

Climate Action Plans— **Adaptive Management Strategies for Utilities**

M71



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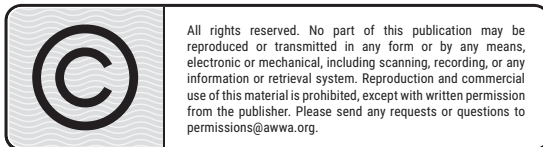
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Preface

American Water Works Association (AWWA) created the Climate Change Committee under the Water Resources Sustainability Division to prepare its members for the “new normal” scenario, in which the potential effects of climate change must be considered for long-term sustainability of our local, regional, national, and global water resources. This manual is geared toward achieving the Climate Change Committee’s goal to document the status of knowledge and describe current and future research activities that will enhance utilities’ understanding of climate change effects and mitigation/adaptation techniques. Specifically, the manual aims to help small and mid-sized utilities develop climate action plans (CAPs) to address adaptation and mitigation strategies countering the impact of climate change.

The committee recognizes that those effects may be more or less severe depending on each utility’s location and situation, but what the committee is recommending is that each utility assess its vulnerability to climate change and prioritize mitigation and adaptation measures in the context of other risks to their operations.

The manual is organized in a way to introduce the concept of climate change to readers by providing the fundamentals of climate change planning and decision making. The concepts of engineering design and planning in the realm of climate change uncertainty is discussed. The manual also includes a detailed summary of the various impacts of climate change, specifically from a utility perspective, and provides the step-by-step process of developing a CAP. The manual includes a brief summarization of the challenges and issues associated with the public and stakeholder engagement. A review of various CAP case studies is included as part of the manual to familiarize readers with the other research material available for their use. In a world of climate change planning, where information and science is changing and improving at a breakneck speed, the authors’ goal is to provide relevant reference material for the information presented. The manual will be reviewed and revised as and when information presented in the manual needs to be updated.

The ultimate goal of the manual is to provide a starting point for utility managers for whom climate change adaptation planning and developing a CAP are of interest. While the manual does not lend the reader to preparing a fully developed CAP, it guides the reader to all the relevant information they will need to develop one on their own. There is no cookie-cutter approach that can be applied to the process of developing climate action plans that includes a step-by-step checklist as the infrastructure vulnerabilities, the climate change impacts, the stakeholder engagement, and the adaptation and response measures vary by region and utility.

The template for the manual is set in such a way that the reader can easily access any of the chapters individually, without having to read the entire manual from the beginning to the end, to grasp the content in the individual chapters. Each chapter is focused on a specific topic and the relevant information supporting the chapter material and the references are included along with the chapter content.

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Our sincere thanks goes to the staff and leadership of the US Environmental Protection Agency (USEPA) for its continued response to our questions related to USEPA's Creating Resilient Water Utilities (CRWU) initiative and the Climate Resilience Evaluation and Awareness Tool (CREAT).

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Executive Summary

American Water Works Association (AWWA) created the Climate Change Committee under the Water Resources Sustainability Division to prepare its members for the “new normal” scenario, in which the potential effects of climate change must be considered for long-term sustainability of our local, regional, national, and global water resources. The manual aims to help small and mid-sized utilities develop climate action plans to address adaptation and mitigation strategies countering the impact of climate change. The ultimate goal of the manual is to provide a starting point for utility managers for whom climate change adaptation planning and developing climate action plans are of interest. While the manual itself doesn’t lend the reader to preparing a fully developed climate action plan, it guides the reader to all the relevant information so that they able to develop a report on their own.

The manual is divided into eleven chapters, each chapter addressing various aspects of the climate action plan development process. Together, the 11 chapters form a cohesive source of information that guides utility managers through the process of developing climate action plans.

Chapter 1—Introduction includes discussion on the importance of climate change impacts on various aspects of water resource management and utility infrastructure planning and management. Developing a sound climate action plan (CAP) that addresses the adaptation and mitigation aspects of site-specific climate change impacts is critical to efficient management of water utilities. The purpose of this manual is to provide a comprehensive guidance document to generate, review, report, and disseminate information on water supply planning and management relating to issues of climate change, both mitigation and adaptation, and to facilitate awareness among water utilities and the broader community on developing and maintaining CAPs. Impacts of climate change on water quality, quantity, operational reliability, and financial and institutional aspects of utility management are discussed in this chapter. The various solutions to help address the impacts that are discussed include mitigation measures, long-term planning processes, demand management, operational controls, carbon footprint reduction, energy

management, regional cooperation, building resiliency by securing additional water supplies, encouraging public participation by raising awareness, and other management measures.

Chapter 2—Purpose and Audience is a key chapter that sets the foundation for the relevance and application of this manual. It describes the purpose of the manual and its intended audience. So much information is available in the climate change scientific community in the form of reports funded by public and private entities. It is important to discern what information is relevant and what is not. Along similar lines, it is important to clarify what the stated goals of this manual are and who benefits from the use of this manual.

Chapter 3—Science of Climate Change is perhaps one of the most important chapters in the entire manual. Before venturing into the process of understanding and developing CAPs, it is important to have a basic understanding of the science of climate change. There are thousands of peer-reviewed and published reports that discuss the science of climate change. The reader could very easily get lost in that knowledge. For readers who are initially trying to grasp the details of climate change science, it is easy to get confused about the level of detail to focus on. In this chapter, the science of climate change and the important pieces of information required to develop climate action plans is gathered and presented to the reader in a concise manner. The information is also presented at a level of detail that is appropriate for utility managers and utility operators. The chapter includes a discussion on the details of climate change variability, greenhouse gas emissions and how they are used to measure and monitor climate change, and global climate model projections and inherent assumptions. The chapter also includes a summary of the impact of climate change on the hydrologic cycle and how utility managers should plan for a future that is driven by climate uncertainty. Several resources are presented and discussed in detail for readers who wish to gather more information on certain portions of the information presented in the chapter.

Regional impacts of climate change are discussed in this chapter. It is well known that climate change does not impact all regions and hydrologic environments in the same manner. Therefore, a cookie-cutter approach to analyzing climate change science and developing adaptation and mitigation measures does not serve well for utility management. It is important to understand the local and regional impacts of global climate change so that adaptation and mitigation measures discussed in the CAP are geared toward directly addressing the relevant impacts. Finally, the chapter provides a summary of the system vulnerability and various methods for assessing vulnerability.

Chapter 4—Principles of Engineering Practice is a utility managers' guide for operating and managing infrastructure while accounting for the effects of climate change. All utility managers are trained in the traditional concepts of engineering practices that include evaluating past practice, designing for a predictable future, defining level of service for infrastructure, assuming redundancy and resiliency in the form of factor of safety, and traditional engineering approaches to problem solving. However, these traditional concepts are challenged by the uncertainty associated with climate change impacts. Most engineering assumptions and practices that served utility managers in the past can fail when trying to plan for an uncertain future. This chapter includes a detailed discussion on various approaches adopted by utilities all over the world to incorporate the uncertainty into their planning and engineering processes. The chapter includes a discussion on climate change impact assessment and lays out best management practices for arriving at design solutions. Practical planning strategies and adjustments to defining level of service, planning for new infrastructure, and the role of engineering judgment are discussed.

Chapter 5—What Is a Climate Action Plan? defines exactly what a CAP is and is not. Most of the information presented in the previous chapters is relevant to understand

climate change and determine how to apply engineering practice to address climate change impacts. Before the reader embarks upon the journey of developing the CAP, a clear description is required to understand what a cap actually is. The chapter tries to define the impacts that the climate action plan must address and the measure and actions it must include. The chapter also includes a discussion on the tools available to develop and prepare the climate action plans. These tools act as guidance material only and the ultimate responsibility of developing a climate action plan tailored to the utility needs falls on the shoulders of the utility managers.

Chapter 6—Why Do Utilities Need a Climate Action Plan? focuses on a relevant and important question. While it is good to understand the science and pertinent impacts of climate change, utility managers need to ask themselves these questions: *Do we need to develop a climate action plan and if so, to what end? What is the primary purpose of developing a climate action plan and how do we plan to integrate the details of the climate action plan into day-to-day utility operations?* The chapter discusses the key drivers for developing CAPs and the details of evaluating the vulnerability and resiliency of the utility in addressing climate change impacts. The information in this chapter is presented in a practical manner with the help of various examples from events and scenarios driving the development of CAPs for various entities in the United States.

Chapter 7—How Do Utilities Develop a Climate Action Plan and Keep It Current? This key chapter of the manual includes a detailed discussion on how utilities actually develop the CAP. The reader will have enough background information from Chapters 1–6 to understand what it takes to prepare a CAP. By following the information presented in this chapter, the reader can effectively develop a CAP that serves the utility’s needs in the best possible manner. The chapter includes a plan for developing the mitigation and adaptation aspects of the CAP. The discussion about addressing the adaptation measures in the CAP includes assessing vulnerabilities, setting a context for the climate action plan development, selecting adaptation strategies and actions and implementing the climate action plan. Most of the discussion in this chapter is focused on the adaptation measures that are typically included in a CAP as that is the primary focus of the manual. The chapter does discuss mitigation measures but in less detail.

Chapter 8—Stakeholder Involvement and Public Participation is the most important aspect of successful development and implementation of the CAP. The chapter focuses on identifying the key stakeholders, defining the terms and conditions for public participation, encouraging and involving public feedback in the planning process, and developing a detailed plan for communicating and seeking feedback on various plan milestones. Since stakeholders and the public tend to be the consumers, customers, and rate payers of the water utility, it is important to engage them from the beginning of the process.

Chapter 9—Estimating the Cost of a Climate Action Plan is a brief summary of the process of determining the cost associated with the development and implementation of CAPs. Most utilities benefit significantly if appropriate funding sources are available to fund various infrastructure projects. The chapter provides detailed information on the funding sources available for undertaking the process of developing a CAP from the ground up. The chapter also includes a summary of case studies of utilities where CAPs were developed and details of the costs incurred by those entities.

Chapter 10—Case Studies of Climate Action Plans and Adaptation Measures is the most relevant chapter for utilities and readers interested in developing CAPs. Before developing this manual, the authors of spent a significant amount of time conducting gap analysis and research on the available information related to CAPs. While reviewing the information available, the authors compared the information readily available with the intended purpose of this manual to avoid any redundancies and replication of efforts. The summary

of the review process and the information collected in the process of reviewing the case studies is included in the chapter. While the case studies cannot be directly adopted and used by a specific utility, they can serve as reference material and guidance documents while developing a CAP catered to meeting the needs of a specific utility.

Chapter 11—Summary and Conclusions includes a brief discussion of why this manual is important and how this work will be beneficial to water resource managers and utilities in general. There is no bigger concern for utility managers than that of not providing the services intended to be provided by the utility. While many factors impact the ability of a utility to serve their customer needs, no other factor impacts the utility operations in a complex, uncertain, and overwhelming way like climate change does. Already, there are several instances of utilities facing the worst-case impacts driven by climate change and being caught unprepared and off-guard in terms of responding to the impacts of climate change. The impacts of various hurricanes on the East and Southeast coasts of the United States are a very recent example. The staggering impact of the wildfires in California is another example of the overwhelming scale and magnitude of climate change. In the face of uncertainty and the exponential increase in the frequency of extreme events, it seems prudent for utilities to understand the impacts of climate change and their system vulnerabilities and develop a CAP to stay prepared and resilient.

Chapter **1**

Introduction

Addressing the impacts due to climate change on water utilities is a challenge faced by water utility managers on a day-to-day basis. The varied types of impacts due to climate change combined with the variety of system vulnerabilities within a water utility pose challenges for water utility managers. Developing a sound climate action plan (CAP) that addresses the adaptation and mitigation aspects of site-specific climate change impacts is critical to efficient management of water utilities. The purpose of this manual is to provide a comprehensive guidance document to share information on water supply planning and management relating to issues of climate change, both mitigation and adaptation, and to facilitate awareness among water utilities and the broader community on developing and maintaining climate action plans.

The manual provides step-by-step guidance to water utility managers by helping them define the various concerns associated with the impacts of climate change to management of water supplies. Chapter 1 includes a comprehensive summary of the various threats to water utility management due to climate change and the severity of the impact. Chapter 2 includes a brief review on the purpose of the document and its intended audience. Chapter 2 also includes a description of frequently used terms to ensure uniform applicability and understanding of some of the frequently used terms in the field of climate change and water resource management.

Chapter 3 is a detailed review of the science of climate change and it includes a comprehensive summary of the “what,” “why,” and “how” of the climate change dynamics. Chapter 4 connects the science of climate change to the engineering and describes the importance of incorporating the study of impacts of climate change for efficient management of water utilities and water resources. The most elegant way of incorporating the study of climate change impacts into utility management is to develop a CAP. What is a CAP and what constitutes the process of developing a CAP is described in Chapter 5. Chapter 6 makes a very strong case for why developing a CAP is important for effective management of water supplies and water infrastructure. It also talks about the challenges and issues associated with not developing the CAP. Chapter 7 includes a detailed description of the

process of developing the CAP and the steps necessary for preparing a meaningful CAP for any utility. Public participation and stakeholder management are major drivers for developing and implementing a CAP. Chapter 8 covers the details of addressing the issues associated with public and stakeholder participation along with a summary of techniques for improving this approach. Chapter 9 provides a brief summary of the approach for costing the CAPs and an estimate of the effort and budget involved in preparing the CAP. Chapter 10 is a compilation of case studies of CAPs and other resources that are helpful to water utility managers when faced with the challenge of developing a CAP for their utility.

UNDERSTANDING THAT CLIMATE CHANGE IS A REALITY

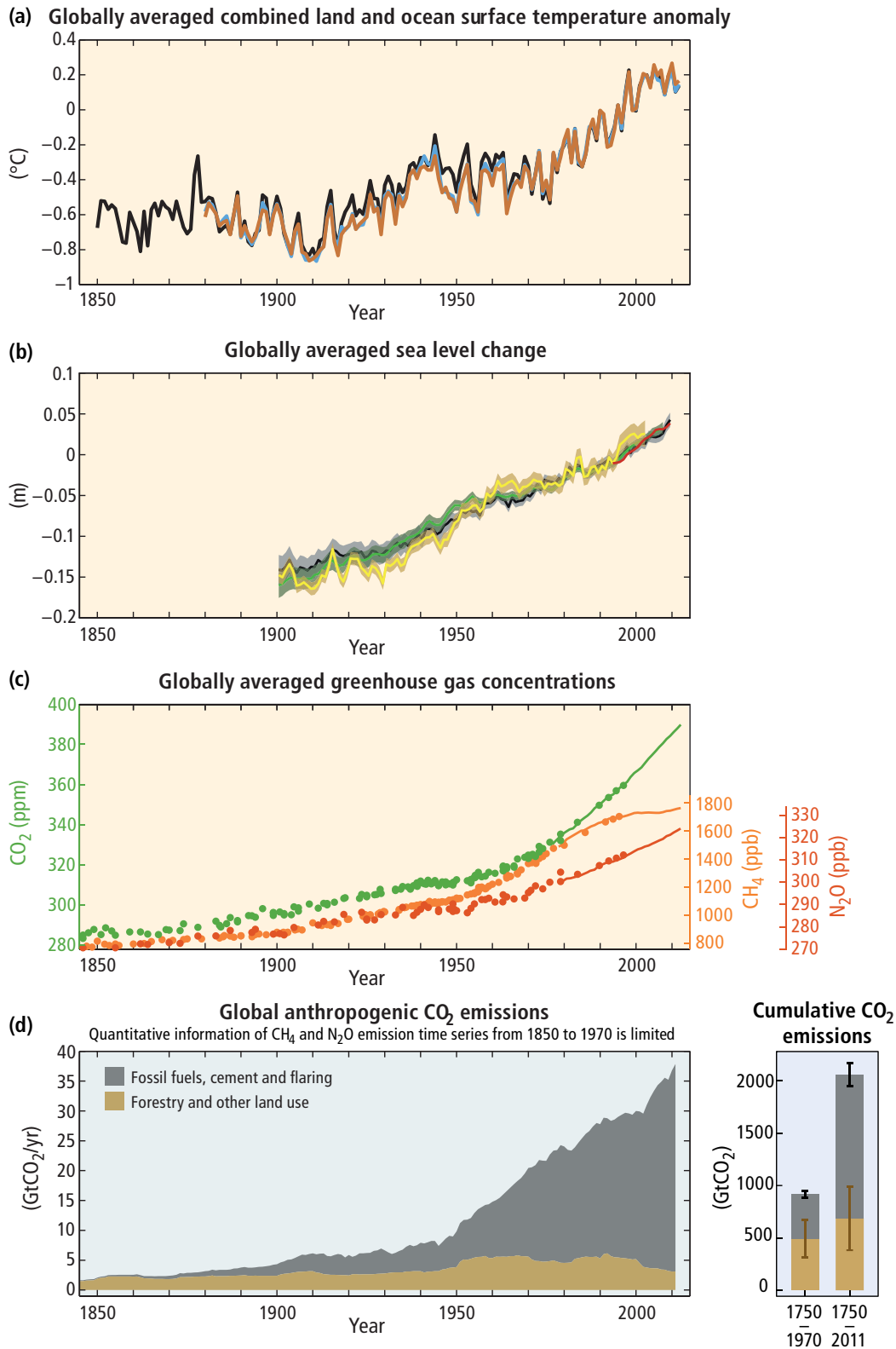
After decades of debate, most scientists and engineers throughout the world have generally accepted climate change as a reality. A report from the United Nations Intergovernmental Panel on Climate Change (IPCC) was released in 2007 (IPCC 2007). Written by a panel of senior scientists from around the world, the report finds the proof of climate change “unequivocal.”

The findings documented in the 2007 IPCC report and the updated 2014 IPCC report substantiate global climate change and conclude that human activities have accelerated most of these observed changes during the past 50 years. The key conclusions of the report are as follows.

1. Warming of the climate system is evidenced by increased global average air and ocean temperatures, increase in greenhouse gases (GHGs), and rising sea level. These changes recorded during the past 85–150 years are documented in the IPCC Report and are shown in Figure 1-1.
2. During the past 100 years, the Earth has warmed by 1.5°F (0.76°C) on average, and the rate of warming has increased over time. The 11 warmest years on record have all occurred in the past 12 years. The latest data show the warmest 17 years on record have all occurred since 2001. (NASA, nd)
3. Rates of observed sea level rise have almost doubled in the past 50 years, increasing from 18 cm per century during 1961–2003 to 31 cm per century during 1993–2003. The concentration of carbon dioxide (CO₂) and other GHGs in the atmosphere have continued to increase because of man-made emissions. Concentrations of CO₂ and methane are at their highest levels in at least 650,000 years.
4. Extreme weather events have increased, and regional climate patterns are changing. Heat waves and other weather extremes, as well as changes in atmospheric circulation patterns, storm tracks, and precipitation, can now be traced back to climate change.

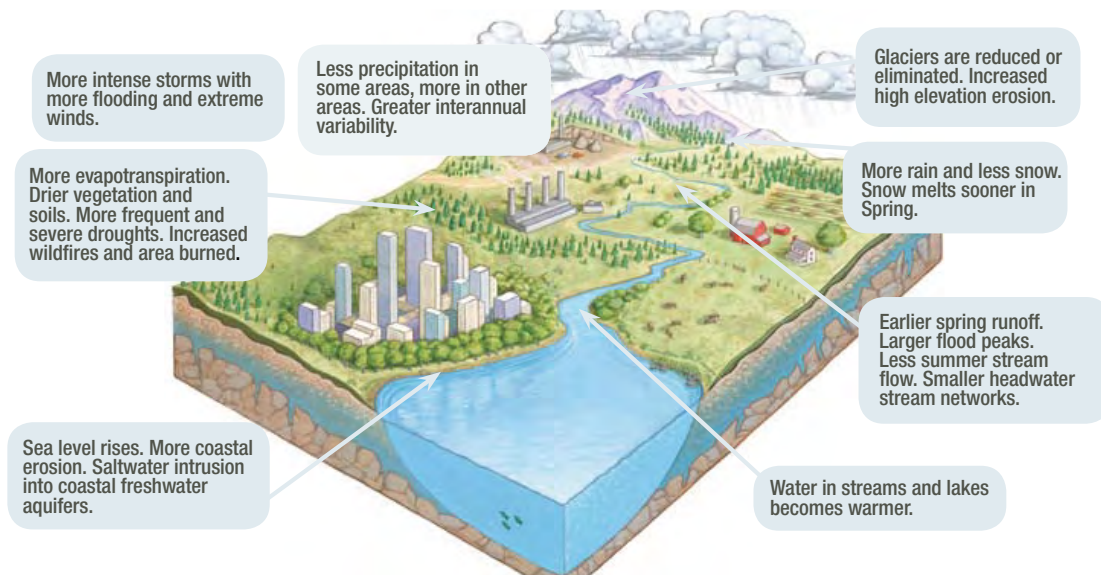
Past climate variability shows that significantly different climate conditions occurred just before the standard hydrologic record, as demonstrated by paleoclimate reconstructions from tree rings or other methods used to understand climate history. Some agencies have begun to use stream flow reconstructions based on tree-ring analysis, and papers have been written to support using this method in decision-making (Rice et al. 2009).

Though the evidence proves the existence of climate change, the entire gamut of effects from such change is not yet fully understood and is difficult to quantify. Figure 1-2 shows a representation of probable future effects of climate change on our water environment. The effects of climate change on our water resources could significantly change the way our resources are managed and how water utility business is conducted.



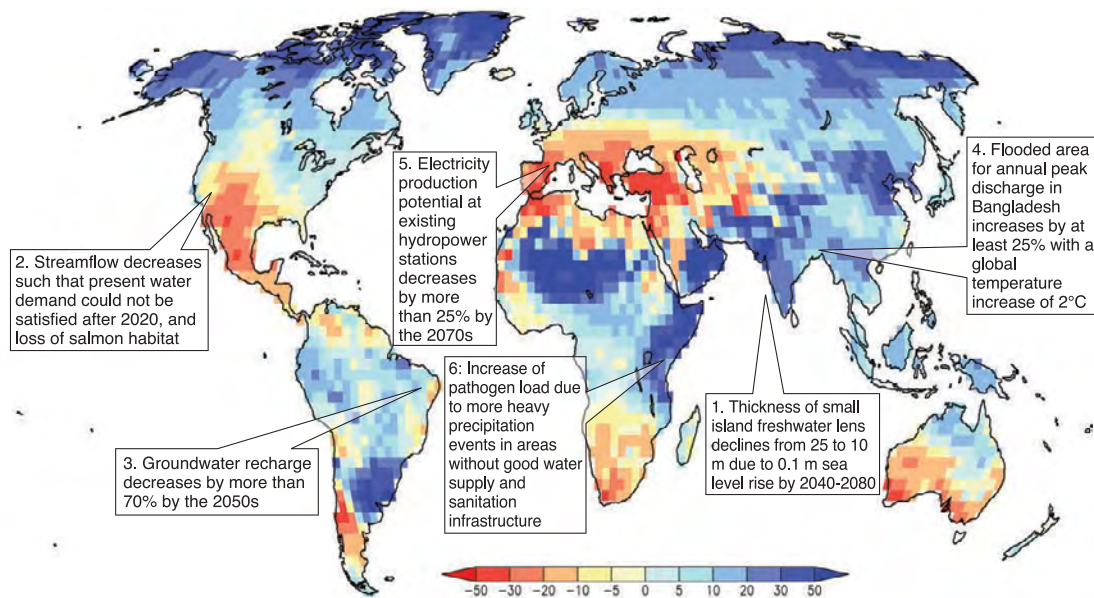
Source: IPCC, 2014: Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change

Figure 1-1 Changes in global average air and ocean temperatures, greenhouse gases (GHGs), and sea level during the past 85–150 years



Source: US Department of Agriculture, FS 908 - Sustaining Healthy Watersheds, June 2008

Figure 1-2 A representation of probable future effects of climate change on our water environment



Source: IPCC, 2007: Climate Change 2007: Synthesis Report. Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change

Figure 1-3 Illustrative map of future climate change impacts on freshwater which are a threat to the sustainable development of the affected regions

APPRECIATING THE POTENTIAL EFFECTS OF CLIMATE CHANGE ON WATER UTILITIES

Scientists and engineers continue to work to define the full scope of effects and timing of climate change on our water resources, which will affect the quantity and quality of water available for potable use, food production, industrial use, power generation, and other vital services. Figure 1-3 shows some predicted climate change effects related to freshwater availability in various regions of the world.

A report prepared by CH2M HILL and the Association of Metropolitan Water Agencies (AMWA) quantified the costs of adaptation for water utilities through 2050 under various climate change scenarios, concluding the costs to be approximately \$325 billion to \$692 billion (CH2M HILL 2009). The Water Research Foundation (WRF), in its research, has broadly categorized climate change effects on water resources as water quantity effects, water quality effects, operational reliability effects, and financial and institutional effects.

Water Quantity Effects

The largest effects of climate change on water resources include changes in temperature and precipitation variability; some areas may receive more precipitation and others much less. These changes are reflected in greatly increased or reduced stream flows, changes in timing and intensity of precipitation, changes in snowmelt quantity and timing of runoff, and changes in aquifer recharge.

Balancing increasing water demand associated with warmer temperatures with reductions in available supply associated with decreased precipitation will be particularly challenging for some suppliers. Unpredictability related to the uncertainty of the types and temporal nature of effects and other complex water resources challenges (e.g., Endangered Species Act, Clean Water Act, Safe Drinking Water Act compliance) are likely to become significant management issues for utilities.

Water Quality Effects

Climate change effects such as increased precipitation intensity could cause changes in sediment and pathogen loading in urban runoff and increase sewer overflows. Temperature changes could cause algal blooms/eutrophication of surface water bodies, changes in watershed vegetation, and changes in growth/migration patterns of invasive species (e.g., quagga mussel, zebra mussel). Saltwater intrusion caused by rising sea levels could threaten the quality of groundwater supplies. Such changes in source water quality can create significant treatment, operational, and budgetary challenges for water utilities.

Operational Reliability Effects

Changes in the quantity and quality of available water supplies could affect operational reliability of water utilities. Optimization of water supplies could require increased monitoring in conjunction with other control techniques such as water conservation/demand management, recycling and reuse of water as well as the use of nonpotable supplies, and the greater uptake of non-climate-dependent supply sources such as seawater desalination. Offsetting reduced surface water supplies with increased groundwater pumping could result in lowering of the groundwater table. A lowered groundwater table could in turn cause soil drying, subsidence issues, and settling and an associated increase in pipe breakage and water loss. Saltwater intrusion will increase pipe corrosion in affected areas and may force utilities to implement expensive groundwater treatment and/or create hydrologic barriers to prevent saltwater intrusion. Growth of invasive species may cause complex operations and maintenance issues in addition to further reducing available supplies by outcompeting native species with lower water consumption requirements (also, increased ambient temperatures may have implications for sewer corrosion rates and treatment processes).

Utility managers will likely need to invest more time and money in understanding the extent of possible climate risks and effects to maintain system reliability in the future. The implementation of real-time monitoring technology, along with conjunctive water resources management practices, may become vital to sustaining operations. Additionally, costs associated with protecting infrastructure from effects may be significant.

Financial and Institutional Effects

Effects on water supply quantity, quality, and operational reliability will necessitate changes in utility operations. The projected increase in operational complexity in future years may result in a significant increase in operational costs. Increased infrastructure costs associated with acquiring, conveying, treating, and distributing potable water are also expected to increase. These cost increases will generate a need for increased revenue, and utilities will likely need to develop new rates that reflect the true cost of water under these “new normal” scenarios.

Further, significant population fluctuations associated with en masse migration away from water-scarce areas may necessitate institutional changes to address changing population centers and increased competition for limited resources. Additionally, new regulatory requirements to minimize energy consumption and achieve improved per capita carbon emissions to meet greenhouse gas (GHG) mitigation goals may affect water utility operations in that investments will likely be required to implement more efficient technologies and to develop behind-the-meter renewable energy sources.

Table 1-1 presents a summary of observed/possible effects to water resources from climate change. Although many studies have defined the scope of anticipated climate change effects and a variety of literature is available with investigative study results, significant uncertainty and data gaps also exist that could cause utilities to be ill-prepared to identify and address potential effect scenarios.

CLIMATE CHANGE AND SUSTAINABILITY

Although water utility operations may be sustainable under the relatively short historical record of existing climate conditions, any change to these recorded conditions should be evaluated to determine whether utility operations will continue to be sustainable under the wider variability predicted by current downscaled global climate models. Some degree of variability is inherent in any norm or statistical average. Water utilities typically account for this variability in their planning, allowing them to develop the systems needed to provide for reliable water service. However, projected changes in climate indicate that there could be significant deviations from the historical norm and statistical variability. In other words, future climate conditions are predicted in some circumstances to deviate significantly from recent historical climate conditions, rendering obsolete the analysis of recent historical climate data as a planning tool for water utilities.

A climate change assessment conducted for the State of Washington by the Climate Impact Group (CIG) at the University of Washington ran 20 different general circulation models (GCMs), which are used to forecast future trends in the norm or average climate conditions based on various atmospheric GHG concentration scenarios (CIG 2009). They found that after 50 years, each model projected a range of temperature increases, whereas 70 percent of the models projected a precipitation increase. The projected temperature increases ranged from 1.5 to 4.5°F, and the projected precipitation changes ranged from -4 to +9 percent. In addition, climate change was projected to alter historical patterns for snowpack, storm events, flooding, sea level, and water quality.

These changes will affect water supply sources and yield, water demand, water quality, and infrastructure planning. Each of these changes plays a role in the sustainability of a water supply system. Perhaps the most obvious effects are the surface water supplies. Climate effect studies have been performed for water utilities in the western United States that are dependent on snow-fed sources or are within snow-transient zones. The consistent finding is that as the temperature rises, the snow line rises and snow volume decreases. The result of this shift is that more precipitation falls as rain in the midwinter months and lower flows start earlier in the year and on average are lower during the summer.

Table 1–1 Observed and possible effects of climate change

Observed Effect	Observed/Possible Effect
Increase in atmospheric temperature	Reduction in water availability in basins fed by glaciers that are shrinking, as observed in some cities along the Andes in South America (Ames, 1998; Kaser & Osmaston, 2002)
Increase in surface water temperature	Reduction in dissolved oxygen content, mixing patterns, and self-purification capacity
Sea-level rise	Increase in algal blooms
Shifts in precipitation patterns	Salinization of coastal aquifers
Increase in interannual precipitation variability	Changes in water availability caused by changes in precipitation and other related phenomena (e.g. ground water recharge, evapotranspiration)
Increased evapotranspiration	Increases the difficulty of flood control and reservoir utilization during the flooding season
More frequent and intense extreme events	Water availability reduction
	Salinization of water resources
	Lower ground water level
	Floods affect water quality and water infrastructure integrity, and increase fluvial erosion, which introduces different kinds of pollutants to water resources.
	Droughts affect water availability and water quality

Source: Climate Change and Water, IPCC Technical Paper VI, Intergovernmental Panel on Climate Change, June 2008.

This, in effect, reduces natural available storage and thereby reduces the reliable yield of the supply system. In the Pacific Northwest, this reduction ranges from 4 to 25 percent (CIG 2009). There is also a related shift in the timing of snowmelt, with snow melting earlier in the year, resulting in increased streamflow during the winter and decreased flow during the late spring and fall. This projected trend is significant for water suppliers, who need to provide for the highest water demands during summer months while meeting instream flow requirements during drier months of the year.

Increases in winter precipitation could increase groundwater recharge but could also result in a greater proportion of precipitation running off saturated soils and not percolating into the aquifer. Further, decreased runoff during summer dry periods could result in a net annual reduction in aquifer recharge.

On the demand side of the utility picture, warmer temperatures and drier conditions in summer months, when water demand increases because of outdoor irrigation, would likely result in increased water demands. Water demand forecasts were performed for three major counties in Washington to project the effect of climate change (CIG 2009). The result of this study was that after 50 years, the average annual water demand could increase by 5–12 percent, depending on which GCM was used to forecast temperature and precipitation changes.

Although climate change effects to surface water bodies have been fairly well-studied, there has been much less research on the effect of climate change on groundwater. This is partly attributable to the greater difficulty in measuring groundwater systems. Increases in winter precipitation would, in principle, increase groundwater recharge. However, this increase may be offset by an increase in evaporation associated with warmer temperatures. Further, an increase in precipitation intensity may result in a greater proportion of precipitation running off saturated soils rather than percolating directly to the groundwater basin. These trends, however, are dependent on the geology and soils of the specific watersheds. It is believed that natural effects to groundwater are not as well understood and not as immediate in comparison to surface water effects; however, the direct effects on groundwater are not well-substantiated by research, and effects to major aquifers may be significant. For example, one might consider the relationship between aquifers and surface waters, particularly streams and rivers, which can reduce flows if aquifers are stressed sufficiently.

Climate change effects could also affect the sustainability of some aspects of water supply infrastructure. The most affected utilities would be coastal utilities and those vulnerable to flooding. With an increase in winter precipitation falling as rain, as opposed to snow, coupled with a probable increase in precipitation during the winter months, there will be an increase in flooding risk. Water intake facilities on rivers and facilities in floodplains will be more susceptible to flood damage. To prevent damage, these facilities may have to be armored or possibly relocated. Further, water and wastewater utility infrastructure located in low-lying coastal areas could be affected by rising sea levels and saltwater intrusion, which could result in effects ranging from an increase in corrosion of buried infrastructure to complete inundation.

Water quality is expected to be adversely affected by climate change. More intense and frequent precipitation events may result in increased erosion which could lead to increased turbidity and organic material content in surface waters. This may result in elevated disinfection by-product concentrations in finished water as well as changing filter run times and operating protocols. Also, elevated temperatures can accelerate organic growth rates within water impoundments, thereby lowering filtering rates. However, higher temperatures can be beneficial as they increase filter rates (or run times) in conventional and membrane filters. In addition, higher water temperatures increase chemical reactions. So there might be some benefit in higher temperatures, including better disinfection and possibly less need for chemicals. However, this will likely be offset by more algal growth, which can decrease filter rates. Similarly, if the additional algae and organics are removed before filtration, then chemical costs and sludge will increase. Higher temperatures likely will lead to poorer raw water quality but may increase treatment effectiveness. The net effect of climate change on treatment processes will need to be evaluated locally by each utility.

ADDRESSING CLIMATE CHANGE AND WATER RESOURCES MANAGEMENT

Climate change effects on water resources need to be managed through short- and long-term mitigation and adaptation strategies. These strategies are responses to either mitigate adverse effects or adapt to the “new normal” (changed water resources) conditions. Mitigation refers to actions that may be taken by a water utility to address the causes of potential climate change. For water utilities, mitigation actions may include reducing the carbon footprint of the treatment and distribution system by (1) reducing energy needs, (2) using more energy-efficient transportation, (3) implementing renewable energy sources, and (4) changing business and operational practices.

Adaptation refers to actions and responses that may be taken to address potential effects from climate change. Such responses to anticipated climate change effects may include a new basis for yield analysis of water sources, new water treatment and conveyance designs and standards, different source management and treatment operating rules, development of new infrastructure, enhanced stormwater management practices, increased demand management, innovative water allocation arrangements, and perhaps new water laws and regulations.

Water resources planning and management will require greater focus on risk management, integrated resources planning, and holistic or systems thinking as well as decision-support tools specific to climate change that can be included in integrated modeling systems to manage regional water resources. Such planning requires an understanding of relationships among physical factors, water resources, infrastructure, regulations, and operational practices. Modeling these relationships allows resource managers to evaluate and assess the potential effects of changes in physical factors and identify future utility practices and policies to respond to changing conditions. Figure 1-4 shows the relationship

between climate change effects, effects on water resources, and management responses to address those effects.

Mitigation and Adaptation Techniques

Because the sustainability of our water resources will be influenced by the effects of climate change, it would be prudent for utilities to start thinking about appropriate mitigation and adaptation techniques to tackle upcoming challenges. Adaptation measures will typically be based on specific climate change conditions in the local region, which will require analyzing projected climate conditions to evaluate a specific utility's vulnerabilities. Mitigation measures, on the other hand, may be driven as much by laws and regulations as operational constraints.

Many of the mitigation and adaptation techniques presented in the remainder of the chapter are good practices that most utilities should consider adopting and are discussed in AWWA manuals of practice. However, climate risk and vulnerability should be understood and incorporated into these practices to improve a utility's resiliency to climate threats.

Long-Term Planning for Water Supply and Water Quality

While [AWWA Manual M50, *Water Resources Planning*](#) addresses long-term planning for water supply and water quality, climate change and the consideration of paleoclimate reconstructions are expected to strongly influence variables that in turn can create substantial risks to a water utility's direct operations that must be addressed. Climate change is expected to affect the quantity, quality, timing, and distribution of water available to utilities. Climate change-induced shifts within the hydrologic cycle are expected to pose substantial effects to both the reliability and quality of water supplies.

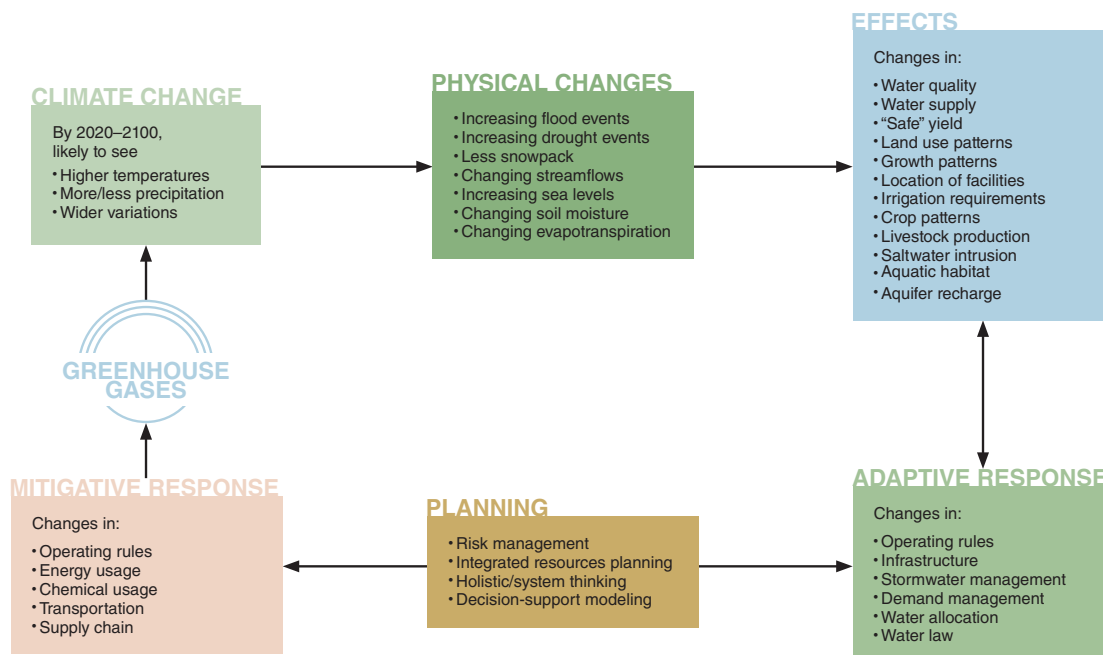


Figure 1-4 Relationship between climate change effects, effects on water resources, and management responses

However, the uncertainties associated with climate change need to be put in the context of multiple uncertainties and vulnerabilities that water utilities deal with on a regular basis, such as growth projections, changes in regulations, changing water consumption patterns, catastrophic events, and financing challenges.

From a water utility's perspective, almost all climate change-induced effects have the potential to severely alter the level of service provided to customers. Although it may not be possible to precisely predict the extent, location, timing, and rate of potential climate change effects, methods exist for developing a range of potential future hydrologic conditions that can help utilities develop flexible and adaptive management strategies. Specialized decision-support methods are also required to enable planners and managers to make long-term decisions given the significant uncertainty in climate projections. Further, long-term plans should be periodically updated based on our evolving understanding of climate change and changing service area conditions for utilities to continue to provide an adequate level of service capable of meeting projected demands well into the future. For more information on long-term planning, please refer to [AWWA Manual M50, *Water Resources Planning*](#).

Water Demand Management Options

Many utilities have already realized the benefits of integrating water demand management into their operations. Demand management techniques such as leak detection and water conservation programs have proven successful for many utilities by postponing the need for infrastructure expansion through reductions in water demands by its customers. Demand management tools, approaches, and techniques can be adapted to a range of local water management conditions. These techniques typically focus on the dual priorities of improving water use efficiency and maximizing the effective reallocation of stored water. Examples of demand management options include

- reducing the quantity of water required to accomplish a specific task or service;
- managing and reducing water quantity system losses from source to tap; and
- shifting peak demand for water so that high water demand periods are attenuated, resulting in a more balanced water demand over a given period.

The unifying principle among the demand management measures is the goal of reducing and controlling water demands and improving water use efficiency. For agricultural zones, a shift to less water-intensive crops or more efficient water delivery and application practices may reduce local demand for water. For urban/suburban areas, controlling outdoor water use may be important to sustaining water resources. Reducing outdoor water use may be accomplished through incentive programs such as cash for grass programs, regulatory controls such as watering restrictions, or conservation rate structures. Long-term controls require an integrated planning approach in which, for example, subdivision controls limit lawn area, and certain irrigation technologies, such as soil moisture sensors, are required for all new development. For utilities, an aggressive loss prevention/leak detection program can yield significant savings in water wasted through distribution system losses and changes in basic operating practices related to maintenance and delivery of water from source to tap. For more information on demand management, refer to [AWWA Manual M52, *Water Conservation Programs—A Planning Manual*](#) and [AWWA Manual M36, *Water Audits and Loss Control Programs*](#).

Operational and Management Controls to Revise Current Utility Operations

Several operational and management controls are available to assist water utilities in responding to predicted effects associated with climate change. Vulnerability analyses can

be undertaken to identify the most urgent priorities in processes in which effects could be most detrimental to a utility's level of service. The changes in operational and management practices may include revision of reservoir operating procedure, drought management rule, or interagency agreements to tackle emergency situations. This may also require educating the customers, applying restrictions on water use type and quantities for large commercial and industrial users, or encouraging use of non-potable or reclaimed water for irrigation and toilet flushing. This will also require utilities to develop forward-thinking rate structures to encourage water conservation while recovering all utility costs, particularly if overall water usage goes down.

Integrated resource planning (IRP) can also be applied to a utility's current and future operations. The IRP approach has been used extensively in the water resource industry and often integrates environmental, socioeconomic, and engineering considerations into water supply planning. These considerations and their interactions are managed to provide maximum flexibility and resiliency within the water supply and distribution system. For more information on the IRP approach, see [AWWA Manual M50, Water Resources Planning](#).

Reduce Carbon Footprint

The primary means for water utilities to reduce their contributions to climate change is to reduce GHG emissions from water utility operations. The Water Research Foundation and the California Urban Water Agencies (CUWA) published a study in 2009 (WRF 2009) that provides comprehensive guidance on standard protocols for quantifying direct and indirect GHG emissions and options to reduce those emissions. The following is drawn from that study.

There are many reasons that water utilities may begin to assess the emissions caused by their operations and to evaluate the projects or actions that may reduce or offset those emissions. These include, but are not limited to, existing and developing regulations requiring inventory and reporting of emissions, developing "carbon tax" and "cap-and-trade" regulation of GHG emissions, stakeholder initiatives demanding action, and environmental stewardship goals.

Suggested procedures for development of an overall climate change strategy for a water utility begin with an estimation of GHG emissions inventory and footprint, as well as the potential effects of climate change on the utility (e.g., a change in source water supply). After the development of an inventory and footprint, potential internal and external projects for mitigation of effects can be identified and assessed. Potential internal project types may include energy efficiency efforts, addition of onsite renewable generation, and fleet management. The breadth of potential external project types is much greater and may include water conservation projects, terrestrial or geologic sequestration, energy efficiency, and many other project types that could be pursued through direct funding or via carbon brokers. After potential project types are identified, an overall reduction strategy can be developed and funding appropriated.

Energy Management

Effective energy management is essentially the process of maximizing efficiency while minimizing energy demand and reducing costs and GHG emissions. It applies to all aspects of business that consume energy including new construction, facility renovations, purchasing activities, operations, and maintenance. Energy efficiency may be the cheapest option and may provide a utility the best return on investment. Certain approaches such as using renewable energy through solar energy, have the potential to greatly reduce the environmental effect and GHG emissions associated with plant operations.

Other approaches target reducing the on-site consumption of energy through improvements to energy-intensive equipment and processes including pumps, motors, lighting, blowers, and aerators. Approaches to limit process energy requirements may include power monitoring, controls, chemical balancing, and other process improvements. As part of an overall energy management strategy, one must understand operational constraints while analyzing existing rate tariffs and comparing them against alternatives.

Although activities such as energy improvement projects or supply-side energy analyses are important aspects of an energy management program, the overall energy and carbon reduction potential is greatly increased when energy becomes a primary consideration in all aspects of operations. As an example, replacement motors or lights might be purchased on a regular basis. Periodically reviewing available options to identify more efficient alternatives may yield significant energy savings over time. Expansion projects and repair and replacement activities provide opportunities to greatly enhance energy performance. By developing a facility-wide energy management initiative and tracking and reporting results on a regular basis, the potential for achieving sustainable energy savings is greatly increased.

Regional Cooperation

Regional cooperation is important when evaluating climate change effects and developing adaptation strategies because the effects will cross multiple jurisdictional boundaries. Regional planning agencies and state water resource agencies are well-positioned to assist in efficiently evaluating climate change impacts to multiple agencies in a coordinated effort. For example, a regional planning agency could work with state or federal agencies to develop revised rainfall frequency analyses and drought frequency analyses that could then be used by multiple agencies, generating consistent planning assumptions across multiple agencies. Similarly, some response actions to buffer climate effects, such as increased raw water storage, may be best developed through a cooperative regional effort. This cooperative effort may be more successful than a localized agency effort in overcoming the challenges of siting and permitting new storage facilities. Adding regional emergency interconnections between water systems can also reduce risk of inadequate supplies during extreme droughts by balancing demands and supplies across a larger pool of sources and users.

Supplemental Water Supplies

For some utilities, management and operational modifications may not be sufficient to address effects to existing supplies, in which case additional supplies will be required to meet demands. In some cases supply augmentation will only be needed occasionally to supplement supplies during severe drought conditions and can be met with short-term solutions, such as purchasing water rights options from agricultural interests or other cooperative agreements. However, other utilities may need to pursue permanent supplies to meet their needs and to maintain the reliability of supply. In either case, significant investment in infrastructure is often required and may take many years to develop. Further, many localities face an array of political and financial constraints that may increase the time and effort required to implement any plan. Given the difficulty in implementing large water-supply projects and the level of uncertainty associated with climate change, utilities may find that increasing their water supply portfolio with several small projects will allow them to diversify supplies and hedge future uncertainties while costing less and being more politically feasible. Drawbacks may include significant increases in complexity of the system, which may require more sophisticated forecasting and planning tools to help

inform decision-makers to optimize operations and meet a diverse range of objectives (e.g., cost, regulatory, public health, environmental).

Increased Awareness

Although water utilities routinely assess threats and vulnerabilities to their systems and source water supplies, it is critical to emphasize the need to include the probabilities and risks associated with water-related climate change effects and the possible range of adaptations available to respond to these changes. Multi-utility and multidisciplinary knowledge is being developed that can help streamline these efforts and provide useful tools for assessing risks and identifying approaches to address climate change effects. The need for increased awareness also extends outside the water industry to include the general public. Planning decisions and mitigation measures driven by effects posed by climate change will affect public policy and budgets. The inclusion of climate change considerations in community and critical water infrastructure planning will require a greater understanding of climate change, its effects, and the costs to adapt to those effects. Difficult climate-related decisions by utilities will be easier to make if there is sufficient political will driven by a well-informed community.

Other Supporting Management Measures

Other management measures supporting climate change adaptation include reducing, reusing, and recycling water and non-climate-dependent sources such as seawater desalination. Water demand reduction can be achieved through water use efficiency techniques applicable to both indoor and outdoor settings. Some of the indoor techniques include high-efficiency toilets and waterless urinals, water-efficient appliances (WaterSense labels on dishwashers, clothes washers), and leak repair. Some of the outdoor techniques include native and drought-resistant plant species selection (xeriscaping); use of artificial grass and efficient watering with drip systems, including generating daily and hourly weather data for use in water management practices; micro misters; and subsurface irrigation systems.

Rainwater capture refers to the collection of rainwater for outdoor irrigation and internal nonpotable uses through the use of cisterns or other storage techniques. Condensation collected from air conditioners and cooling towers could be considered for reuse as well. Rain gardens and green roofs can be established, and rainwater can be diverted or percolated via porous pavement and curb cuts. Gray water reuse involves collecting water that is discharged down interior drains such as sinks and showers, treating it with on-site systems, and reusing it for nonpotable indoor and outdoor uses, such as for toilets and irrigation. Gray water reuse is limited in some areas of the United States by regulations aimed at protecting against potential public health effects associated with reuse of untreated domestic water.

Water reclamation involves reusing treated municipal wastewater (i.e., reclaimed water). Reclaimed water can be used for outdoor irrigation, process cooling, and indoor nonpotable uses such as toilet flushing. In addition, advanced treated recycled water can be used to augment groundwater supplies and establish saltwater intrusion barriers. Reclaimed water is also being used in the United States and abroad to replenish drinking water aquifers and reservoirs (indirect potable reuse). A landmark project in Singapore, the NEWater project, returns treated municipal wastewater for direct use as drinking water (direct potable reuse). As fresh water supplies become increasingly scarce in many parts of the United States and the world, water reclamation should be considered a critical element of a sustainable water supply portfolio. For more information on water reclamation, see [AWWA Manual M24, Planning for the Distribution of Reclaimed Water](#).

There are various challenges and threats posed by climate change and varied options for addressing the threats. The path forward for any utility or entity faced with climate change–related concerns is to develop an entity-specific evaluation of climate change impacts, system vulnerabilities, and available adaptive and mitigation measures to address the threats and vulnerabilities by means of a CAP. The remainder of the manual focuses on the information required to prepare a robust CAP.

REFERENCES

- (AWWA) American Water Works Association. 2019. [M24](#), *Planning for the Distribution of Reclaimed Water*. Denver: AWWA.
- AWWA. 2017. [M50](#), *Water Resources Planning*. Denver: AWWA.
- AWWA. 2017. [M52](#), *Water Conservation Programs—A Planning Manual*. Denver: AWWA.
- AWWA. 2016. [M36](#), *Water Audits and Loss Control Programs*. Denver: AWWA.
- CH2M HILL. 2009. *Confronting Climate Change: An Early Analysis of Water and Wastewater Adaptation Costs*. Association of Metropolitan Water Agencies, 2009. Englewood, Colo: CH2M HILL.
- Huxley, D.E., Bellamy, W.D., Sathyanarayan, P., and Ridens, M. 2009. *Greenhouse Gas Emission Inventory and Management Strategy for Water Utilities*. The Water Research Foundation (formerly AwwaRF) (WRF) and California Urban Water Agencies (CUWA). 2009. Englewood, Colo: CH2M HILL.
- IPCC (Intergovernmental Panel on Climate Change). 2014. *Climate Change 2015: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Core Writing Team, R.K. Pachauri and L.A. Meyer, editors.]. Geneva, Switzerland: IPCC, 151 pp.
- IPCC. 2007. *Climate Change 2007: Synthesis Report. Contribution of Working Groups I, II, and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [Core Writing Team, R.K. Pachauri and A. Reisinger, editors.]. Geneva, Switzerland: IPCC, 104 pp.
- Littell, J.S., Elsner, M.M., Whitely Binder, L.C., and Snover, A.K. 2009. *The Washington Climate Change Impacts Assessment: Evaluating Washington’s Future in a Changing Climate – Executive Summary*. In: *The Washington Climate Change Impacts Assessment: Evaluating Washington’s Future in a Changing Climate*. Seattle: Climate Impacts Group, University of Washington.
- NASA. *Global Climate Change: Vital Signs of the Planet*. climate.nasa.gov/vital-signs/global-temperature/ (accessed Feb. 13, 2020).
- Rice, J.L., Woodhouse, C.A., and Lukas, J. 2009. Science and Decision Making: Water Management and Tree Ring Data in the Western United States. *Journal of American Water Resource Association*. 45(5):1248-1259.
- United State Department of Agriculture (USDA). *Sustainable Watersheds*, June 2008, www.fs.fed.us/kidsclimatechange/products/water-climate-brochure.pdf (accessed April 5, 2020).

Chapter 2

Purpose and Audience

The purpose of this manual is to help water and wastewater utilities plan for the short- and long-term impacts of climate change by guiding them through the development of a climate action plan (CAP). This manual can be used by water utilities, wastewater utilities, consultants, research institutions, academic institutions, and other organizations that may develop a CAP. A CAP may be a stand-alone document or developed as part of a master planning effort. This manual will help the user determine whether a CAP would be beneficial to a utility and identify the appropriate approach to develop it. Each chapter of this manual may be used as an independent resource. The manual also provides case studies that show examples of different approaches to developing a CAP as well as references for additional studies.

This manual presents a proactive voluntary approach to CAP development, which has typically been driven by local government agencies or cities. Additionally, the manual highlights adaptation rather than mitigation as there is already a significant body of work in the scientific and engineering community on the mitigation aspects of climate change.

This manual was developed through voluntary efforts by experts across the United States and around the world. The primary objective was to focus on North America, and the authors have sought to address climate change impacts, responses, and strategies throughout that continent. While the manual focuses on North America, information applicable to other countries is included as well.

DEFINITIONS OF KEY TERMS

Adapt, adaptation: (1) Adjustment in natural or human systems to a new or changing environment that exploits beneficial opportunities or moderates negative effects (NRC 2010a-d). (2) Implementation of measures intended to reduce the vulnerability of natural and/or human systems against actual or expected climate change effects. Various types of adaptation exist, e.g., anticipatory and reactive, private and public, and spontaneous and planned (IPCC 2009).

Adaptive capacity: The ability of a system to adjust to climate change (including climate variability and extremes) to moderate potential damages, to take advantage of opportunities, or to cope with the consequences (NRC 2010a-d).

Conservative estimate: One that provides for the full range in quantity or degree of an impact due to climate change in order to assess the full range of potential consequences, damages, or opportunities.

Mitigation: (1) An intervention to reduce the causes of changes in climate, such as through reducing emissions of greenhouse gases (GHGs) to the atmosphere (NRC 2010a-d). (2) Technological or operational change and/or substitution that reduces the forcing of the climate system (i.e., reduces resource inputs and GHG emissions per unit of output). Although several social, economic, and technological policies would produce an emission reduction, with respect to climate change, mitigation means the *implementation* of technological or operational change and/or substitution to reduce GHG emissions and enhance sinks (IPCC 2007).

Resilience: A capability to anticipate, prepare for, respond to, and recover from significant multi-hazard threats with minimum damage to social well-being, the economy, and the environment (NRC 2010a-d).

Risk: A combination of the magnitude of the potential consequence(s) of climate change impact(s) and the likelihood that the consequence(s) will occur (NRC 2010a-d).

Stationarity: The idea that natural systems fluctuate within an unchanging envelope of variability (NRC 2010a-d).

Uncertainty: Ranges from confidence just short of certain to informed guesses or speculation. Some categories of uncertainty are quantifiable, while other categories cannot be expressed readily in terms of probabilities. Uncertainties arise from such factors as linguistic imprecision, statistical variation, measurement error, variability, approximation, subjective judgment, and disagreement (Schneider et al 2002).

Vulnerability: The degree to which a system is susceptible to, or unable to cope with, adverse effects of climate change, including climate variability and extremes. Vulnerability is a function of the character, magnitude, and rate of climate variation to which a system is exposed, its sensitivity, and its adaptive capacity (NRC 2010a-d).

REFERENCES

- IPCC (Intergovernmental Panel on Climate Change). 2007. *Climate Change 2007: Synthesis Report*. Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, Pachauri, R.K and Reisinger, A., editors]. Geneva, Switzerland: IPCC, 104 pp.
- National Research Council. 2010. "Advancing the Science of Climate Change." Washington, DC: The National Academies Press.
- Schneider, S.H., Rosencranz, A., Niles J.O., editors. 2002. *Climate Change Policy: A Survey*., Washington D.C.: Island Press. https://stephenschneider.stanford.edu/Publications/PDF_Papers/Ch02ClimatePolicy.pdf (accessed April 5, 2020).

Chapter **3**

Science of Climate Change

Climate change is such a broad topic that it is easy to get lost in the available literature if one does not narrow the focus. This chapter reviews the literature on the science of climate change and summarizes the information relevant to hydrological impacts.

CLIMATE CHANGE AND CLIMATE VARIABILITY

Climate change is not just “changing weather.” *Weather* refers to atmospheric conditions at a specific location at a given point in time (NWS Glossary, n.d.). In contrast, climate is defined as regional weather conditions averaged across a period of years (NWS Climate Prediction Center, n.d.). Generally speaking, climate is the statistical distribution of weather over the long term, typically interpreted as at least 30 years. Climate change refers to a change in the statistical distribution—the state of the climate—over decades.

Over millennia, the climate has varied due to natural forcings, such as volcanic eruptions and changes in solar irradiance. Patterns of internal climate variability occur due to the exchange of heat, water, energy, and gases between the atmosphere, ocean, cryosphere, and land surface. For example, the El Niño–Southern Oscillation (ENSO) is a multiyear pattern created by fluctuating sea surface temperature anomalies in the Pacific Ocean. ENSO directly influences storm tracks, temperature, and other weather events across the globe (NOAA’s El Niño Portal 2015). Other modes of variability include high- and low-frequency phenomena like the Pacific Decadal Oscillation (PDO), the North Pacific Oscillation (NPO), the North Pacific Gyre Oscillation (NPGO), the North Atlantic Oscillation (NAO), the Madden-Julian Oscillation (MJO), Atlantic Multidecadal Oscillation (AMO), and the Indian Ocean Dipole (IOD).

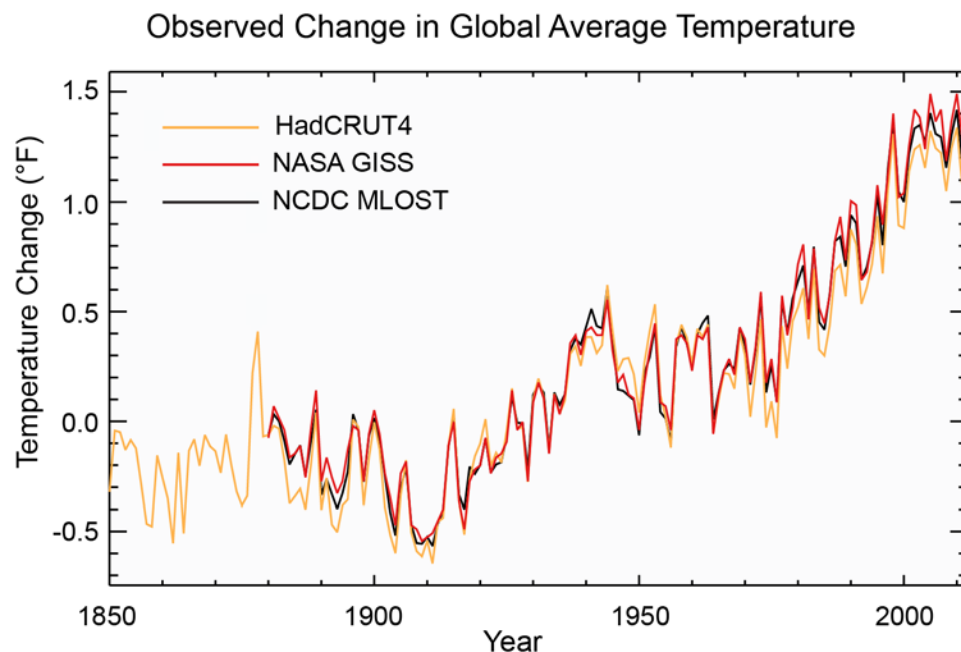
At regional scales and short time periods, internal climate variability can dominate climate (Melillo et al. 2014). For example, La Niña (the cool phase of ENSO) can still occur

even though global average temperatures are increasing due to climate change. Such climate variability will continue to modify the pace of climate change in regions like the Pacific Northwest of the United States for the next several decades (Abatzoglou et al. 2014). These processes will continue to drive seasonal and interannual changes in temperature and precipitation and can magnify or moderate the effects of long-term climate trends in a given region.

Although these natural modes of variability dominate in the short term, external forcings on the climate system in the form of anthropogenic greenhouse gas (GHG) emissions are the primary cause of current global warming. Atmospheric concentrations of GHGs such as carbon dioxide, methane, and nitrous oxide have increased since the pre-industrial era, driven largely by economic and population growth (IPCC 2000). The heat-trapping effects of these GHGs, together with the impact of other human activities (like deforestation) have been detected throughout the climate system and are extremely likely to have been the dominant cause of the observed warming since the mid-20th century (IPCC 2000). Figure 3-1 illustrates the change in global temperature records over the last century. Though temperatures fluctuate year to year, it is clear that the average global temperature has increased over the past century.

GLOBAL CLIMATE MODELS AND GREENHOUSE GAS EMISSIONS

To project how GHG emissions and other anthropogenic forcings will affect the climate system, climate scientists use atmosphere–ocean general circulation models (AOGCMs) or general circulation models (GCMs). The AOGCMs/GCMs are three-dimensional, computer-based mathematical representations of atmospheric, oceanic, and land surface



Source: Peter Thorne, Nansen Environmental and Remote Sensing Center; adapted by Third National Climate Assessment, 2014
 HadCRUT4—Global Temperature Dataset developed by Climate Research Unit and Hadley Center (United Kingdom), NASA GISS—National Aeronautics and Space Administration Goddard Institute for Space Studies, NCDC MLOST—National Oceanic and Atmospheric Administration Merged Land-Ocean Surface Temperature Analysis

Figure 3-1 Observed change in global average temperatures from three global surface temperature records

processes based on the fundamental laws of physics and mathematical discretizations that resolve atmospheric and oceanic processes (IPCC 2007). GCMs typically divide the globe into grid cells of around 100–200 km² and are able to simulate certain physical parameters well at each grid cell, but other processes that occur at finer scales often need to be parameterized or estimated (e.g., clouds, aerosols, thunderstorms). Over recent decades, GCMs have become better able to simulate Earth's observed climate, including temperature, precipitation, radiation, wind, ocean temperatures, ocean currents, and sea ice cover (IPCC 2007).

To project future conditions, GCMs are “forced” with different boundary conditions; in particular, GHG emissions scenarios. Emissions scenarios are developed by the Intergovernmental Panel on Climate Change (IPCC). Currently, two different types of future emissions scenarios are widely used in the global climate modeling community.

The first category of scenarios comes from the Special Report on Emissions Scenarios (SRES; IPCC 2000). These scenarios were used in the IPCC Third Assessment Report (TAR) published in 2001, and in the IPCC Fourth Assessment Report (AR4) published in 2007. The SRES represent different future global economic, technological, or population storylines (IPCC 2000).

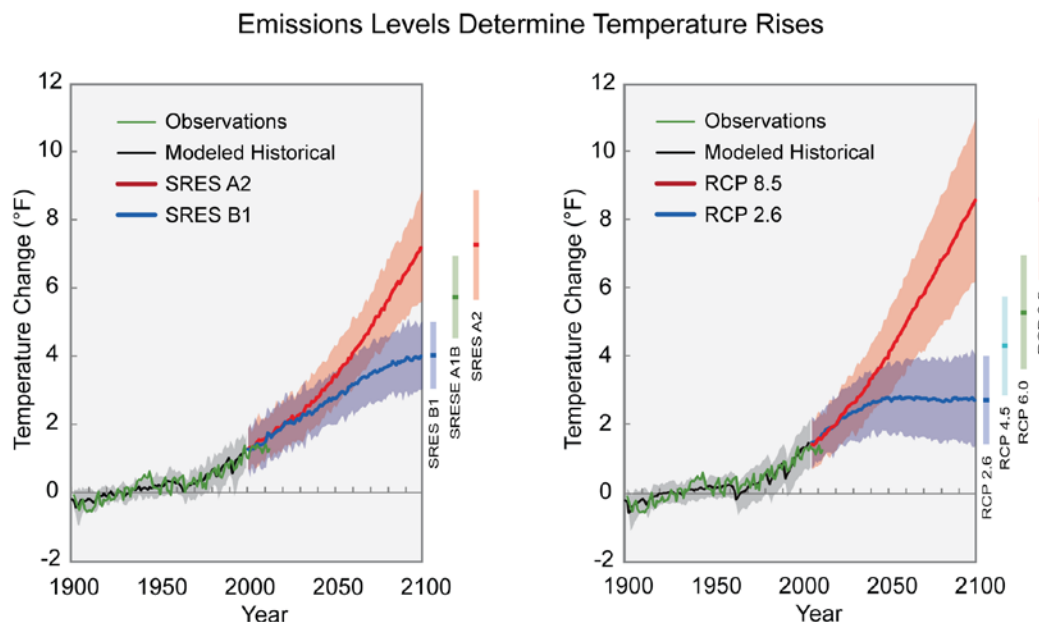
More recently, Representative Concentration Pathways (RCPs) were used in the 2014 IPCC Fifth Assessment Report to quantify the amount of future solar radiative forcing. The four RCPs represent a broad range of climate outcomes: stringent GHG mitigation scenario (RCP2.6) in which emissions decrease before mid-century and the change in global temperature above pre-industrial levels is kept below 2°C; two intermediate GHG scenarios (RCP4.5 and RCP6.0) where emissions stabilize and then decrease by mid-century or increase through mid-century but then decrease by late-century, respectively; and one scenario with very high GHG emissions that increase through the end of the century (RCP8.5). RCP 8.5 is considered similar to a continuation of the current path of global emissions increases in the absence of significant reductions in global GHGs (Melillo et al. 2014). These pathways are shown in Figure 3-2.

The SRES were applied to “force” the generation of GCMs from the Coupled Model Intercomparison Project 3 (CMIP3) that were used for IPCC AR4, and the RCPs were used more recently in the Coupled Model Intercomparison Project 5 (CMIP5) model runs for the IPCC Fifth Assessment Report. CMIP is a program of standardized global model experiments and comparisons (WCRP 2015) that include experiments from several “families” of climate models—models that were developed by the same scientific institution or modeling research center. The CMIP models include an ensemble of more than forty different models, several of which are from the same family.

GLOBAL CLIMATE MODEL PROJECTIONS AND ASSUMPTIONS

Though GCMs provide credible quantitative estimates of future climate change, particularly at continental and global scales, there is still uncertainty within the models. One source of uncertainty is the quantity of future emissions—generally the choice of emissions scenarios becomes more important toward the end of this century (Northrop and Chandler 2014) when different emissions choices lead to diverging warming projections. The choice of emissions scenario can significantly impact the model's future temperature and precipitation projections.

Another key assumption is that a model's ability to simulate observed climate indicates the model's ability to project future climate. This cannot be proven, especially because the reliability of future projections does not account for positive or negative feedbacks in the climate system that could change future outcomes. The climate is a chaotic system: small changes in physical processes in one part of the climate system can have significant



Source: Melillo et al. 2014

RCP—Representative Concentration Pathways, SRES—Special Report on Emissions Scenarios

Figure 3-2 Emissions levels using SRES or RCP scenarios determine the amount of global temperature change

Notes:

Observations: temperature observations.

Modeled historical: Temperature change modeled using climate models for a historical period of 1900 to early 2000s. Values in this plot represent an average of all climate models.

RCP 8.5: Temperature change modeled using climate models for a future period from 2020–2100. A worst-case greenhouse gas emission scenario represented by RCP 8.5 is used to represent future socioeconomic conditions.

RCP 2.6: Temperature change modeled using climate models for a future period from 2020–2100. A best-case greenhouse gas emission scenario represented by RCP 8.5 is used to represent future socioeconomic conditions.

impacts on another part of the climate system. Because there is no way to experiment with the Earth's climate in a laboratory, scientists do not know for sure if a model's performance in replicating historical climate is a perfect indication of its ability to project future climate.

Furthermore, climate models are not probabilistic—they cannot predict the future definitely, and no single model provides a more likely prediction than another. Instead, models project a range of plausible different futures. Using a different model will yield different results. Because individual models have different strengths and weaknesses, it is best to use a suite of climate models to bracket a broader range of future projections. Scientists have also evaluated model performance in certain regions of the United States based on how accurately they reproduced temporal and spatial statistics of 20th century observed climate, and then ranked models relative to one another according to the set of performance metrics considered (Rupp et al. 2013).

Despite these uncertainties and assumptions, GCMs still offer the most scientifically robust approach to projecting future climate. Additional modeling efforts localize large-scale GCMs to yield projections that are more relevant to water utility planning. See Chapter 4 of this manual for more information on modeling and downscaling.

The following online resources provide more information on the scientific basis of climate change and GCMs:

- Climate Change 2013: The Physical Science Basis. Fifth Assessment Report Working Group 1 (IPCC 2013)

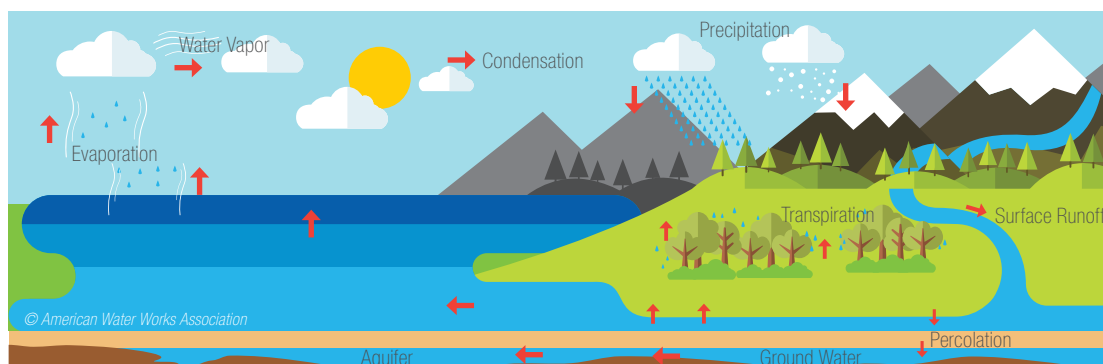
- Climate Change Evidence & Causes: An Overview From the Royal Society and the US National Academy of Sciences (2014)
- Climate Models: An Assessment of Strengths and Limitations, US Climate Change Science Program, Synthesis and Assessment Product 3.1 (2008)
- COMET MetED: Introduction to Climate Models
- US Global Change Research Program Third National Climate Assessment (2014)

CLIMATE CHANGE AND THE HYDROLOGIC CYCLE

How does a warming climate affect water utilities? Climate is a key driver of the water cycle and influences the timing, intensity, seasonality, and spatial distribution of water resources. Figure 3-3 illustrates how surface flow, runoff, snowmelt, infiltration, and groundwater flow are affected by climatic processes such as evaporation, precipitation, and condensation. A warmer atmosphere can hold more moisture, so water vapor acts as a GHG in the atmosphere, creating a positive feedback loop where more water vapor leads to more warming (The Royal Society and National Academy of Sciences 2014), compounding the warming effect of adding more GHGs to the atmosphere.

Warming is already leading to an intensification of the water cycle across North America. Hydrologic impacts from climate change include an increase in the frequency and intensity of storms and heavy rain events; changes in seasonal precipitation patterns; increased likelihood of flood events; reduced snowfall and snowpack; earlier snowmelt runoff; sea level rise; saltwater intrusion of coastal aquifers; decreased groundwater recharge and availability; decreased soil moisture; intensification of droughts; and deteriorating water quality due to increases in water temperature, nutrients, sediment, and pollutants (Melillo et al. 2014). These shifts in the water cycle have consequences for the reliability of water supplies and water quality for drinking water systems and the management of stormwater and wastewater systems.

Many of the impacts noted previously have already been observed and are expected to become more pronounced as climate warming continues. However, impacts will differ by region and type of water system. Local changes in climate can be very different from global projections. Critically, changes in climate and changes in hydrology are not always linearly connected—even small changes in average climate can produce large changes in extremes, according to paleohydrologic studies (Milly et al. 2008).



Source: DrinkTap.org

Figure 3-3 The water cycle

From Static to Dynamic Systems

In his book *Living With Water Scarcity*, David Zetland states that “climate change will increase the rate of assumption failure” (2014). This captures one of the main challenges that climate change presents to water utilities: how to plan within the context of a more uncertain future climate, where past is no longer prologue.

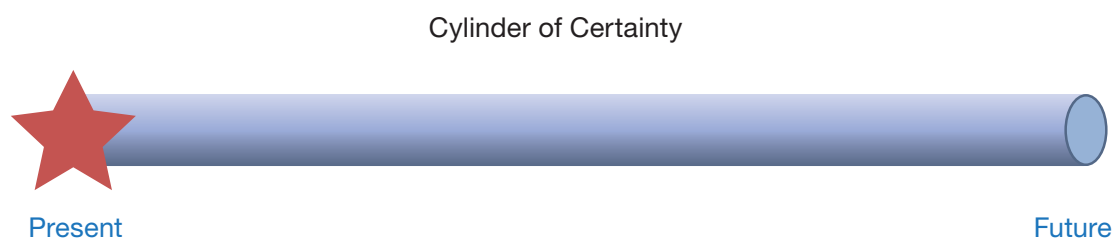
Water utilities have traditionally assumed some level of stationarity in short and long-term planning. Historical hydrology data and time series are considered sufficient representations of what to expect in the future. This approach assumes the average, extremes, and variability of climate and hydrology will not significantly differ in the future and is illustrated by a “cylinder of certainty” as shown in Figure 3-4.

But the science of climate change suggests that the assumption of a static climate and hydrology may be limited. Climate change is shifting conditions beyond the historical variability that water utilities have observed. Of concern to water managers is that climate change “threatens to make this variability greater, shifting and intensifying the extremes, and introducing greater uncertainty in the quantity and quality of supply over the long term” (Grayman et al. 2012).

The bell-curve distribution of historical “normal” climate in Figure 3-5 illustrates how the distribution of weather or climate is centered around average events which are the most likely to occur, but the climate system also infrequently experiences extreme events at each tail of the distribution (e.g., extreme storms, floods, hurricanes, or droughts). Many water utilities have traditionally planned within the historical range; however, climate change is shifting the entire distribution curve (Figure 3-5). Historical extremes will become the new “normal” conditions, and a set of new extremes will emerge. This does not indicate a shift from one static state to another, but rather a continuous change over time as the climate continues to shift and increase in variability.

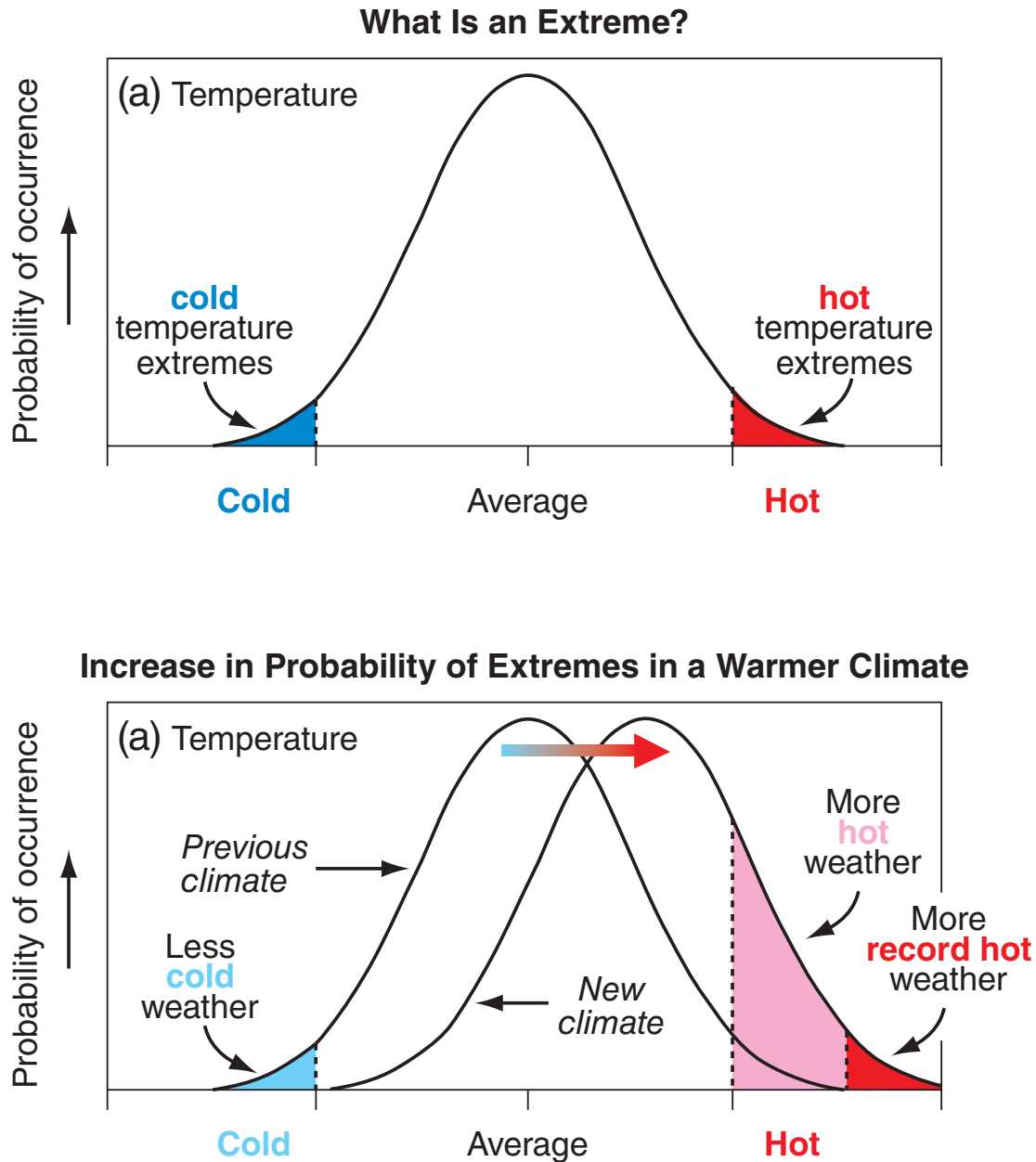
These shifts in the distribution of both weather and climate will create a nonlinear climate and hydrologic system where small changes in the main drivers of the water balance—temperature, evapotranspiration, and precipitation—could lead to cascading impacts on peak runoff, snowpack, stream temperature, and other hydrologic conditions. Water utilities may no longer be able to rely on observed or historical weather to design and plan infrastructure and water supplies. Instead, utilities will need to think more dynamically about their systems in order to incorporate future climate uncertainty into planning.

Therefore, while climate modeling helps identify a spectrum of future changes, there is no way to know how accurate climate model projections will be. Water utilities may consider a range of plausible climate futures, depicted as the “cone of uncertainty” in Figure 3-6.



Source: Adapted from L. Kaatz, Denver Water, 2015

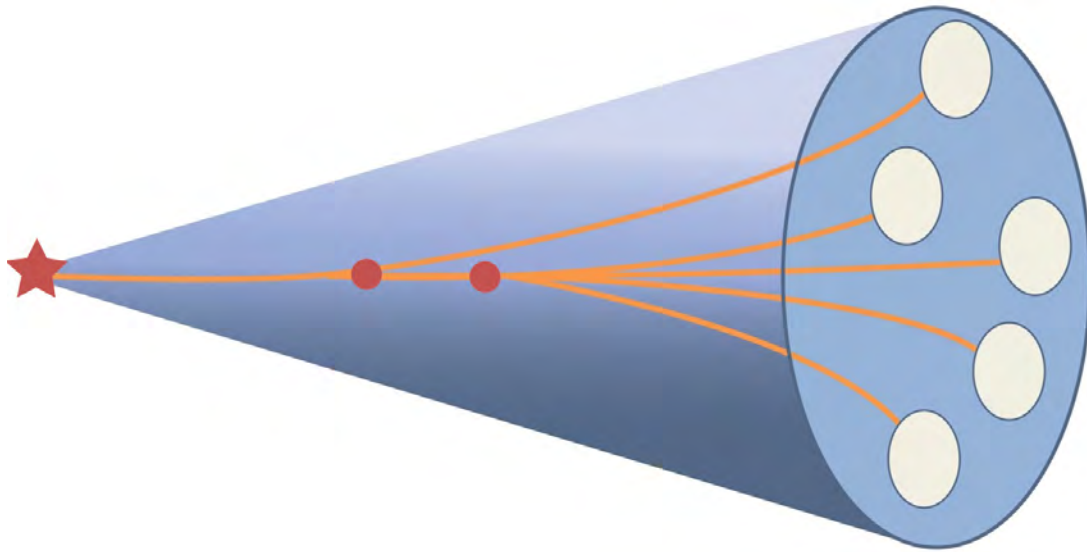
Figure 3-4 The “cylinder of certainty” illustrates how future conditions will be the same as present or past conditions



Source: IPCC 2001, Figure 2.32 of Climate Change 2001: The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change

Figure 3-5 "Normal" or historical weather distribution (top); how climate change is expected to shift the distribution of weather and climate (bottom)

While Chapter 4 provides more information about changing engineering practices in light of increased climate variability, water planners will find it helpful to first understand projected local climate change impacts on the vulnerability of specific water systems. The next two sections summarize key regional impact information and considerations for assessing the vulnerability of a specific system.



Source: Stratus Consulting & Denver Water 2015; adapted from L. Kaatz, Denver Water, 2015

Figure 3-6 The “cone of uncertainty” illustrates the concept of planning for multiple futures, in contrast to the “cylinder of certainty”

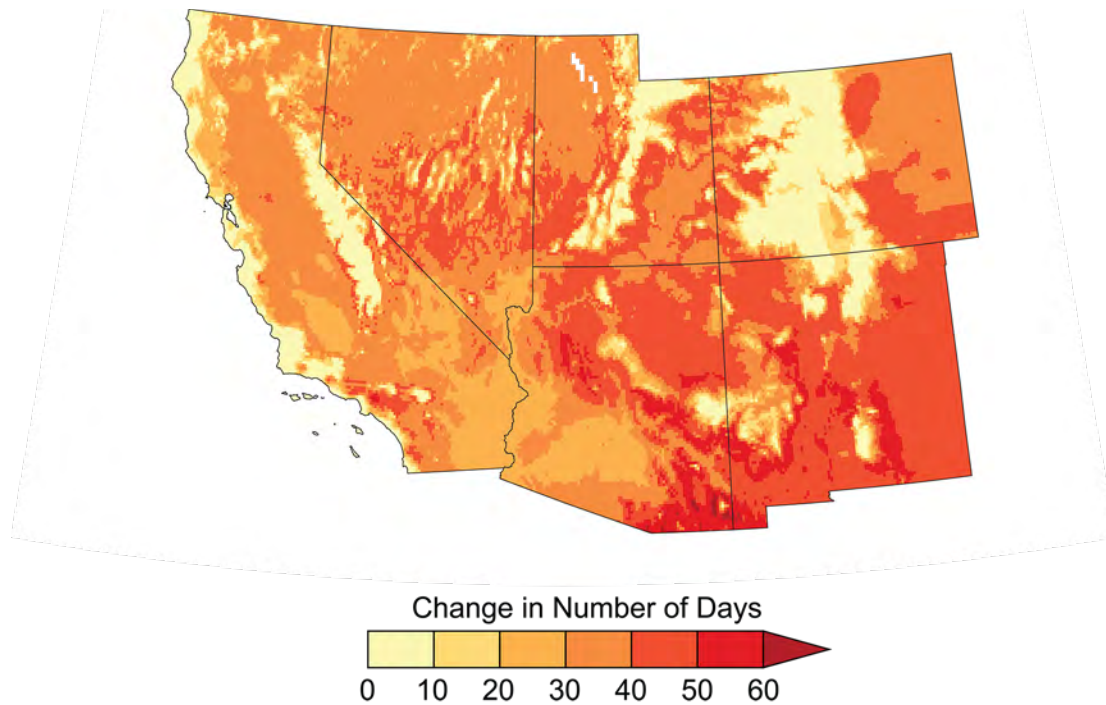
REGIONAL HYDROLOGIC IMPACTS OF CLIMATE CHANGE

This section highlights how climate change will impact hydrologic systems across different regions of North America. Specific summaries are provided for several regions of the United States, and broader summaries for Canada and Mexico. These summaries are not comprehensive, but they describe the general trends that are anticipated to affect water resources across most regions of North America. The resources listed at the end of this section provide additional information on regional climate impacts.

Southwestern United States

The southwestern region of the United States comprises the states of Arizona, California, Colorado, Nevada, New Mexico, and Utah. It is the hottest and driest region of the United States, where the availability of water has defined the region’s landscapes, economy, and history of human settlement. The Southwest experienced its warmest decade from 2001 to 2010, with fewer cold air outbreaks, more heat waves, and temperatures almost 2°F higher than historical averages (Hoerling et al. 2013). Regional annual average temperatures are projected to rise due to climate change, with the greatest increases in the summer and fall months.

In contrast, precipitation trends vary considerably across the Southwest, with some areas experiencing decreases and others experiencing increases. Projections of precipitation changes are less certain than those of temperature (Kunkel et al. 2013a, Cayan et al. 2013). But seasonal changes, such as reduced winter and spring precipitation, are consistently projected for the southern areas of the Southwest by 2100. In the northern areas of the region, seasonal precipitation changes are smaller than natural variations (Kunkel et al. 2013b). Flooding may intensify in Southwest regions, even in areas where total precipitation is projected to decline. An increase in winter flood hazard risk in rivers is projected due to increases in flows of atmospheric moisture into California’s coastal ranges and the Sierra Nevada (Dettinger 2011, Dettinger et al. 2011).



Source: US Global Change Research Program 2019, as adapted from Voss et al. 2017.

Figure 3-7 US drought monitor map of California for April 2019

Variability and uncertainty are the dominant characteristics of Southwest water resources. Geographic variation and unpredictable precipitation make it challenging to manage water needs. For example, California's water resources vary dramatically across the state because of extreme differences in precipitation (Dettinger 2011). Figure 3-7 shows that more than two-thirds of California is under the threat of "extreme" or "exceptional" drought due to a combination of lack of rainfall, lack of snowpack, and high temperatures. Climate change is expected to cause droughts and water supply challenges in California and other parts of the Southwest. Snow is a main source of water supply, but warmer temperatures are already causing more precipitation to fall as rain rather than snow (CDM 2011). This is leading to earlier spring snowmelt and runoff and decreasing surface water supply reliability.

The Southwest is historically prone to drought, and paleoclimate records show severe mega-droughts at least 50 years long (Cook et al. 2010; Meko et al. 2007; Routson et al. 2011). However, future droughts are projected to be substantially hotter. For major river basins, such as the Colorado River Basin and other parts of the region, drought is projected to become more frequent, intense, and longer lasting than in the historical record (Cayan et al. 2013), essentially intensifying with climate change. Climate change is also expected to affect water demand, groundwater withdrawals, and aquifer recharge, reducing groundwater availability in some areas of the region.

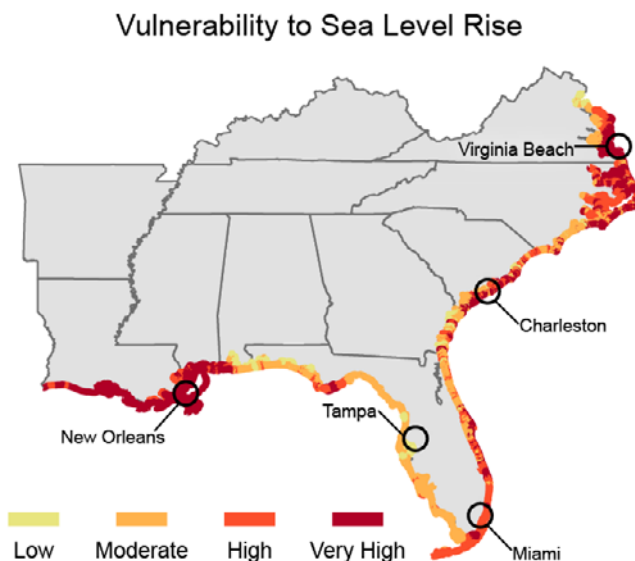
Additionally, regional Pacific Ocean sea level rise, extreme high tides, and storm surges are projected to affect California's coastal cities and infrastructure. Flooding and erosion in coastal areas is already occurring even at existing sea levels. Future sea level rise could increase the salinity of coastal aquifers in the state.

Southeastern United States and Caribbean

The southeastern United States and Caribbean region includes the states of Arkansas, Louisiana, Kentucky, West Virginia, Virginia, North Carolina, South Carolina, Kentucky, Tennessee, Mississippi, Alabama, Georgia, and Florida, as well as Puerto Rico and the US Virgin Islands. The region encompasses the Appalachian Mountains and the coastal plains, so the geographic distribution of climate impacts and vulnerabilities depends on location (Melillo et al. 2014). However, there are several common impacts that will affect large parts of the region. Future temperature rise is expected to cause significant increases in the number of hot days (95°F or above) and decreases in freezing events. Higher temperatures are also expected to increase harmful blooms of algae and several disease-causing agents in inland and coastal waters. The region is exceptionally vulnerable to sea level rise, extreme heat events, hurricanes, and decreased water availability due to projected climate change (Melillo et al. 2014). The number of Category 4 and 5 hurricanes in the North Atlantic and the amount of rain falling in very heavy precipitation events have increased over recent decades, and further increases are projected (Melillo et al. 2014).

The region, home to more than 80 million people, includes some of the fastest-growing metropolitan areas in the United States. Cities and water supplies along the Atlantic seaboard and Gulf Coasts are vulnerable to the impacts of regional sea level rise and storm surge, as shown in Figure 3-8. New Orleans—with roughly half of its population below sea level—and other major cities such as Miami, Tampa, Charleston, and Virginia Beach are among those at risk. Furthermore, as a result of current sea level rise, the coastline of Puerto Rico around Rincón is being eroded at a rate of 3.3 feet per year. Puerto Rico has one of the highest population densities in the world, with 56 percent of the population living in coastal municipalities. Sea level rise and storm surge can have impacts far beyond the area directly affected.

Freshwater supplies from rivers, streams, and groundwater sources near the coast, especially porous aquifers, are also at risk of accelerated saltwater intrusion due to higher sea levels. Some cities have had to abandon their drinking water wells due to the effects of saltwater (Melillo et al. 2014).



Source: US Global Change Research Program 2014

Figure 3-8 Vulnerability to sea level rise in the southeastern United States

In the future, several stressors are expected to reduce the availability of water in the Southeast. These include continued urban development, irrigated agriculture, and an increase in evaporative losses due to higher temperatures. Many small Caribbean islands are also likely to face severe water stress (Melillo et al. 2014).

The Midwest and Great Lakes

The Midwest and Great Lakes states of Minnesota, Wisconsin, Michigan, Ohio, Indiana, Illinois, Iowa, and Missouri are vulnerable to climate change. Direct effects will include increased heat, flooding, drought, and late spring freezes. Water quality impacts are a major concern in the region, in the form of increased watershed pollutants and toxic algal blooms due to higher temperatures and extreme weather events. Many cities have aging infrastructure and are particularly vulnerable to flooding. Heavy downpours have increased in the region, resulting in the discharge of untreated sewage into combined sewage–overflow systems in a number of Midwestern cities (Melillo et al. 2014). The region has previously experienced waterborne disease outbreaks due to drinking water source contamination from heavy precipitation and failing infrastructure (Patz et al. 2008). Extreme rainfall events and flooding due to climate change could exacerbate water quality challenges, cause erosion, and damage infrastructure. In particular, climate change risks to large water supplies like the Great Lakes, a source of drinking water for 40 million people (Alliance for the Great Lakes 2015), could manifest in harmful blooms of algae, declining beach health, and more invasive species.

The Great Plains

The Great Plains states—Wyoming, Texas, Oklahoma, Nebraska, Kansas, North Dakota, South Dakota, and eastern Montana—experience a diverse climate due to the region’s large north–south spread and elevational gradient extending from sea level to the Continental Divide. Climate change impacts will therefore differ across the region.

Historically, the region has observed maximum temperatures of 95°F to 100°F over seven days or more on average. Continued warming means that these high temperatures are expected to occur much more frequently (Melillo et al. 2014). Seasonal winter and spring precipitation is projected to increase in the northern states. The central states are expected to experience small changes in summer and fall precipitation, with Texas and Oklahoma projected to suffer longer dry spells by mid-century. The frequency of heavy precipitation in the northern states is projected to increase by mid-century (Melillo et al. 2014).

Climate change will stress water resources in the region due to higher temperatures, more dry days and heat waves, increased drought frequency and intensity, and increased evaporation rates. Anticipated sea level rise along the Texas Gulf Coast will increase the risk of damage from storm surges in an area already prone to hurricanes and tropical storms (Melillo et al. 2014).

Northeastern United States

In the past several decades, the Northeastern states of Maine, New Hampshire, Vermont, Massachusetts, Rhode Island, Connecticut, New York, New Jersey, Pennsylvania, and Maryland have experienced higher temperatures and more extreme weather events. These changes are expected to escalate by the end of the century. Climate projections indicate that Northeast temperatures will rise by 2.5°F (1.4°C) to 4°F (2.2°C) in winter and by 1.5°F (0.8°C) to 3.5°F (1.9°C) in summer (Frumhoff et al. 2007). The number of days that exceed 90°F and the amount of precipitation are expected to continue to increase in the region (Frumhoff et al. 2007).

Unlike other regions of the United States where no clear change in annual precipitation is expected, the annual average precipitation in the Northeast is projected to increase between 7 and 14 percent by 2100. An 8 to 9 percent increase in precipitation intensity is projected by mid-century, climbing to 10 to 15 percent by the end of the century (Frumhoff et al. 2007). Heavy precipitation, defined as more than 2 inches of rain falling within 48 hours, is also expected to increase in both intensity and frequency, with the number of heavy precipitation events increasing by 8 percent by mid-century and 12 to 13 percent by the end of the century (Frumhoff et al. 2007). Precipitation changes affect the replenishment of groundwater supplies when soil becomes oversaturated, causing heavy rainfall to run off as surface flow rather than infiltrating into the soil. These conditions can cause outbreaks of waterborne diseases, as high soil saturation conditions increase the transportation of microbial organisms (Currerio et al. 2001). Coupled with projected sea level rise, the surge in precipitation frequency and intensity is anticipated to increase the risk of severe flooding events in this region. The US Environmental Protection Agency (USEPA) estimates that by the end of this century, New York City may experience a 100-year flood every 10 to 22 years (USEPA 2016).

As in other regions, rising temperatures have skewed the snow-to-rainfall ratio, with the ratio decreasing by as much as 30 percent in some Northeastern stations. Snowpack depth has declined, with some stations reporting a decrease of up to 16 percent in March/April snowpack (Hayhoe et al. 2007).

Northwestern United States

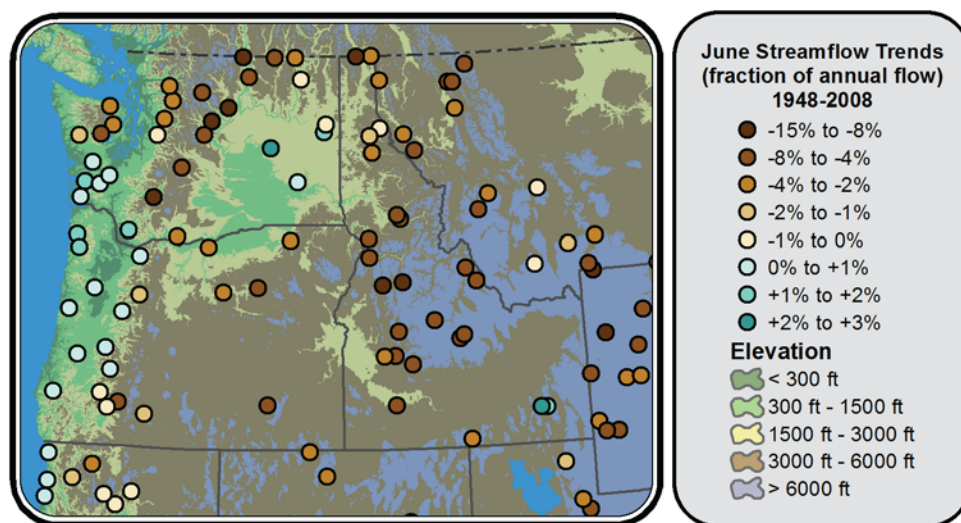
The Northwest states of Oregon, Washington, Idaho, and western Montana span a diverse range of geographic conditions and ecotones, including plateaus, high deserts, and coastal old-growth forests. The Cascade Range creates a strong rain shadow effect that divides the region into wetter and drier areas, and the Pacific Ocean influences regional climate variability through teleconnections like ENSO and the PDO. In the near term, this variability will continue to significantly influence Northwest climate.

However, the region has seen an increase in temperature since the late nineteenth century, despite seasonal and inter-annual variability. Future climate model temperature projections indicate that Northwest temperatures will rise year-round, with hotter summers and more incidences of extreme heat (Dalton et al. 2013). To date, annual mean precipitation has exhibited considerable variability and there has been no clear trend in extreme precipitation. Climate models do not agree on a change in amount of annual precipitation for the region. However, many models project an increase in extreme daily precipitation events over one inch, as well as a change in the seasonality of precipitation, with drier summers and wetter spring, fall, and winter seasons (Dalton et al. 2013).

Much of the low-elevation maritime snowpack in the region hovers around melting point 1°F (0°C) for most of the winter. Multiple studies show an observed decrease in mountain snowpack and snow water equivalent, as illustrated in Figure 3-9, and a shift toward earlier snowmelt and streamflow center of timing (Melillo et al. 2014, Hidalgo et al. 2009, Mote 2006, Nolin and Daly 2006). Even annual streamflows in the region show significant declines in the lowest quartile of flows because warming temperatures have led to less snow in snow-dominated watersheds (Luce and Holden 2009).

Warmer winter temperatures will cause more precipitation to fall as rain, leading to declining snowpacks, earlier spring snowmelt and peak runoff in snow-fed systems, and lower summer streamflows. The hydrologic regimes of watersheds during winter months are also likely to change: many mixed rain–snow (or transitional) watersheds are expected to shift to rain-dominant watersheds by the end of the century, with snow-dominant watersheds shifting to mixed rain–snow. Changing hydrographs will likely cause warmer stream temperatures that affect endangered species like salmon, decreased summer

Observed Shifts in Streamflow Timing



Source: US Global Change Research Program 2014, as adapted from Fritze et al. 2011

Figure 3-9 Reduced June flows in many Northwest snow-fed rivers is a signature of warming in basins that have a significant snowmelt contribution

water availability for instream uses and agriculture, and consequences for hydropower generation (Dalton et al. 2013, Melillo et al. 2014). In addition, an increase in extreme storms and the changing rain-snow ratio in snow-dominant watersheds are projected to lead to increased flood risk (Salathé et al. 2014), which can stress infrastructure and create water quality problems.

Coastal parts of the Northwest are vulnerable to sea level rise, although projected impacts vary by locality. Some coastlines are expected to experience a relative decrease in sea level because tectonic uplift may outpace sea level rise, while other areas could see an increase in sea level of 50 inches or more (Dalton et al. 2013).

Overall, the impact of climate change Northwestern drinking water supplies will vary across the region. Systems which rely on snow for water supply will become more vulnerable. Water supplies from groundwater wells and aquifers may experience further declines (especially due to increasing withdrawals), although river basins that have a significant groundwater component may be somewhat buffered from climate change (Tague et al. 2013).

Alaska and Hawaii

Alaska has warmed twice as fast as the rest of the United States, leading to rapidly melting sea ice, shrinking glaciers, and thawing permafrost (Melillo et al. 2014). Summer sea ice in the Arctic is expected to disappear by the middle of the century. The decline in sea ice creates a positive feedback loop that generates more warming. Additionally, warming ocean temperatures are projected to increase ocean acidification and impacts on marine fisheries. Native communities are highly vulnerable to these changes, despite their history of adaptation to change (Melillo et al. 2014).

Hawaii and the US Affiliated Pacific Islands will also experience warmer ocean temperatures in the future, along with coastal flooding and erosion due to both sea level rise and high water levels from tropical and extra-tropical storms. Sea level rise is expected to threaten freshwater availability due to saltwater intrusion into coastal aquifers, especially in low-lying areas. Warmer future temperatures, decreased rainfall, and increased risk of drought will also reduce available water supplies for both drinking water and agriculture on most islands in the region (Melillo et al. 2014).

Canada

Canada's significant land mass experiences a range of climates that vary by region and season. Warming has been observed across the country, especially in the north and west, and less so in the east. In particular, daily minimum temperatures have increased faster than daily maximum temperatures over the last 60 years (Bush et al. 2014). Annual precipitation has increased by about 16 percent over the same time period, with most stations showing increased seasonal precipitation in spring and fall. Some sites in western Canada show a decrease in winter precipitation due to the decline in winter snowfall (Bush et al. 2014). Precipitation in Canada is greatly influenced by natural climate variations like ENSO and the PDO.

Climate model projections on average indicate that the nation is projected to warm by about 3–5°F (1.5–2.5°C) by the middle of the century, even in a low emissions scenario (Bush et al. 2014). Winter temperatures in particular are expected to increase by about 5–13°F (3–7°C) by the end of the century under a higher emissions scenario. Some regions like the High Arctic and Hudson Bay will experience much greater warming (Bush et al. 2014). Projected precipitation changes are more variable across models, although most of the country is projected to be wetter in all seasons, with the exception of southern Canada (Bush et al. 2014). Extreme heat days will occur more often, and the return period of extreme daily precipitation events is expected to become shorter (Bush et al. 2014).

Effects on Canada's water resources will depend on regional conditions. In river basins fed by glaciers, the loss of glacier ice is expected to reduce runoff, with potential long-term impacts on water availability for drinking water and hydropower generation (Bush et al. 2014). Similar trends in the rain–snow ratio will affect the timing of spring runoff and will decrease the amount of summer runoff in many river systems. Some coastal areas could see increases in sea level, especially during storm surges, leading to coastal erosion and other impacts (Bush et al. 2014).

Mexico

Mexico spans a range of climate conditions and ecosystems, from arid high plateaus to forested tropical zones. The country is expected to see a decrease in precipitation with climate change. Declines of up to 30 percent by 2040 are projected across many regions of the country, with the most acute declines projected in semi-arid northwestern Mexico (IPCC 2014), the primary region of irrigated grain farming. In areas of Mexico with significant subsistence agriculture, climate change scenarios suggest an increase in temperature from 2–4°F (1–2°C) and a reduction in precipitation by 10 percent, which may cause declining water availability as drought risk increases as well as increased exposure of rural populations and the agricultural sector (IPCC 2014). Although in some regions an increase in precipitation may contribute to greater rangeland productivity (IPCC 2014), the effects of maximum summer temperatures on livestock heat stress are expected to reach the level at which losses can occur by 2020 and will continue to rise (IPCC 2014).

While overall precipitation may decline in most areas, extreme precipitation events and powerful hurricanes may lead to higher flood risk. As a result, many of Mexico's

agricultural communities are considered highly vulnerable, especially due to their high sensitivity and low adaptive capacity to these changes (IPCC 2014). Migration from Mexico to the United States has been associated with natural disaster occurrence and poverty trends (IPCC 2014), as well as with decreasing precipitation (IPCC 2014). Climate change may exacerbate these migration drivers.

ASSESSING WATER SYSTEM VULNERABILITY

Considering potential regional climate impacts is a necessary first step for water utilities, but impacts are strongly dependent on locality and the particular hydrologic system. Utilities must be familiar with how each system or watershed operates in historical and current climate conditions before projecting how climate change could affect the hydrologic regime. The following questions are intended to guide further consideration of climate change vulnerabilities.

- Is the water supply surface water, groundwater, or both? How could changes in annual or seasonal temperature or precipitation affect the system?
- Is the hydrology of the system dominated by rainfall or snowmelt? What are the implications in regions where the rain–snow ratio is expected to change?
- How sensitive historically is the hydrology and water quality of the system to changes in temperature, precipitation phase, or groundwater recharge rates?
- What extreme events has the water system experienced (floods, rainstorms, windstorms, wildfires, heat, droughts, storm surges)? How has the system responded?
- Are there any extreme event thresholds above which the system fails?
- Where are facilities and infrastructure located? Are they exposed to flooding, storm surges, sea level rise, or wildfires?
- How does customer water demand change based on temperature and precipitation?

Most water utilities have access to extensive data sets available from historical weather records, maps, stream gages, snow telemetry (SNOTEL) sites, tidal gauges, and other monitoring efforts. These data sets can be analyzed to help answer the previous questions, even if a utility has not used climate models to project future changes to its system.

Some studies have also analyzed paleoclimatology, which uses proxy data such as tree rings, ice cores, and pollen to reconstruct and extend the historical hydrologic and climatologic record. The paleo-record may indicate that a watershed or region has experienced extreme events such as long-term drought that predate the historical record. Paleoclimate or dendrohydrology information “can be used to define an expected range of variability, including worst-case scenarios, to guide operational strategies in the face of extreme future uncertainty” (Biondi and Strachan 2012). For example, tree-ring data used to reconstruct streamflows in the Upper Colorado River Basin indicated that streamflows vary over decades or longer and that short-term records may be inadequate for long-term planning (Woodhouse et al. 2006).

Resources on Regional Climate Impacts and Assessing Water System Vulnerability

This section provides summaries of publicly available (online) resources that provide an array of information, data sets, and interactive tools that water utilities can use to further understand potential regional climate impacts and to assess the vulnerability of hydrologic systems to climate change.

Adaptation Strategies Guide for Water Utilities, Climate Ready Water Utilities.

This guide, prepared by the USEPA Climate Ready Water Utilities (CRWU) program, provides drinking water and wastewater utilities with a basic understanding of how climate change can impact utility operations and missions, as well as examples of actions utilities can take (i.e., adaptation options) to prepare for these impacts.

Canada in a Changing Climate: Sector Perspectives on Impacts and Adaptation.

This report is a 2014 update to the 2008 science assessment report “From Impacts to Adaptation: Canada in a Changing Climate.” Led by Natural Resources Canada, this report involved more than 90 authors and 115 expert reviewers and synthesized more than 1500 recent publications to update the state of climate science for Canada.

Changes in Water Use under Regional Climate Change Scenarios, Water Research Foundation. This research study by the Water Research Foundation sought to increase the adaptive capacity of water utilities in planning for and responding to climate change impacts, concentrating on the demand for water.

Climate Adaptation Knowledge Exchange (CAKE). CAKE was founded by EcoAdapt and Island Press in July 2010 and is managed by EcoAdapt. It aims to build a shared knowledge base for managing natural and built systems in the face of rapid climate change. CAKE helps users vet and organize the best information available. It also builds a community via an interactive online platform, creates a directory of practitioners to share knowledge and strategies, and identifies and explains data tools and information available from other sites.

Climate Change Handbook for Regional Water Planning. This handbook was developed as a partnership of the Environmental Protection Agency Region 9, the California Department of Water Resources, US Army Corps of Engineers South Pacific Division, and the Resources Legacy Fund. Although this handbook is focused on the California Integrated Regional Water Management Planning process, it can be used by other practitioners nationally and internationally when incorporating climate change into any watershed or water supply planning process. This handbook considers both climate change adaptation and mitigation.

Climate Change and Water Resources: A Primer for Municipal Water Providers.

This primer was prepared by the National Center for Atmospheric Research and sponsored by the AWWA Research Foundation (AwwaRF) in 2006. The goals of this Primer are to (1) introduce water utility managers to the science of climate change; (2) suggest the types of impacts it can have on water resources; and (3) provide guidance on planning and adaptation strategies.

Climate Data Initiative. This US federal government data initiative provides data related to climate change that is related to coastal flooding, food resilience, water, ecosystem vulnerability, human health, energy infrastructure, transportation and the Arctic region to help inform and prepare America’s communities, businesses, and citizens.

CREAT: Climate Resilience Evaluation and Awareness Tool. This risk assessment tool from the Environmental Protection Agency CRWU program allows water utilities to evaluate potential impacts of climate change and identify adaptation options to address impacts using both traditional risk assessment and scenario-based methods. Users are able to quantify the cost of climate hazards to utilities, with and without adaptation.

Implications of Climate Change for Urban Water Utilities. This report was prepared by Stratus Consulting for the Association of Metropolitan Water Agencies. The paper is designed to help urban water utilities move past the initial barrier of information overload and uncertainties related to climate change. The intent is to provide an essential understanding and then turn to consideration of the issues involved in developing suitable water sector responses to climate change.

National Climate Assessment. The US Global Change Research Program (USGCRP) Fourth National Climate Assessment was completed in 2018 and summarizes the impacts