available online at http://www.nyc.gov/html/om/pdf/2009/NPCC_CRI.pdf.

NYSDEC (New York State Department of Environmental Conservation). (2010). State enforcement targets quality of water near New York City. Environment DEC. Available online at http://www.dec.ny.gov/environmentdec/18679.html.

Palmer, RN. (2007). Final report of the climate change technical committee. A report prepared by the Climate Change Technical Subcommittee of the regional water supply planning process. Seattle, WA. Available online at http://www.climate.tag.washington.edu/techmemos/Final_Report__12-13-07_.pdf.

Parry, ML; O Canziani, JP; Palutikof, C; et al; eds. (2007) Climate change 2007: Impacts, adaptation and vulnerability. Contribution of Working Group II to the fourth assessment report of the intergovernmental panel on climate change. New York: Cambridge University Press. Available online at http://www.ipcc.ch/ipccreports/ar4-wg2.htm.

PlaNYC. (2007a) Climate change. Reduce global warming emissions by more than 30%. Available online at http://www.nyc.gov/html/planyc2030/downloads/pdf/report_climate_change.pdf.

PlaNYC. (2007b) Water network. Available online at http://www.nyc.gov/html/planyc2030/html/plan/water_network.shtml.

PlaNYC. (2008) Sustainable stormwater management plan 2008. Available online at http://www.nyc.gov/html/planyc2030/downloads/pdf/sustainable_stormwater_plan.pdf.

PlaNYC. (2008–2010) Progress reports for 2008 through 2010. Available online at http://www.nyc.gov/html/planyc2030/html/downloads/download.shtml.

Polebitski, A; Traynham, L; Palmer, RN. (2007a). Technical memorandum #4: approach for developing climate impacted meteorological data and its quality assurance/quality control. A report prepared by the Climate Change Technical Subcommittee of the Regional Water Supply Planning Process. Seattle, WA. Available online at http://www.govlink.org/regional-water-planning/tech-committees/climate-change/UWreports/TechnicalMemo4(12-13-07).pdf.

Polebitski, A; Wiley, MW; Palmer, RN. (2007b) Technical memorandum #2: methodology for downscaling meteorological data for evaluating climate change. A report prepared by the Climate Change Technical Subcommittee of the Regional Water Supply Planning Process. Seattle, WA. Available online at http://www.govlink.org/regional-water-planning/tech-committees/climate-change/UWreports/TechnicalMemo2(12-13-07).pdf.

Rosenzweig, C; Major, DC; Demong, K; et al. (2007) Managing climate change risks in New York City's water system: assessment and adaptation planning. Mitigat Adapt Strat Global Change 12(8):1391−1409.

RWSP (Regional Water Supply Planning). (2010) Regional watter supply planning. Seattle, WA. Available online at http://www.govlink.org/regional-water-planning/index.htm.

Smit, B; Pilifosova, O; Burton, I; et al. (2001) Adaptation to climate change in the context of sustainable development and equity. In: McCarthy, J; Canziana, N; Leary, NA; et al; eds. Climate change 2001: impacts, adaptation, and vulnerability, chapter 18. New York: Cambridge University Press; pp 877−912. Available online at http://www.grida.no/climate/ipcc_tar/wg2/pdf/wg2TARchap18.pdf.

Spartanburg Water. (2009) Lake Blalock buffer management plan. Public works of the city of Spartanburg, SC. September 2009. Accessed March 10. Available online at http://www.sws-sssd.org/pdfs/lbbmp.pdf.

Spartanburg Water. (2010a) Spartanburg water system/Spartanburg sanitary sewer district service areas. Public works of the city of Spartanburg, SC. Accessed March 10. Available online at http://www.sws-sssd.org/water-sewer/index.html.

Spartanburg Water. (2010b) Spartanburg lakes. Public works of the city of Spartanburg, SC Accessed March 10. Available online at http://www.sws-sssd.org/lakes/index.html.

Spartanburg Water. (2010c) Drought Committee summary. Received via e-mail from Rebecca West, Deputy General Manager of Technical and Engineering Services, on April 22.

Spartanburg Water. (2010d) SWS 10 year CIP August 2009. Received via e-mail from Rebecca West, Deputy General Manager of Technical and Engineering Services, on April 22.

Spartanburg Water. (2010e). Operations CIP items table. Received via e-mail from Rebecca West, Deputy General Manager of Technical and Engineering Services, on April 22.

SPU (Seattle Public Utilities). (2006a) Water shortage contingency plan: supplement to the Seattle public utilities 2007 water system plan. City of Seattle, Washington. July. Available online at http://www.cityofseattle.net/util/stellent/groups/public/@spu/@rmb/@resplan/@plancip/documents/webcontent/watershor_200312021018123.pdf.

SPU (Seattle Public Utilities). (2006b) SPU 2007 water system plan. City of Seattle, Washington. November. Available online at http://www.cityofseattle.net/util/About_SPU/Water_System/Plans/2007WaterSystemPlan/index.asp.

SPU (Seattle Public Utilities). (2008) South Fork Tolt watershed management plan. Prepared by Tetra Tech Infrastructure Group and Triangle Associates. City of Seattle, WA. November. Available online at http://www.cityofseattle.net/util/stellent/groups/public/@spu/@ssw/documents/webcontent/spu01_004082.pdf .

SPU (Seattle Public Utilities). (2010a) Demographics and water use statistics. City of Seattle, WA. Available online at http://www.seattle.gov/util/About_SPU/Water_System/History_&_Overview/DEMOGRAPHI_200312020908145.asp.

SPU (Seattle Public Utilities). (2010b) History of the watershed. City of Seattle, WA. Available online at http://www.seattle.gov/util/About_SPU/Water_System/Water_Sources_&_Treatment/Cedar_River_Watershed/COS_001714.asp.

SPU (Seattle Public Utilities). (2010c) Tolt River watershed. City of Seattle, WA. Available online at http://www.seattle.gov/util/About_SPU/Water_System/Water_Sources_&_Treatment/Tolt_River_Watershed/index.asp.

SPU (Seattle Public Utilities). (2010d) Tolt treatment facility. City of Seattle, WA. Available online at http://www.seattle.gov/util/About_SPU/Water_System/Water_Quality/Tolt_Treatment_Facility/index.asp.

SPU (Seattle Public Utilities). (2010e) Water system history. City of Seattle, WA. Available online at http://www.seattle.gov/util/About_SPU/Water_System/History_&_Overview/WATERSYST_200312020908156.asp.

SRCC (Southeast Regional Climate Center). (2010) Landrum, South Carolina 1971–2000 Monthly Climate Summary. Accessed May 3. Available online at http://www.sercc.com/.

Stewart, I.T., D.R. Cayan, and M.D. Dettinger. (2004) Changes in snowmelt runoff timing in western North America under a ‘business as usual’ climate change scenario. Clim Change 62:217−232. Available online at http://meteora.ucsd.edu/cap/stewart_clch.pdf.

Stratus Consulting. (2010) Climate change vulnerability assessments: a review of water utility practices. Prepared for Jill Neal, EPA Office of Research and Development.

Towey, A. (2010) Water reuse, EBMUD. Personal communication on April 9, 2010.

U.S. EPA (Environmental Protection Agency). (2002) Cases in water conservation: how efficiency programs help water utilities save money and avoid costs. Available online at http://www.epa.gov/WaterSense/docs/utilityconservation_508.pdf.

U.S. EPA (Environmental Protection Agency). (2009a) New York City watershed. Region 2. Available online at http://www.epa.gov/Region2/water/nycshed/.

U.S. EPA (Environmental Protection Agency). (2009b) Proceedings of the first national expert and stakeholder workshop on water infrastructure sustainability and adaptation to climate change. Office of Water, Washington, DC; EPA 600/R-09/010. Available online at http://www.epa.gov/nrmrl/wswrd/wqm/wrap/workshop.html.

USGS (U.S. Geological Survey). (2009) Taste and odor occurance in Lake William C. Bowen and Municipal Reservoir #1, Spartanburg County, South Carolina. USGS Fact Sheet 2009-3043. Available online at http://pubs.usgs.gov/fs/2009/3043/.

UW-CIG (University of Washington Climate Impacts Group). (2010a) About Pacific Northwest climate. Joint Institute for the Study of the Atmosphere and Ocean, University of Washington, Seattle. Available online at http://cses.washington.edu/cig/pnwc/pnwc.shtml.

UW-CIG (University of Washington Climate Impacts Group). (2010b). Case study: Seattle public utilities. Joint Institute for the Study of the Atmosphere and Ocean, University of Washington, Seattle. Available online at http://cses.washington.edu/cig/fpt/casestudyspu.shtml.

UW-CIG (University of Washington Climate Impacts Group). (2010c) Climate change. Joint Institute for the Study of the Atmosphere and Ocean, University of Washington, Seattle. Available online at http://cses.washington.edu/cig/pnwc/cc.shtml.

WA DOE (Washington State Department of Ecology). (2001) Appendix B: Summary of major ASR projects in Washington. Appendix to ASR 2001 Report to the Legislature. http://www.ecy.wa.gov/programs/wr/asr/images/pdf/ASRLegRptApdx.pdf.

Wallis, MJ; Ambrose, MR; Chan, CC. (2008). Climate change: charting a water course in an uncertain future. *JAWWA* 100(6):70−79. http://www.ebmud.com/sites/default/files/pdfs/Journal-06-08_0.pdf.

Water-technology.net. (2010) Croton water filtration plant, New York, USA. Available online at http://www.water-technology.net/projects/crotonfiltration/.

West, R. (2010) Deputy General Manager of Engineering & Technical Services, Spartanburg Water. Personal communication on April 1.

WRCC (Western Regional Climate Center). (2010) Western U.S. climate historical summaries. Available online at http://www.wrcc.dri.edu/Climsum.html.

WUCA (Water Utility Climate Alliance). (2010) About us. Accessed May 3, 2010. Available online at http://www.wucaonline.org/html/about_us.html.