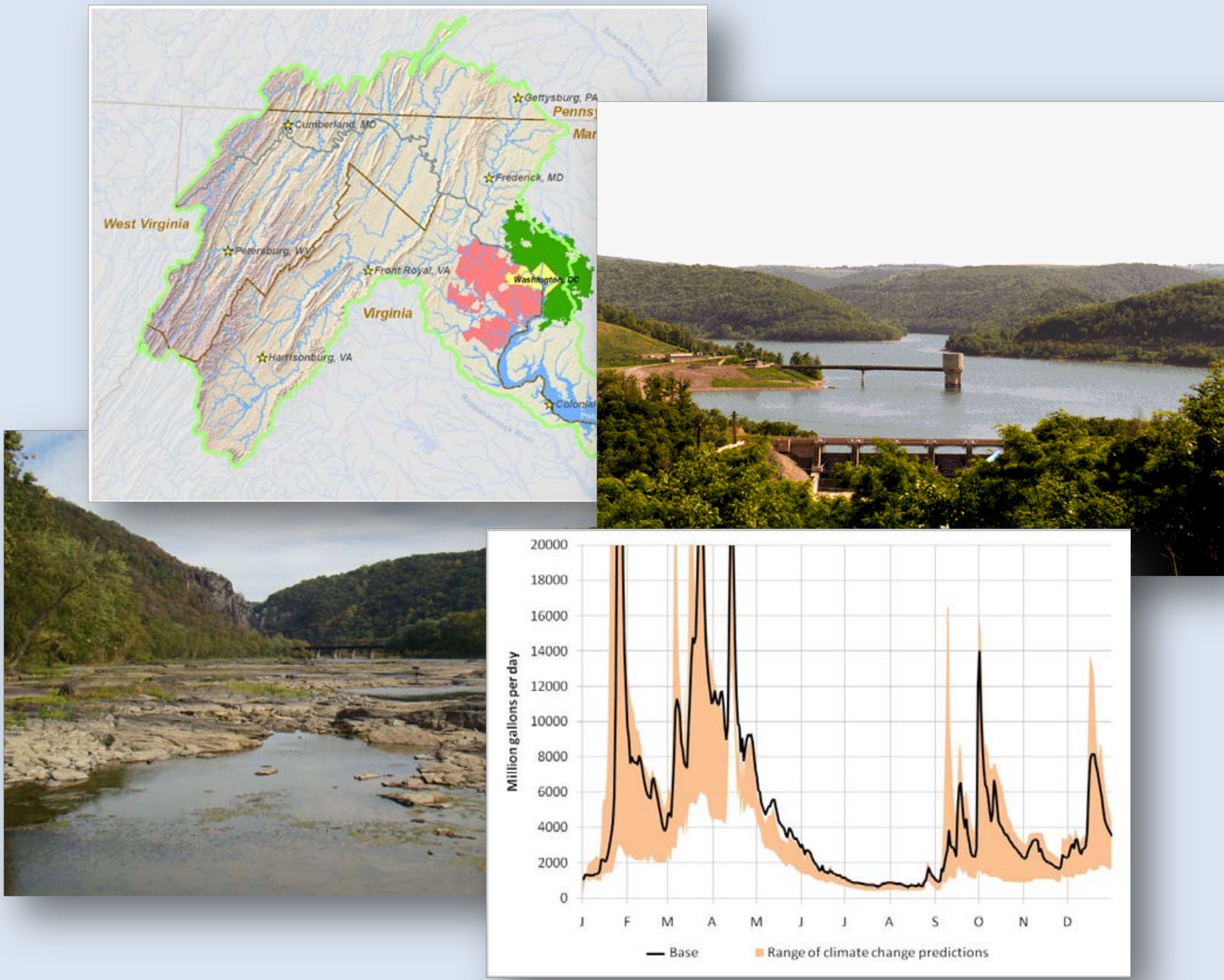
2010 Washington Metropolitan Area Water Supply Reliability Study

Part 2: Potential Impacts of Climate Change



Interstate Commission on the Potomac River Basin

51 Monroe Street, Rockville, MD 20850
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2010 Washington Metropolitan Area Water Supply Reliability Study

Part 2: Potential Impacts of Climate Change

Prepared by

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April 2013

Section for Cooperative Water Supply Operations on the Potomac

Interstate Commission on the Potomac River Basin
51 Monroe Street, Suite PE-08
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Abbreviations

°C	Degrees Celsius
°F	Degrees Fahrenheit
ARIMA	Autoregressive integrated moving average
bg	Billion gallons
CBPO	Chesapeake Bay Program Office
CDF	Cumulative distribution function
CO-OP	ICPRB's Section for Cooperative Water Supply Operations on the Potomac
DC Water	D.C. Water and Sewer Authority
FTABLE	HSPF function table
GCM	General circulation model
GHG	Greenhouse gas
HSPF	Hydrologic Simulation Program – FORTRAN
ICPRB	Interstate Commission on the Potomac River Basin
IPCC	Intergovernmental Panel on Climate Change
LS	Little Seneca Reservoir
MCCC	Maryland Commission on Climate Change
mg	Million gallons
mgd	Million gallons per day
MWCOG	Metropolitan Washington Council of Governments
NCDC	National Climatic Data Center
PET	Potential evapotranspiration
PHDI	Palmer Hydrological Drought Index
PRRISM	Potomac Reservoir and River Simulation Model
R^2	Coefficient of determination
USGS	U.S. Geological Survey
VARFTABLE	HSPF variable FTABLE
WCRP CMIP3	World Climate Research Programme Coupled Model Intercomparison Project
WMA	Washington, D.C., metropolitan area
WSSC	Washington Suburban Sanitary Commission

Acknowledgments

Funds were provided for this study by the three major Washington, D.C., metropolitan area water suppliers: Washington Suburban Sanitary Commission, Washington Aqueduct Division of the U.S. Army Corps of Engineers, and Fairfax Water.

This report would not have been possible without the many people who generously provided us with data, information, and technical assistance. We would especially like to thank Ross Mandel of ICPRB; Gary Shenk, Jing Wu, Michael Barnes, Mohammed Khan, and Gopal Bhatt of the Chesapeake Bay Program Office; Mark Bennett of the USGS Virginia Water Science Center; Lauren Hay of the USGS National Research Program; and Marc Baldo and Jay Day of Riverside Technology, Inc. for their data, models, advice, and general guidance and for taking the time to answer our many questions. We would also like to thank Greg Prelewicz and Traci Kammer Goldberg of Fairfax Water, Craig Fricke of Washington Suburban Sanitary Commission, and Tom Jacobus and Anne Spiesman of Washington Aqueduct for editorial assistance in the preparation of this document.

The lower leftmost photo on the cover of this report was provided courtesy of Danny Pendergraft, formerly of the Washington Suburban Sanitary Commission and now retired. It shows the Potomac River at Harpers Ferry during a low flow period which occurred in September 2010.

Disclaimer

This report was prepared by staff of the Interstate Commission on the Potomac River Basin, Section for Cooperative Water Supply Operations on the Potomac. The opinions expressed are those of the authors and should not be construed as representing the opinions or policies of the United States or any of its agencies, the several states, the Commissioners of the Interstate Commission on the Potomac River Basin, or the water suppliers.

Executive Summary

A wide range of evidence indicates that the earth has been warming over the past century. This warming is causing the melting of mountain glaciers and sea ice in many parts of the world, a rise in sea levels, and changes in patterns of precipitation. Most scientists agree that these trends are likely to continue and to accelerate largely due to increasing levels of carbon dioxide and other "greenhouse" gases in our atmosphere. Changes in temperatures and precipitation may impact the availability, use, and management of water resources.

This report evaluates the potential impact of climate change on the water supply resources of the Washington, D.C., metropolitan area. This is the second part of a two-part study on water availability and water demand in the region through the year 2040. The first part of the study, *2010 Washington Metropolitan Area Water Supply Reliability Study – Part 1: Demand and Resource Availability Forecast for the Year 2040* (Ahmed *et al.*, 2010), forecasted annual water demands and assessed the ability of current resources to meet those demands through the year 2040, based on the assumption that the historical record for temperature, precipitation, and stream flow is a good indication of future conditions. The Section for Cooperative Water Supply Operations on the Potomac (CO-OP) of the Interstate Commission on the Potomac River Basin (ICPRB) has been conducting such studies on behalf of the major Washington, D.C., metropolitan area water suppliers since 1990.

Background

The focus of this study is the free-flowing portion of the Potomac River – the primary water supply for the Washington, D.C., metropolitan area, which is comprised of the District of Columbia and the city's Maryland and Virginia suburbs. This region has three major water suppliers:

- Washington Aqueduct (a Division of the U.S. Army Corps of Engineers), serving the District of Columbia via the D.C. Water and Sewer Authority (DC Water), and parts of northern Virginia;
- Washington Suburban Sanitary Commission (WSSC), serving Montgomery and Prince George's counties and providing wholesale water on a limited basis to other suppliers in Maryland; and
- Fairfax Water, serving Fairfax County, Virginia, and providing wholesale water to other suppliers in northern Virginia.

These suppliers obtain approximately 78 percent of their water from the Potomac River. They jointly fund the storage of water in two upstream reservoirs, Jennings Randolph and Little Seneca, and contribute to operations and maintenance costs of a third, Savage Reservoir. Water in these three reservoirs can be used to augment natural Potomac River flow during times of drought. In addition, Fairfax Water and WSSC rely on water stored in reservoirs outside of the drainage area of their Potomac River intakes, on the Occoquan and Patuxent rivers, respectively.

Washington Aqueduct, WSSC, and Fairfax Water participate in a cooperative system of water supply planning and management that is based on a set of agreements entered into more than 30 years ago. The Low Flow Allocation Agreement of 1978 provides for the allocation of water during shortages. The Water Supply Coordination Agreement of 1982 commits the three suppliers to operate "in a coordinated manner" to optimize the use of available resources and specifies that water demand and availability forecasts be conducted every five years. Also in 1982, the water suppliers signed a set of agreements that provide for joint funding of water supply storage in upstream reservoirs.

Study Approach

Teams of scientists throughout the world have constructed computer models to simulate the physics and chemistry of the global climate to help forecast future changes in temperature and precipitation. They have also used projections of future economic, technological, and societal changes to construct scenarios of future global greenhouse gas emissions. The current study is based on results from six different global climate models under three greenhouse gas emission scenarios, listed in Chapter 3. This provided 18 climate change scenarios for the Potomac River basin for the year 2040, that is, 18 separate projections of how future temperatures, precipitation, and stream flows might be altered under climate change.

This study benefited from information, data, and models provided by several organizations. The National Research Program of the U.S. Geological Survey (USGS) “downscaled” the 18 global climate predictions to the Potomac River basin and to other areas as part of a separate project on climate change being conducted by the Chesapeake Bay Program Office and the USGS’s Virginia Water Science Center. The Chesapeake Bay Program Office’s Phase 5 Watershed Model was used to estimate the impact of changing temperatures and precipitation on Potomac basin stream flows. Finally, ICPRB’s Potomac Reservoir and River Simulation Model was used to evaluate what impact changing temperature, precipitation, and stream flows could have on the reliability of the Washington metropolitan area’s water supply system.

Projections of future climate are subject to considerable uncertainty, especially at the regional scale. Though global climate models are continually being refined and improved, they cannot capture the full complexity of the earth’s inter-related land, water, and atmospheric systems. Confidence in global model projections is higher for temperature than for precipitation, higher for larger spatial scales than smaller scales, and higher for longer averaging periods than smaller periods. Though it is predicted that precipitation will increase on a global scale, in many areas of the United States, including the Potomac River basin, models differ on whether precipitation will increase or decrease. Watershed models are used to simulate the effect of a changing climate on stream flows, adding additional uncertainty to projections of water availability.

Finally, though it is believed that as the earth warms, the variability of climate is likely to increase, with extreme weather events becoming more frequent and more intense, this change is not well-represented by most currently available global model output. The current study uses the historical variability in temperature and precipitation from a relatively short time period, 1988 through 1999, to represent the potential variability in future conditions under climate change. This historical period includes a moderate drought, occurring in 1999, but does not capture the full range of conditions that could be experienced in 2040 under an altered climate, such as a severe long-term drought similar to the drought of 1930.

Results

Water demands

Total average annual water demand in the Washington metropolitan area was projected in Part 1 of this study to be 611 million gallons per day (mgd) by the year 2040, assuming likely future water use rates.

Demand varies seasonally in the region, largely due to lawn watering and other outdoor water uses, and is highest in the months of July and August. Because outdoor water use depends on temperature and rainfall, demand is expected to be affected by changes in climate.

Water use restrictions may be declared in the Washington metropolitan area during times of drought and other water supply emergencies as described in the *Metropolitan Washington Water Supply and Drought Awareness Response Plan: Potomac River System* (MWCOG, 2000). This plan specifies triggers for "voluntary" and "mandatory" water use restrictions, which may include recommended reductions or actual limits on both outdoor and indoor water uses. The simulations conducted in this study included estimates of unrestricted daily demands as well as estimates of reductions in demands that would occur due to implementation of water use restrictions triggered by falling reservoir levels.

If demands are left unrestricted, they will tend to increase with higher temperatures and less precipitation. But simulation results predict that under climate change, a moderate drought would cause the response plan's management measures to be implemented, causing demands to fall. This is evident in Figure ES-1 which shows the range of simulated Washington metropolitan area demands during a moderate drought in the year 2040 under climate change assumptions compared to demands in the unaltered ("base") case.

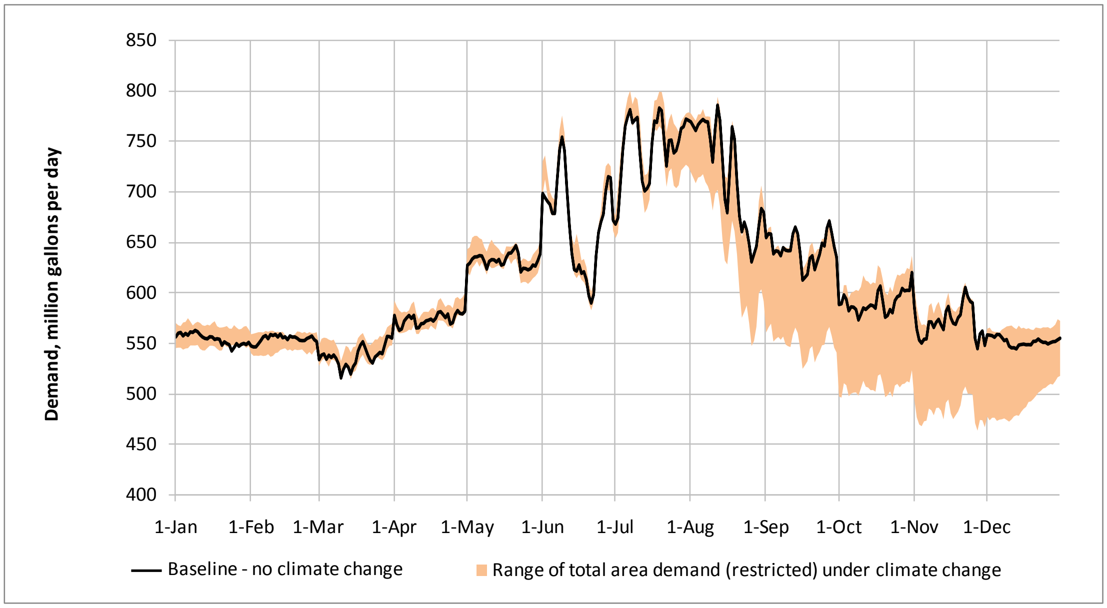


Figure ES-1: Projected total Washington metropolitan area demand (restricted) during a moderate drought in the year 2040.

Climate and stream flow conditions

This study is based on 18 sets of temperature, precipitation, and stream flow data that each represent potential conditions in the region as altered by climate change. In these 18 climate scenarios, the increase in annual average temperature in the Potomac basin by 2040 ranges from 0.7 to 2.3 degrees Celcius (^{o}C) (1.3 to 4.1 degrees Fahrenheit (^{o}F)) when compared with the reference period of 1988 to 1999. The average increase, over all scenarios is 1.5 ^{o}C (2.7 ^{o}F). Future precipitation in the Potomac basin is also likely to change, but model projections are evenly split on whether precipitation will decrease or increase.

The projected change in total annual precipitation ranges from minus nine percent to plus nine percent or -4 to +4 inches, when compared with the average in the reference period of 42.2 inches.

Changes in both temperature and precipitation affect stream flows. Changes in precipitation directly affect the amount of water that runs off the land surface and enters streams during rain events. Precipitation also affects the amount of water replenishing groundwater aquifers, which are the primary source of stream flow during dry weather periods. Rising temperatures will cause more precipitation to be lost to evaporation from the soil, streams, and other surfaces in the basin and will increase transpiration, that is, the water released to the atmosphere by plants. These increases in evapotranspiration will tend to reduce flow in basin streams.

Though basin precipitation increases in half of this study's 18 climate change scenarios, flow in the Potomac River falls in most scenarios. This is illustrated in Figure ES-2, which shows the range of results for Potomac River flow at Little Falls dam during a moderate drought in the year 2040, under the assumption that no changes are made to the water supply system. Flow at Little Falls dam, which is located just downstream of the Washington metropolitan area water supply intakes, is a key system performance metric since there is minimum flow recommendation at this location of 100 million gallons per day.

Average total annual stream flow in the basin is predicted to decrease in 14 out of the 18 scenarios, by as much as 35 percent. Average annual basin-wide evapotranspiration is predicted to increase by six to eight percent (1.2 to 2.9 inches). Average annual basin-wide groundwater recharge decreases under all but three climate scenarios. According to study results, the seasonal pattern of groundwater recharge does not change significantly under climate change, with January, February, and March remaining the months of greatest recharge. However, the average annual amount of groundwater discharged to basin streams, that is, stream baseflow, is predicted to decrease in 16 out of the 18 scenarios by as much as 34 percent.

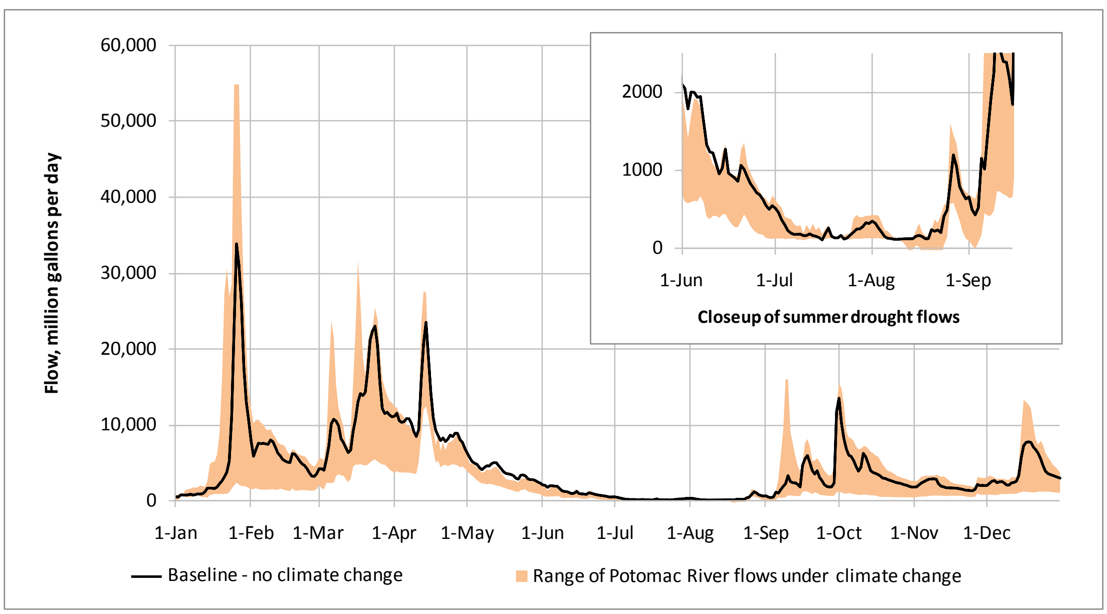


Figure ES-2: Projected Potomac River flow at Little Falls dam during a moderate drought in the year 2040, assuming no changes to the current water supply system.

Washington metropolitan area water supply system

ICPRB's Potomac Reservoir and River Simulation Model (PRRISM) was used to evaluate the effects of climate change on the Washington metropolitan area water supply system in the year 2040. PRRISM is a computer model that simulates, on a daily basis, the various processes that determine water availability, including flow in the Potomac River, water withdrawals to meet human demand, and reservoir releases. PRRISM was run with the 18 sets of temperature, precipitation, and stream flow data that represented potential climate change conditions. For each of these scenarios, PRRISM provided estimates of how well the system would fare in the event of a moderate drought. PRRISM output includes predictions of how often water use restrictions would be imposed in the region, to what extent system reservoirs would be depleted, and how much flow would remain in the river after withdrawals.

Results for the 18 climate scenarios fell into three categories: minor impact, moderate impact, and major impact. Six of the scenarios are predicted to have little impact on the system during a moderate drought. System performance deteriorates to some degree in five of these six "minor impact" scenarios, but actually improves in one. Water demands are met without mandatory or emergency water use restrictions under these scenarios. Minimum storage in system reservoirs falls moderately in most scenarios in comparison with the base scenario which assumes no climate change.

Six of the climate change scenarios fall into the "moderate impact" category. Under these scenarios the region is predicted to experience more frequent and stricter water use restrictions but no water supply shortages during a moderate drought. Reservoir levels are predicted to fall to significantly lower levels during a drought than would occur in the absence of climate change.

The remaining six climate change scenarios indicate a major impact on the Washington metropolitan area water supplies. Under these scenarios, in the absence of operational and/or structural changes to the water supply system, study results predict that both mandatory and emergency water use restrictions would be imposed and most system reservoirs would become empty or close to empty sometime in the course of a moderate drought. In addition, supply shortages would occur, that is, on some days of the drought the Potomac River and/or the Patuxent reservoirs would fail to provide sufficient water to meet demand and environmental needs.

Conclusions

Climate change may have a significant impact on current Washington metropolitan area water supplies. Though it is uncertain whether precipitation will increase or decrease in our region, study results indicate that higher temperatures may raise rates of evapotranspiration to a significant degree. The higher evapotranspiration rates are predicted to reduce the amount of water available to recharge basin aquifers and to decrease flows in the Potomac River and in streams that fill and replenish system reservoirs. Study simulations produced a wide range of effects. However, under the assumption that no changes are made to the WMA system, results indicate that in a basin altered by climate change a moderate drought occurring in the year 2040 may cause the imposition of emergency water use restrictions, nearly empty reservoirs, and lead to water supply shortages.

To ensure that water supply systems continue to meet demands and satisfy environmental flow requirements, it is important that water supply planners keep abreast of developments in climate science and regularly review and assess local trends and projections of how hydrologic conditions might change in the coming decades. Under the set of cooperative agreements which govern water supply planning and management in the Washington metropolitan area, the area's three main water suppliers are committed to conducting regular forecasts of future demands and resources. For the past 15 years this has included assessments of the potential impact of climate change.

Climate change will likely add additional stress to a system facing the challenge of future population growth. The region's suppliers are also committed by cooperative agreements to increase water availability if assessments determine a need to do so. This could be done by funding structural solutions and/or other means of ensuring a reliable supply. To this end, studies on alternatives to increase water supplies have been conducted. These alternative options include use of the Potomac and Occoquan estuaries as supplies and retired quarries as storage facilities. Other measures that could improve system performance under climate change include:

1) increased flexibility in shifting between the system's Potomac and off-Potomac resources,
2) improved stream flow forecasts to inform reservoir release decisions, and
3) earlier and stricter water use restrictions.

Based on the results of this study, it is recommended that future assessments of the Washington metropolitan supply system consider the following:

1) The results of the current study were determined to a large degree by predicted increases in evapotranspiration rates. Confidence in results would be increased by an investigation of the sensitivity of stream flows to changes in the model used to simulate evapotranspiration.
2) The current study was limited by the relatively short time series used to represent potential variations in future climate. The construction of a long-term time series of historical Potomac basin meteorological and land use data, extending back to the year 1930, would allow for the simulation of conditions similar to the drought of record in a basin altered by climate change.
3) The next WMA water supply reliability study, scheduled for completion in 2015, will provide an opportunity for an updated assessment of the relative benefits of selected options for increasing future water supplies.
4) The current cooperative approach to water supply planning and management has served the Washington metropolitan region well over the past 30 years. Impacts of climate change will be felt not just locally, but in communities throughout the Potomac basin. An extension of this cooperative approach to other areas of the basin may be an additional aid in managing resources to meet the challenges of the future.

1 Overview

1.1 Introduction

Over the course of the past century, rising global temperatures have been changing climatic, hydrologic, and ecologic patterns. The Intergovernmental Panel on Climate Change (IPCC) reports that air and ocean temperatures are increasing; snow, sea ice, and mountain glaciers are melting; and global average sea level is rising (IPCC, 2007a; 2007c). Subsequent changes to the atmospheric and oceanic circulation are leading to altered patterns of evapotranspiration, precipitation, and runoff in the hydrologic cycle. The frequency of heavy rains is increasing in some regions, and at the same time, more areas of the globe are being affected by drought. Forests, coastal, and aquatic ecosystems are experiencing changes and shifts in their geographic distributions. Such stresses may impact the availability, use, and management of water resources. Particularly, climate change may make it more difficult to achieve a satisfactory balance between the competing uses of water.

Long-term planning is essential for water suppliers, since they must invest in costly infrastructures that are expected to meet future requirements for decades to come. Suppliers regularly assess the long-term reliability of their systems in the context of future changes in use patterns due to demographic, economic, and societal changes, relying on the historic hydrologic record to evaluate the adequacy of resources to meet future needs. There is consensus in the water resource community that the instrumental and historic records must be augmented and that planning must take into account projections of future temperature, precipitation, and stream flows (Brekke *et al.*, 2009). Water suppliers now need to look beyond demographic, economic, and societal changes and assess system reliability in the context of climate change.

That said, current scientific understanding does not allow for confident projections of the magnitude or precise nature of climatic changes to be made at the regional or local scales relevant for water suppliers. The most recent assessment by the IPCC reports that climate change projections from global climate models are increasingly reliable at the regional scale (IPCC, 2007b). However, significant sources of model uncertainty remain. These include the magnitude of future anthropogenic emissions of greenhouse gases, carbon cycle feedback mechanisms, cloud physics, ocean circulation, and the effects of aerosols and particulates (IPCC, 2007c; NASA, 2012). Confidence in model projections is higher for temperature than for precipitation, higher for larger spatial scales than smaller scales, and higher for longer averaging periods than smaller periods. Though it is predicted that precipitation will increase on a global scale, in many areas of the United States, including the Potomac basin, models differ on whether precipitation will increase or decrease. In the face of these uncertainties, it is important that water supply managers keep abreast of developments in climate science, regularly review the most up-to-date climate projections for their region, and periodically assess how local hydrologic conditions and ecosystems might change in the coming century.

Since 1990, and every five years thereafter, the Section for Cooperative Water Supply Operations on the Potomac (CO-OP) of the Interstate Commission on the Potomac River Basin (ICPRB) has conducted forecasts of water demands and resource availability on behalf of the major water suppliers of the Washington, D.C., metropolitan area (WMA). This assessment of the potential impact of climate change completes the second part of the most recent iteration of these studies. The first part of this study, *2010*

Washington Metropolitan Area Water Supply Reliability Study – Part 1: Demand and Resource Availability Forecast for the Year 2040 (Ahmed *et al.*, 2010), forecasted annual water demands in the WMA and assessed the ability of current resources to meet those demands through the year 2040, under the assumption that future climate will reflect the historical record for temperature, precipitation, and stream flow. The objective of the current study, Part 2, is to assess the potential impacts of climate change on the WMA water supply system's ability to meet future water demands. The assessment was completed by comparing system performance for estimated 2040 demands under the unchanged climate condition to a range of projected climate conditions. The remainder of this report is structured into six chapters that cover the following topics:

- A summary of observed trends and projected changes in meteorological and hydrologic conditions, based on a review of climate literature (Chapter 2),
- a discussion of the origin of the temperature, precipitation, and evapotranspiration projections used in this study (Chapter 3),
- an explanation of how these projections were used to generate stream flow and water demand inputs for CO-OP's planning model (Chapter 4),
- a comparison of the various projected climate conditions (Chapter 5),
- a description of how the WMA water supply system may respond to the various climate scenarios (Chapter 6), and
- a summary of this study's findings and recommendations (Chapter 7).

1.2 Study Area

The focus of this study is the free-flowing portion of the Potomac River, the primary water supply source for the WMA. The WMA, which is comprised of the District of Columbia and the city's Maryland and Virginia suburbs, has three major water suppliers:

- Washington Aqueduct (a Division of the U.S. Army Corps of Engineers), serving the District of Columbia via the D.C. Water and Sewer Authority (DC Water), and parts of northern Virginia;
- Washington Suburban Sanitary Commission (WSSC), serving Montgomery and Prince George's counties, Maryland, and providing wholesale water on a limited basis to other suppliers in Maryland; and
- Fairfax Water, serving Fairfax County, Virginia, and providing wholesale water to other suppliers in northern Virginia.

These three suppliers, sometimes referred to in this study as the WMA suppliers, obtain approximately 78 percent of their water from the Potomac River (Ahmed *et al.*, 2010). The WMA suppliers jointly fund water storage in two upstream reservoirs, Jennings Randolph and Little Seneca, and contribute to operations and maintenance costs of a third, Savage Reservoir. Water in these three reservoirs can be used to augment natural Potomac River flow during times of drought. In addition, Fairfax Water and WSSC rely on water stored in reservoirs which are outside of the drainage area above their Potomac River intakes, on the Occoquan and Patuxent rivers, respectively. The WMA suppliers provide treated water either directly to customers or through independent wholesale suppliers. Figure 1-1 shows the extent of the Potomac River basin, including the tidal drainage area, the locations of system reservoirs, and the areas served by the WMA suppliers. For more information on the WMA water supply system, see Part 1 of this study.

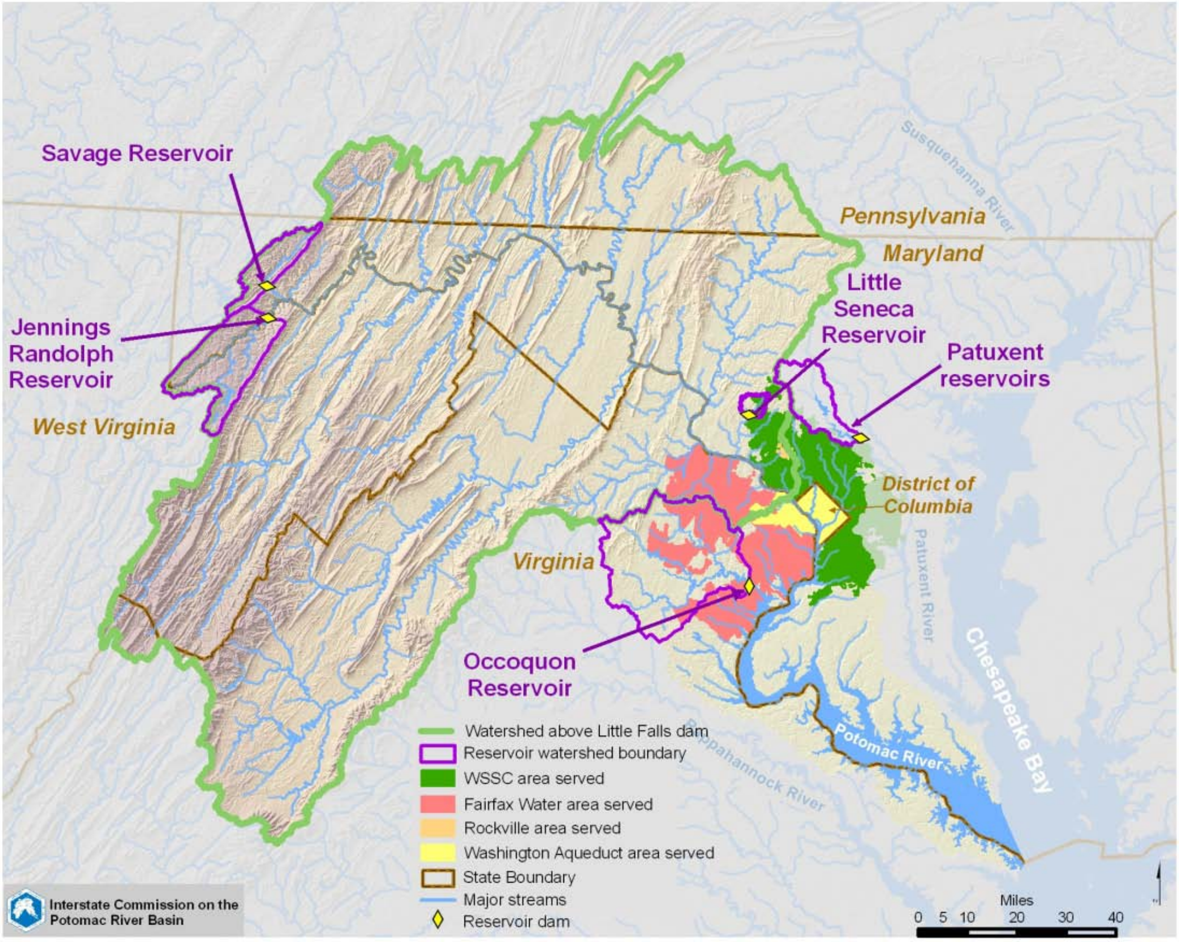


Figure 1-1: Reservoirs and watersheds relied upon by the WMA water suppliers.

The WMA water suppliers participate in a cooperative system of water supply planning and management that is based on a set of agreements entered into over 30 years ago. The Low Flow Allocation Agreement was signed in 1978 by the United States (Secretary of the Army), Maryland, Virginia, District of Columbia, Fairfax Water, and WSSC, and provides for the allocation of available water during water supply shortages. The Water Supply Coordination Agreement was signed in 1982 by the United States (Baltimore District of the U.S. Army Corps of Engineers), Fairfax Water, WSSC, ICPRB, and the District of Columbia. In the Water Supply Coordination Agreement, the suppliers agreed to operate “in a coordinated manner” to optimize the use of available resources. This agreement also provides for system reliability assessments to be completed every five years, beginning in 1990, and since this time, CO-OP has been conducting such assessments on behalf of the water suppliers. Also in 1982, the water suppliers and the District signed a set of agreements providing joint funding for upstream storage.

1.3 Approach

This study relied on CO-OP’s long-term water supply planning tool, the Potomac River and Reservoir Simulation Model (PRRISM), to evaluate whether or not future water demands can be met by the current WMA water supply system under climate change. It also relied on data and models from two partner organizations, the U.S. Geological Survey (USGS) and the Chesapeake Bay Program Office (CBPO). Climate change projections for the Potomac basin were made available by the USGS’s National Research

Program as part of a separate project on climate change in the Chesapeake Bay region, being conducted by the USGS Virginia Water Science Center and the CBPO. Using the USGS's projected changes in temperature and precipitation as input, stream flows were simulated using the CBPO's Phase 5 watershed model. Finally, these stream flows, temperatures, and precipitation were used as input into PRRISM to assess the current WMA system's performance under possible climate change conditions. The various models and data used in the study are depicted in Figure 1-2.

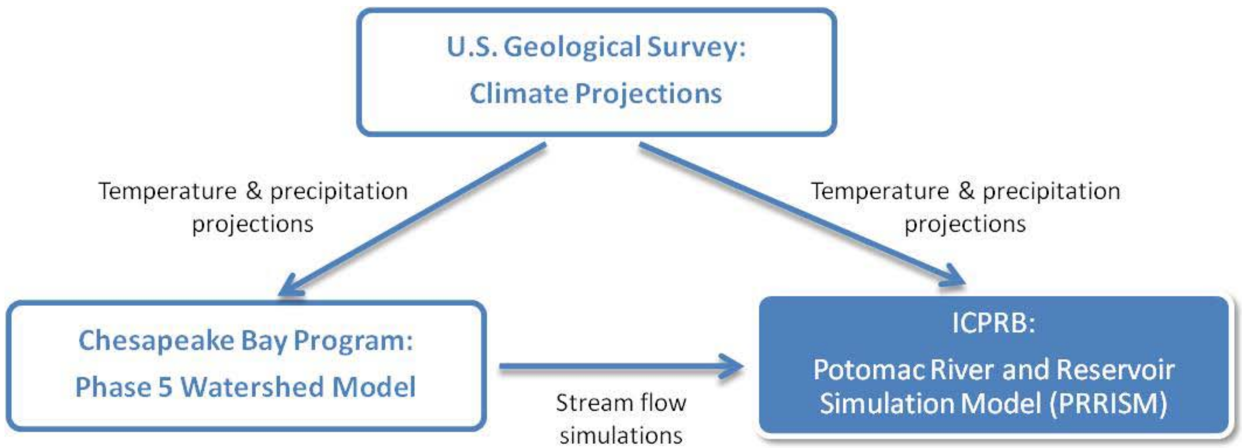


Figure 1-2: Data and models used in this study.

1.3.1 Meteorological Projections

The USGS's National Research Program in Denver, Colorado, obtained monthly projections of temperature and precipitation from the World Climate Research Programme Coupled Model Intercomparison Project phase 3[1] from six global climate models and three separate carbon emission scenarios (Lauren Hay, personal communication, March 13, 2012), resulting in 18 different climate change scenarios for this project. The USGS downscaled the coarse global model projections to the Chesapeake Bay watershed using a simple statistical technique called the "change factor" or "delta change" method (Lauren Hay, personal communication, March 13, 2012; Hay *et al.*, 2011). Using this method, projected mean monthly changes in temperature and precipitation at weather stations in the Chesapeake Bay watershed were applied to historical daily and hourly data at each station for the time period, 1988 through 1999. The result was a set of 18 time series – each 12 years in length – of projected hourly temperature and precipitation. Each of the 12 years in this time series represents potential conditions under climate change in the year 2040. The time series were then used to construct temperature and precipitation inputs for the CPBO's Phase 5 watershed model.

1.3.2 Phase 5 Watershed Model

Stream flow projections for this project were obtained using version 5.32 of the CPBO's Phase 5 Watershed Model. This model has been constructed to estimate point and nonpoint source loads to the Chesapeake Bay from the entire Bay watershed. It is currently being used to develop total maximum daily

[1] http://www-pcmdi.llnl.gov/ipcc/about_ipcc.php

load allocations of nutrients and sediments to the Bay (Linker *et al.*, 2002; USEPA, 2010; Shenk *et al.*, 2012). Phase 5 is based on Hydrologic Simulation Program – FORTRAN (HSPF) (Bicknell *et al.*, 1997), a computer model which simulates the hydrologic processes that occur in a watershed, including surface runoff, evapotranspiration, infiltration, soil and aquifer zone storage, and flow routing in stream channels. The primary inputs of HSPF's hydrologic component are meteorological time series, typically at an hourly or finer time step, including precipitation, air temperature, wind speed, solar radiation, and potential evapotranspiration. Phase 5 currently uses over 20 land use categories and a model simulation period extending from 1984 to 2005.

Each of the 18 scenarios of future temperature and precipitation under climate change, described above, was used by CBPO partners to create inputs for the Bay Program's Phase 5 model. ICPRB staff then used Phase 5 to create a set of 18 simulated stream flows in the Potomac basin and in the Occoquan and Patuxent watersheds under climate change. The stream flow simulations were 12 years in length, with each of the 12 years representing possible conditions in 2040.

1.3.3 PRRISM

ICPRB's PRRISM model was used in this study to evaluate the Potomac water supply system's performance under the 18 climate scenarios. PRRISM is a daily water balance model that simulates flow in the Potomac River and the various inflows and outflows in order to determine water availability for the WMA suppliers. Model inflows and outflows include:

- WMA water withdrawals,
- upstream consumptive use,
- wastewater treatment plant discharges,
- reservoir inflows, and
- reservoir releases.

Key PRRISM inputs are daily natural Potomac River flow and daily reservoir inflow time series, which in this study were estimated from Phase 5 model output, described above. In addition, daily temperature and precipitation values, used by PRRISM to forecast WMA water demands following an approach modified from Kame'enui *et al.* (2005) and Ahmed *et al.* (2010), were obtained from the USGS-provided climate projections.

PRRISM outputs include a variety of reliability metrics, including the daily Potomac River flow at Little Falls dam (located near Washington, D.C., just downstream of the last WMA intake), minimum reservoir storage levels, and number of days in which demands were not met over the model simulation period. Flow at Little Falls is an important metric because of an environmental flow-by recommendation of 100 million gallons per day (mgd) at that location.

In Part 1 of this study (Ahmed *et al.*, 2010), future hydrologic conditions in PRRISM were simulated using data from the 78-year historical period, October 1929 through December 2007. This period includes the following historical droughts:

- Summer and fall of 1930 – A prolonged period of low-flow conditions considered to be the drought of record for the region.
- Summer of 1966 – A relatively brief drought in which Potomac River flow dropped to its lowest ever recorded value.
- Summer of 1999 – Considered to be a moderately severe drought.
- Summer of 2002 – Considered to be a moderately severe drought.

In the current study, Part 2, an assessment is provided for the potential impact of climate change during a moderately severe drought comparable to the drought of 1999. This limitation is due to the form of the daily precipitation and temperature projections that were available from the USGS and CBPO. As described above, mean monthly climate model projections for the year 2040 were combined with historical data from the 12-year period from 1988 through 1999. This results in a set of temperature, precipitation, and stream flow time series, 12 years in length, where each year of represents potential conditions in 2040. However, these 12 years do not capture all of the potential variability in weather conditions that have occurred in the past and that might be expected to occur in any given future year.

1.4 Other Studies on Climate Change and the WMA Water Supply System

1.4.1 Past Studies

The current climate change study is the third in a series that have been conducted by CO-OP staff. Summaries of the previous two assessments are given below.

Water Resources Management in the Potomac River Basin under Climate Uncertainty (Steiner *et al.*, 1997) forecasted that the WMA could experience water supply demand growth of 74 to 138 percent over the 40- year period, 1990 to 2030. This assessment examined projections from five climate models of temperature and precipitation and their effects on WMA system demand and resources in the year 2030. A water balance model based on the Thornthwaite-Mather method (1955) was used to predict stream-flow conditions under altered climate conditions. Depending on the climate projection, resources were significantly stressed or deficient. However, any predicted supply deficit was accommodated with increased conservation to reduce demand. Under most scenarios, existing resources were sufficient through 2030. The study recommended that water managers consider planning for mitigation of potential climate change impacts.

Water Supply Reliability Forecast for the Washington Metropolitan Area Year 2025 (Kame'enui *et al.*, 2005) found that the WMA could meet forecasted 2025 demand given an assumed reduction in stream flow based on projections for the Mid-Atlantic region. In this study, increases were made to temperature records within PRRISM to evaluate the effects of higher regional water demand during droughts. The projected temperature increase of 2.3 degrees Fahrenheit (^{o}F) was based on projections for the Mid-Atlantic region from two climate models. The confidence level associated with these changes is considered "high" for temperature (Najjar *et al.*, 2000; Neff *et al.*, 2000). To explore the sensitivity of the system to potential changes in resources, Potomac stream flow and reservoir inflow was reduced by ten percent during the months of July through October – the time period in which reservoir releases are most likely to occur. The assessment projected that 2025 July through October average unrestricted water demand would increase from 654 to 665 million gallons per day (mgd). In order to meet high estimates of 2025 demand during a repeat of the worst drought of record, model simulations indicated that voluntary and mandatory water use restrictions would become more frequent.

1.4.2 Concurrent Studies

At the same time that CO-OP staff was conducting the modeling and analyses for this study, it participated in two other independent studies on the impact of climate change on the WMA water supply system, sharing information and data with project partners. Both of these separate studies, described below, make valuable contributions to the understanding of the challenges facing the WMA system and options for meeting those challenges, and their findings will be considered in future CO-OP assessments of options to address climate change.

The first study, funded by the Water Research Foundation (WRF) and led by the firm, Hydrologics, Inc., investigated the effectiveness of dynamic reservoir operations to address climate change. Other project partners were Riverside Technologies, Inc. and Hazen and Sawyer, P.C. The WMA water supply system was one of six case studies considered in the WRF project. For the WMA case study, Riverside used its Climate Change Decision Support System and its in-house version of the Middle Atlantic River Forecast Center's hydrologic forecast model to simulate Potomac basin stream flows under climate change. Hydrologics evaluated the effectiveness of more frequent and stricter water use restrictions and increased flexibility in WSSC's Patuxent water treatment plant production rates, and in particular, the benefits of a lower minimum rate. At the time of completion of this report, the report on the WRF study, *Dynamic Reservoir Operations: Managing for Climate Variability and Change*, is in draft form.

The impact of climate change on the WMA water supply system was also the topic of a recent doctoral dissertation by James H. Stagge, a student at Virginia Tech working with Professor Glenn Moglen. Stagge's dissertation is entitled *Optimization of Multi-Reservoir Management Rules Subject to Climate and Demand Change in the Potomac River Basin* (Stagge, 2012). Stagge constructed long duration synthetic climate-adjusted stream flow time series and investigate the impact of climate and land use changes on system reliability. He also explored strategies for better balancing the use of Jennings Randolph and Little Seneca reservoirs to optimize system performance during droughts.

2 Review of Climate Trends, Predictions, and Impacts

Water supplies in the eastern portion of the United States are thought to be less vulnerable to small changes in average climate conditions than in the west (Hurd *et al.*, 1999). However, climate variability and change could still have a moderate impact on water resources in the eastern United States. The sections below provide a brief review of available literature on observed trends and projections for our region for temperature, precipitation, stream flow, water quality, and extreme events.

2.1 Temperature

Temperature influences many climate-induced trends. Evidence of recent global warming is supported by independent analyses of multiple datasets for a broad range of indicators, including land-surface air temperature, marine air temperature, sea surface temperature, tropospheric temperature, snow cover, arctic sea ice extent, and atmospheric surface humidity (Kennedy *et al.*, 2010). According to the IPCC's Fourth Assessment report (IPCC, 2007b), global mean temperature has increased by 0.74 degrees Celsius (^oC) in the last century (1906-2005). Most of the change has occurred over the past 50 years at a rate of 0.13^{o}C per decade.

Global climate model results indicate that temperatures will continue to increase throughout the next century (IPCC, 2007b). Most models agree that during the first part of the 21st century mean surface air temperature will increase at a rate of approximately 0.2^{o}C per decade, which is consistent with observations for the past several decades. The expected increase by the last part of the 21st century (2080 to 2099) relative to temperatures observed in the period (1980 to 1999) is 1.8, 2.7, and 3.1^{o}C, based on means of multiple model runs using low, moderate, and high greenhouse gas emissions scenarios, respectively. Temperature increases are expected to be greatest over land and at higher latitudes in the Northern Hemisphere and smallest over the North Atlantic and over oceans in the Southern Hemisphere.

According to state and regional studies, significant warming has occurred and will continue to occur in the Potomac basin. In the Northeastern United States, from Maine south to Pennsylvania, mean temperature has increased by 0.08^{o}C per decade over the past century, and more recently this rate has risen to 0.25^{o}C per decade, with greater increases experienced in winter months (Hayhoe, 2007). Projected increases in mean temperatures in the Northeast range from 2.9 to 5.3^{o}C by 2070-2099 relative to 1961 to 1990. In the Mid-Atlantic region, the mean annual temperature has risen by approximately 0.5^{o}C from 1895 to 1997 (Polsky *et al.*, 2000). For the Chesapeake Bay watershed, it has been estimated that mean temperature in the period from 2070 to 2099 will increase relative to the period from 1971 to 2000 by 2.0 to 8.7^{o}C, with multiple model averages predicting changes of 3.5 and 4.7 ^{o}C for low and high emission scenarios (Najjar *et al.*, 2009). Temperature in Maryland has increased by approximately 1^{o}C from 1977 to 1999, and over the next century is expected to rise by 2.7 to 5.0 ^{o}C in the summer months and by somewhat less – 2.2 to 3.9^{o}C – in the winter (Boesch, 2008). To the south, temperature in Virginia is expected to increase by 3.1^{o}C between 2000 and 2099, based on a moderate emissions scenario (Bryant, 2008).

2.2 Precipitation

Warmer temperatures change the atmosphere's circulation patterns and increase its water-holding capacity. Global mean precipitation is projected to increase, affecting the amount of water available in streams, lakes, and reservoirs (IPCC, 2007a, b). Global warming is also expected to change the regional distribution of rainfall and the frequency of heavy rain events.

Trends in precipitation are difficult to discern because of high inter-annual and inter-decadal variability. A long-term trend of increasing annual precipitation, at a rate of approximately 0.4 inches per decade, has been reported for the Northeast, though this trend may have reversed since 1970 (Hayhoe *et al.*, 2007). The Mid-Atlantic region has become significantly wetter in the period from 1895 to 1997 (Polsky *et al.*, 2000). Within the Potomac basin, precipitation is highly variable from year to year and no clear trend emerges from weather observation stations in Maryland (Boesch, 2008); however, significant increases of 5 to 20 percent over the last century have been documented in Pennsylvania (UCS, 2008). These regional trends are consistent with studies that have found increasing precipitation and stream flow trends across the United States (Karl and Knight, 1998; Lins and Slack, 1999).

Predictions of future changes in precipitation are mixed for our region. Global models vary widely in their projections of average annual precipitation in the Chesapeake Bay watershed by the end of the 21st century, with changes of -17 to +19 percent predicted for a high emissions scenario, and an estimated change of +3 percent obtained from multiple model averages (Najjar *et al.*, 2009).

2.3 Stream Flow

A recent analysis of runoff at long-term stream gages in the Chesapeake Bay watershed by Rice and Hirsch (2012) indicates that, in general, areas to the north of 40.25 degrees north latitude experienced a greater increasing trend in runoff as compared to those south of that latitude (where the vast majority of the Potomac basin lies) between 1930 and 2010. The authors also found that runoff has become less variable throughout the study area and, specifically, that it is less variable in the north than in the south. They also found an increase in flows after 1970, as others have also found on a national scale.

The study included two gages in the Potomac basin: the Potomac River at Point of Rocks (USGS gage 01638500), which measures flow from a 9,651 square mile watershed; and Goose Creek near Leesburg (USGS gage 01644000), which measures flow from a 332 square mile watershed. On an annual basis at the Point of Rocks gage, the seven-day minimum and mean flow increased and the one-day maximum flow decreased. Increases in all three flow statistics were seen at the Goose Creek gage. The authors suggest that the large increases in runoff seen at this gage could be attributed to urbanization. When these data were looked at seasonally, the most notable result was decreasing summer trends in runoff for all three statistics at the Point of Rocks gage.

Rising temperatures and changes in precipitation patterns could lead to future decreases in water supplies during the summer. For example, increased evapotranspiration from rising temperatures could counteract benefits from increased precipitation by reducing groundwater storage and baseflow in local streams, particularly in the Piedmont and Appalachian provinces (Boesch, 2008). Moreover, more rain and less snow may occur due to warmer temperatures during the winter melting season. The Northeast region as a whole has already seen a seven-day decrease in the number of days between the first and last dates with snow on the ground over the last 50 years (NAST, 2000). This could mean that the upper Potomac basin may see less snow accumulation and earlier snowmelt. This would lead to less runoff from spring snowmelt and more runoff from winter rainfall, resulting in higher winter and spring stream flows and longer summer low-flow periods than at present.

Although the issue of snow accumulation is less important for water supply in the eastern United States and, therefore, to the WMA suppliers, the managers of the Jennings Randolph and Savage reservoirs in the North Branch of the Potomac basin do look to the availability of snowpack for the timing of spring reservoir refill. For instance, less snowpack in the late spring means that there will be a smaller supply in late summer, when water is scarce and demand is high. According to the Climate Action Plan by the Maryland Commission on Climate Change (MCCC) (Boesch, 2008), decreases in winter snow volume are projected to be large enough to reduce the spring river discharge associated with melting snow (25 percent less in 2025 to 50 percent less in 2100). Also, snow accumulation is very likely to be less common in western Maryland, where the main water supply reservoir, Jennings Randolph, is located.

2.4 Water Quality

Increasing temperature and precipitation intensity could influence water quality and habitat suitability. The temperature of the Potomac River outside Washington, D.C., has increased at a rate of 0.046^{o}C per year over the historic record between 1922 and 2006 (Kaushal *et al.*, 2010). The temperature of the Patuxent River in Solomons, Maryland, has increased at a slower rate of 0.022^{o}C per year over the historic record between 1938 and 2006 (Kaushal *et al.*, 2010). Altered water temperatures in reservoirs and lakes influence the potential for algal blooms, which can reduce oxygen levels. More intense precipitation events, when coupled with possible land use and land cover changes, *e.g.* increased urbanization (Hejazi and Moglen, 2008), could increase non-point source pollution, affecting concentrations of suspended sediment, nutrients, and chemical contaminants in rivers and lakes and resulting in greater treatment needs at the water treatment facilities.

Salinity levels in coastal rivers may be affected by alterations in stream flow patterns and sea level rise. Lower salinity levels in the Chesapeake Bay may occur during the winter and spring due to increased precipitation during the months of January through May (Najjar *et al*., 2010). Conversely, higher salinity levels may occur during summertime low flows periods if the frequency or severity of droughts increases. During the 1930 drought, flows were so low that encroachment of saline waters upstream occurred in streams which discharged into coastal waters (Tisdale, 1931). This caused the abandonment of certain public water supplies for domestic and drinking purposes in Maryland, Pennsylvania, and Virginia.

2.5 Extreme Events

Climate projections indicate that the global hydrologic cycle will experience changes in seasonal patterns and precipitation extremes. Depending on location, these changes may lead to more frequent and (or) more intense droughts and floods under future climate conditions. Projected increases in drought frequency could threaten water quantity, while increases in storm intensity could threaten water quality.

The region's drought of record occurred in the 1930s, when the combination of low precipitation and high evaporation, produced by high summer temperatures, depleted Potomac basin water supplies. Precipitation levels for July and August, 1930, were 30 to 40 percent below normal, with Maryland experiencing the greatest precipitation deficit of any state (Tisdale, 1931). At the time, WSSC was responsible for providing water to 56,000 people in areas surrounding Washington, D.C., and their supply system, then dependent on the Anacostia River, failed.

The drought with the lowest recorded Potomac River flow occurred in the 1960s. Drought rationing in the WMA did not occur during this period because the ability to meet water demand was never compromised.

However, WMA demand levels between 1971 and 1982 exceeded the 1966 low flow of the Potomac River 41 times (Ways, 1993). This flow record is significant because it documents a period of natural Potomac River flow prior to the completion of Jennings Randolph and Savage reservoirs. Subsequently, low-flow periods in the summers of 1999, 2002, and 2010 warranted water supply releases from Jennings Randolph and Little Seneca reservoirs. In these years, cooperative operations between ICPRB and the WMA water suppliers ran smoothly, and the augmented flow of the Potomac provided the required water.

Drier summertime and autumn conditions and more frequent droughts are projected to occur in the Northeast, especially under higher greenhouse gas emissions scenarios (Hayhoe, 2007). The incidence of moderate to severe drought has increased in the Southeast, and climate models predict that the frequency and duration of these events will likely increase in the future (Karl *et al.*, 2009). Some researchers predict that long-term or water-supply droughts are not likely to increase under climate change, even though a moderate increase in short-term droughts may occur. Long-term droughts, defined by the MCCC as precipitation deficits of more than 14 inches persisting over a period of two years or more, have occurred slightly less than four percent of the time in both 20th century observations and 21st century model projections (Boesch, 2008). Short-term droughts, however, are more likely to increase in frequency (NAST, 2000).

In contrast to droughts, periods of excess precipitation in Maryland are more likely in the future (Boesch, 2008). There is still much uncertainty as to the degree by which the frequency of these events will actually change (Knutson and Tuleya, 2004; Emanuel *et al*., 2008; Shepherd and Knutson, 2007; Knutson *et al*., 2008). Two-year precipitation excesses of 14 or more inches may occur between 14 and 28 percent of the time in the future, but were almost never observed in the 20th century (Boesch, 2008). A statistically insignificant increase in the frequency of extreme precipitation events (heavy downpours) has occurred in Maryland, but significant increases have been documented in West Virginia, Delaware, and Pennsylvania (Boesch, 2008). Global models indicate that the maximum amount of rainfall occurring in any five-day period and any one-day period will increase in the future.

Greater rainfall-runoff generation may lead to more frequent and intense flood events. There also may be shifts in the seasonal timing of typical high flows. Spring high flows in snow-dominated watersheds are already shifting to earlier in the year because of earlier snowmelt associated with higher temperatures. Floods are expected to worsen along the east coast of the United States (Hurd *et al*., 1999). However, most studies of the historical stream flow record have not shown consistent results that would indicate an increase in flood events in the United States (Lins and Slack, 1999; Douglas *et al*., 2000; McCabe and Wolock, 2002; Kundzewicz *et al*., 2005).

Extreme event patterns can be further exacerbated by land cover and land use changes over time. For example, land use change by itself (simulated by a ten percent increase in basin impervious area) has been shown to produce no significant changes in simulated flow durations (Hejazi and Moglen, 2008). On the other hand, the Middle Potomac Watershed Assessment recently found that land use, especially impervious cover, is closely associated with hydrologic alteration in the Potomac Basin (USACE et al. 2013). Combining the effects of land use change with climate change has been shown to cause more significant decreases in low flows and more significant increases in peak flows than when climate change is modeled alone.

3 Climate Change Scenarios

This study's results are based on 18 climate change projections provided by the USGS National Research Program in Denver, Colorado. The projections, consisting of temperature, precipitation, and potential evapotranspiration data representing possible conditions in the year 2040, were constructed by the USGS as part of a separate project to assess the impact of climate change in the Chesapeake Bay region.

To downscale global climate model output to the Chesapeake Bay region, a statistical method called the change factor method, or the delta change method, was used (Lauren Hay, personal communication, March 13, 2012). This method transforms global climate data to a finer grid and time scale by applying the projected changes from the coarse scale global model output to an observed climate record at individual weather observation station points (Hay *et al.*, 2011). While this method is simple and straightforward, it seems to perform as well as more complicated methods in reproducing mean climatic characteristics (Fowler *et al.*, 2007). The following sections provide some background on climate models, emission scenarios, downscaling, and the change factor method as applied in this study.

3.1 Global General Circulation Models

The most advanced types of models currently being used to project future global climate are general circulation models (GCMs). A GCM is a numerical model which represents the important physical, chemical, and biological processes on the Earth's surface, in the atmosphere, and/or in oceanic systems that affect climate. GCMs simulate conditions in the Earth's atmosphere on a three-dimensional spherical grid. The typical horizontal grid spacing of the current generation of GCMs – 250 to 600 kilometers – is one of the factors which limit accuracy at the regional scale. However, in its most recent assessment, the IPCC reports that regional climate change projections from GCMs are increasingly reliable (Randall *et al.*, 2007).

GCM responses can vary widely depending on the method for modeling the climate system and the initial conditions used for simulations (Hay *et al.*, 2011; Grotch and MacCracken, 1991). One way to address these uncertainties is to use output from a variety of GCMs to obtain a range of potential future climate conditions (Grotch and MacCracken, 1991; Brekke *et al*., 2009) or, alternatively, to report multi-model average results. Multiple GCM outputs are available online through the Data Distribution Centre of the IPCC[2] and the World Climate Research Programme Coupled Model Intercomparison Project phase 3[3] (WCRP CMIP3).

3.2 Emission Scenarios

Increasing atmospheric concentrations of greenhouse gases, such as carbon dioxide, methane, and nitrous oxide, tends to warm the earth by increasing the atmosphere's capability to "trap" heat. Future emission scenarios are key inputs to GCMs. Emissions scenarios describe various hypotheses on future releases of greenhouse gases, aerosols, and other pollutants into the atmosphere, along with information on land use and land cover. These hypotheses are based on assumptions about driving social forces such as patterns of future economic and population growth, technology development, and other factors. Levels of future

[2] http://ipcc-ddc.cru.uea.ac.uk/ddc_gcmdata.html
[3] http://www-pcmdi.llnl.gov/ipcc/about_ipcc.php

emissions are highly uncertain. Using more than one emission scenario to provide alternative GCM inputs allows for a range of future climate possibilities to be assessed within a single model.

A range of potential emissions scenarios was developed and described in the IPCC's, *Special Report on Emissions Scenarios* (IPCC, 2000). Figure 3-1 and 3-2, from the IPCC's *Climate Change 2007: Synthesis Report* (IPCC, 2007c), show how different assumptions about societal changes can lead to very different patterns in greenhouse gas emissions and warming. Figure 3-2 shows warming predictions over the 21st century from three emissions scenarios– relatively low emissions (B1), medium emissions (A1B), and high emissions (A2). It indicates that future emissions are likely to have a strong effect on global temperature, with temperatures rising almost 2 ^{o}C more under scenario A2 than under scenario B1.

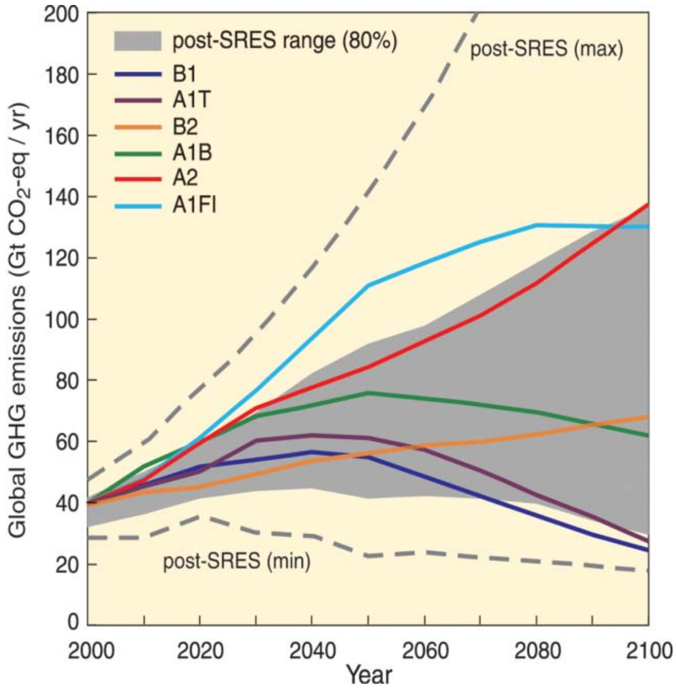


Figure 3-1: Projections of global greenhouse gas (GHG) emissions, under a variety of hypothetical emissions scenarios (B1, A1T, B2, A1B, A2, and A1F1), for the next century in the absence of additional climate policies, expressed in gigatons of carbon dioxide equivalent emissions per year (reprinted from IPCC, 2007c).

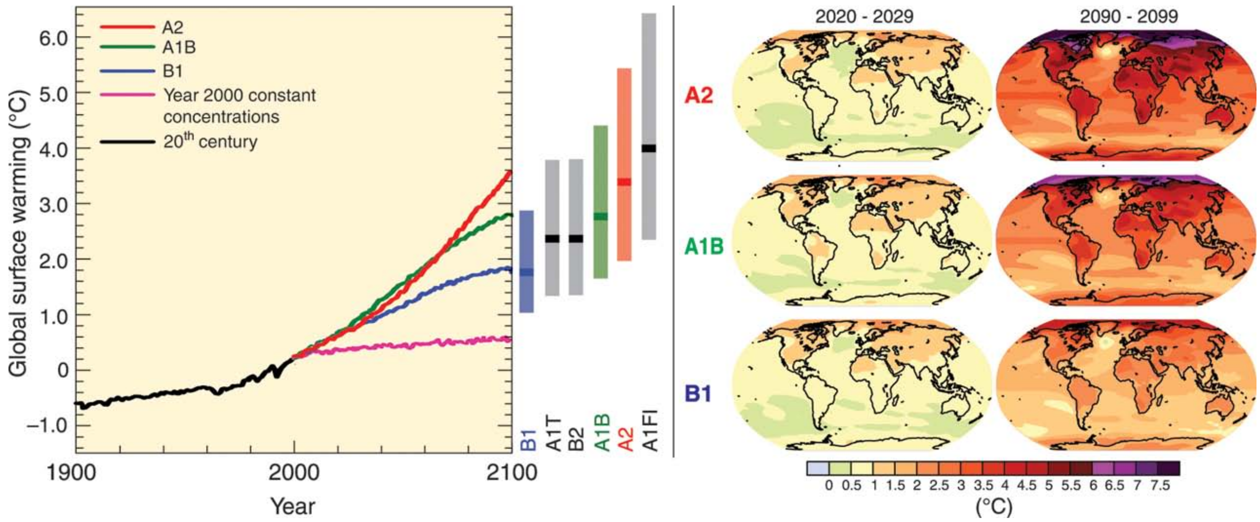


Figure 3-2: The graph on the left shows averages of multiple model projections for global warming under emissions scenarios, A2, A1B, and B1. The lower-most line on this graph, "Year 2000 constant concentrations," is a plot of the average projection assuming no future increase in atmospheric concentrations of greenhouse gases. The graph in the center (vertical bars) shows ranges of model projections of warming by 2090-2099, relative to the period, 1980-1999, for a variety of emissions scenarios. The maps on the right show projected increases in global surface temperature for scenarios A2, A1B, and B1 from multiple model averages. (Reprinted from IPCC, 2007c)

3.3 Climate Data for the Current Study

GCM data used in this study were obtained by the USGS from the WRCP CMIP3 multi-model dataset archive. Table 3-1 lists the six GCMs selected for use in this study; the selection was based on monthly data availability at the start of the USGS effort. Table 3-2 describes the three future emission scenarios that were considered: A2, A1B, and B1. The three emission scenarios and six GCMs result in a set of 18 global climate scenarios of mean monthly temperature and precipitation at the global scale. In this report, scenarios are sometimes identified by combining GCM abbreviations, from Table 3-1, with emission scenario acronyms, from Table 3-2. For example, a NCAR-CCSM3_0 model run which was made using emissions scenario, A2, is denoted N_A2.

Table 3-1: Six GCMs that generated the output used in this study.

GCM Acronym	GCM Abbreviation	Institution/Model	Country
NCAR-CCSM3_0	N	National Center for Atmospheric Research	USA
BCC-BCM2.0	B	Bjerknes Centre for Climate Research	Norway
CSIRO-Mk3.0	C3.0	Commonwealth Scientific and Industrial Research Organisation	Australia
CSIRO-Mk3.5	C3.5	Commonwealth Scientific and Industrial Research Organisation	Australia
INM-CM3.0	I	Institute for Numerical Mathematics	Russia
MIROC3.2(medres)	M	National Institute for Environmental Studies	Japan

Table 3-2: Three future emission scenarios considered in this study (IPCC, 2000; 2007c).

Emission Scenario Acronym	Emission Scenario Description
A2	High population growth, slow economic development and slow technological change
A1B	Very rapid economic growth and technological change, population peak mid-century, balance of energy sources
B1	Similar to A1B, but change toward service and information economy

Output from multiple runs is available for some of the GCMs. For example the MIROC 3.2 (medres) model has three runs available for each of the major scenarios (B1, A1B, and A2). The USGS included data from multiple runs by taking the mean of the runs that were available for a given model and emissions scenario (Lauren Hay, personal communication, July 11, 2012).

3.4 Regional Downscaling to the Chesapeake Bay Watershed

Downscaling is an intermediate step needed to adjust spatial differences between the output of global-scale GCMs and the required input for basin-scale regional models (Hay *et al.*, 2002). Downscaling can follow either statistical or dynamical methods (Giorgi and Mearns, 1991; Hay *et al.*, 2002; Wilby and Wigley, 1997). Statistical downscaling involves fitting empirical relationships between GCM simulated output and local- or station-scale historical time series in order to transform the climate data to a finer resolution (Wilks, 1995). Statistical downscaling methods depend on regression of a linear or nonlinear relationship between large-scale atmospheric predictor and local criterion variables. Alternatively, dynamical downscaling uses GCM outputs as boundary conditions to drive a regional climate model to produce regional-scale information at a finer resolution (Hay *et al.*, 2002).

A major difference between statistical and dynamical downscaling relates to the concept of stationarity. The stationarity assumption, which hypothesizes that the future will be statistically indistinguishable from the past, has been used in planning, design, operation, and major rehabilitation of local and regional water resource systems for decades (Brekke *et al.*, 2009). Stationarity is fundamental to most statistical downscaling methods. Under climate change, however, the future is governed by a non-stationary process; in other words, the future will not be the same as the past (Milly *et al*., 2008; Bates *et al*., 2008; Ramage, 1983). In contrast to statistical downscaling, dynamical downscaling is more physically based and is more transferable from current to future climates, with less reliance on the past (Hay *et al*., 2002).

In terms of modeling hydrology, both statistical and dynamical downscaling can simulate more realistic climate conditions than the coarse-resolution GCM data used to drive the downscaling (Wilby *et al.*, 2000). Generally, downscaling processes can improve the spatial properties of the GCM data (Giorgi *et al.*, 1998). Sometimes significant improvements in climate data are not necessarily due to smaller resolution, but are a result of the downscaling method having a better representation of local conditions (Liang *et al.*, 2006; Han and Roads, 2004).

For the purpose of using the GCM data with the Phase 5 model, a statistical downscaling method called the change factor method, or the delta change method, was used (Lauren Hay, personal communication, March13, 2012). This method transforms GCM climate data to the basin-scale by applying the change from baseline conditions in the global-scale GCM projections onto the observed climate record at individual weather observation station locations in the watershed of interest (Hay *et al.*, 2011). The method was applied as follows for this study (Lauren Hay, personal communication, March 8, 2012):

1) Each weather station used by the Phase 5 model was paired with a monthly change from the closest GCM grid cell (where temperature change was calculated as a delta and precipitation change was calculated as a factor);
2) The modified daily weather station data (from step one) was then distributed to a five kilometer grid;
3) Gridded daily weather data (from step two) was then disaggregated to an hourly time scale based on the closest hourly weather station;
4) Gridded hourly weather data (from step three) was then spatially aggregated to Phase 5 land segments.

The monthly GCM changes referred to in step one above were averaged over the period, 2035-2045, so that they centered on the 2040 demand forecast year used in this study. These 2040 average monthly changes in temperature and precipitation were then applied to observed or simulated 1988-1999 daily weather patterns in order to obtain 2040 climate projections at the daily time scale. This method assumes that the pattern of daily variability extracted from the historical data persists in a changed climate.

3.5 Potential Evapotranspiration

One of the input datasets required by the Phase 5 model is potential evapotranspiration (PET), which is a measure of the potential loss of water from the watershed due to combined evaporation from land and water surfaces and transpiration by plants. A data set for PET was provided by the USGS. PET was estimated using the Hamon method (Hamon, 1961; Lauren Hay, personal communication, August 28, 2012). This method assumes that daily PET in millimeters is computed as a function of daily mean air temperature and possible hours of sunshine using Equation 3-1:

$$PET = hamon_{coef} * dayl^2 * vdsat$$ **Equation 3-1**

where $hamon_{coef}$ is the monthly air temperature coefficient used in Hamon potential evapotranspiration computations, *dayl* is the hours of daylight for each day in units of 12 hours, and *vdsat* is the saturated water-vapor density (absolute humidity) at the daily mean air temperature (^{o}C) in grams per cubic meter computed by (Federer and Lash, 1978):

$$vdsat = 216.7 * \frac{vpsat}{tavgc + 273.3}$$ **Equation 3-2**

where *tavgc* is the daily mean air temperature in ^{o}C, and *vpsat* is the saturated vapor pressure in millibars at the daily mean air temperature (^{o}C) and is computed as (Murray, 1967):

$$vpsat = 6.108 * exp\left(17.26939 * \frac{tavgc}{tavgc + 273.3}\right)$$ **Equation 3-3**

The USGS used 0.0055 for $hamon_{coef}$ as suggested by Hamon (1961). It is possible that this coefficient value underestimates potential evapotranspiration for some regions (Leaf and Brink, 1973; Federer and Lash, 1978). Additionally, this coefficient value may underestimate potential evapotranspiration for the winter months more than for the summer months (Lauren Hay, personal communication, August 28, 2012).

4 Developing PRRISM Inputs

The PRRISM model simulates daily water availability and daily public water supply demand in the WMA. Water availability is based on a set of input time series which represent reservoir inflows and Potomac River "natural" flow, that is, flow in the absence of withdrawals and reservoir releases. Water demand is based on forecasted average annual demand, historical monthly variations in demand, and on statistical models of daily variations which depend on temperature, precipitation, and other data. Part 1 of this study assessed the ability of the WMA system to meet forecasted demands if past hydrologic conditions were to reoccur. To do this, PRRISM inputs were constructed using historical data from the 78-year time period, 1929 through 2007. In contrast, the current portion of the study, Part 2, uses PRRISM inputs constructed from 18 climate change scenarios modified from a 12-year observed record from 1988 through 1999, such that each year is representative of potential conditions in 2040 under climate change.

This chapter discusses changes made to PRRISM to allow simulation of water availability and demand under climate change, including changes to PRRISM input time series and changes to its demand model. To construct the flow time series required by PRRISM, 18 sets of downscaled GCM projections for temperature, precipitation, and evapotranspiration were used as input to the Phase 5 watershed model. Phase 5 then produced 18 sets of stream flow scenarios for the entire Chesapeake Bay watershed. Phase 5 –simulated stream flows matching USGS stream flow gage locations used by PRRISM were identified. These simulated stream flows were then run through a post processor to correct for Phase 5's low-flow bias.

To simulate demand under climate change, downscaled temperature and precipitation projections matching National Climatic Data Center (NCDC) weather station data used by PRRISM were identified. These precipitation and temperature inputs were modified following the same procedures used in Part 1 of this study in order to model non-linear demand response to climate inputs. In this response model, demand forecasts are designed to respond differently to a lower half of a data set (*e.g.*, temperatures below 90^{o}F) when compared to the upper half of a data set (*e.g.*, temperatures equal to or above 90^{o}F). Finally, these time series were run through PRRISM to generate 18 reliability scenarios for a moderately severe drought (similar in likelihood to the drought of 1999) in 2040, assuming no management changes to the water supply system (highlighted in orange). More details are provided below.

One additional change to PRRISM is also described in this chapter, which is related to the assumed minimum withdrawal from the Patuxent reservoirs.

4.1 Stream Flow Inputs

Required PRRISM inputs include six flow time series: five time series of reservoir inflows and a time series representing "natural" Potomac River flows, that is, estimates of flows that would have occurred without the impact of withdrawals and reservoirs. These were generated for each climate change scenario using output from a modified version of the Phase 5 model. The modifications made to allow natural Potomac River flow to be computed include: (1) removal of upstream reservoirs and (2) removal of certain downstream withdrawals. Once the flow time series were generated, a bias correction procedure was applied. Table 4-1 summarizes the Phase 5 river segments and corresponding USGS gage locations used to estimate each of the PRRISM flow time series. Figure 4-1 depicts the selected gage and river segment locations. For information on Phase 5 segmentation, see the model documentation (EPA, 2010).

Table 4-1: PRRISM input flow time series and associated Phase 5 river segments andUSGS gage locations.

PRRISM Input Flow Time Series	USGS Gage(s)	Selected Phase 5 River Segment	USGS Gage ID
Jennings Randolph Reservoir Inflows	North Branch Potomac River at Steyer, MD	PU2_4720_4750	01595000
Savage Reservoir Inflows	Savage River near Barton, MD	PU1_3850_4190	01596500
Little Seneca Reservoir Inflows	Seneca Creek at Dawsonville, MD	PM1_4250_4500	01645000
Occoquan Reservoir Inflows	Cedar Run near Catlett, VA	PL1_5370_5470	01656000
Patuxent reservoirs Inflows	Patuxent River Near Unity, MD	XU0_4130_4070	01591000
Little Falls adjusted w/o inflows from Jennings Randolph, Savage, & Little Seneca reservoir watersheds, plus consumptive use	Luke, MD Little Falls (Adjusted), DC Seneca Creek at Dawsonville, MD	PU4_4440_0003 PM7_4820_0001 PM1_4250_4500	01598500 01646502 01645000

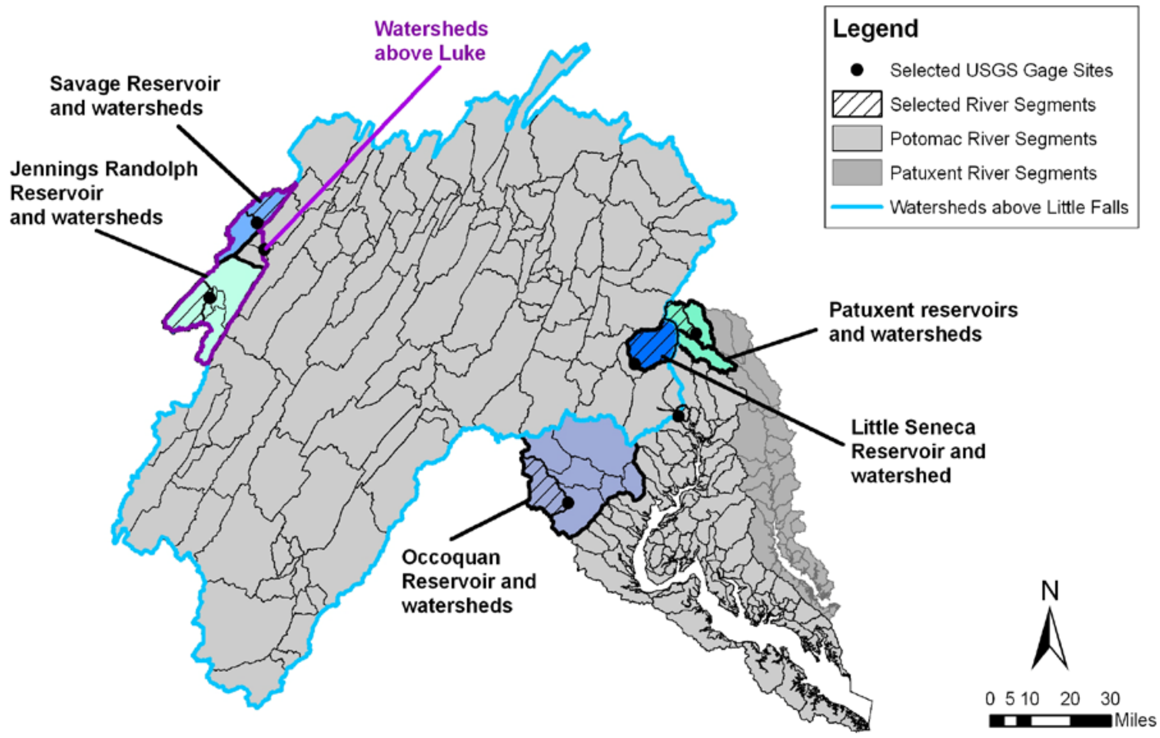


Figure 4-1: Locations of USGS gages and Phase 5 river segments used to generate PRRISM reservoir inflow and natural Potomac River flow input time series.

4.1.1 Reservoir Removal Modification to Phase 5

Reservoirs were removed from the Phase 5 model because, rather than relying on Phase 5, this study used the PRRISM model's more accurate simulations of reservoir releases. Reservoir operations are defined by the Phase 5 model as either a stationary function table (FTABLE) or a variable FTABLE (VARFTABLE). To remove the reservoirs, new stationary FTABLEs were created for all of the impounded segments using the USGS's XSECT program. Then modifications were made to the gen_info_rseg.csv file in order to indicate to the Phase 5 model code that the river segment should be modeled as a river instead of a lake and that a stationary FTABLE should be used instead of a VARFTABLE. (More detail on the general process of creating FTABLEs using the USGS's XSECT program is explained in Moyer and Bennett, 2007.) Table 4-2 summarizes the reservoirs that were removed and the corresponding river segment for which those FTABLEs are stored in the Phase 5 model.

Table 4-2: Seven of the Phase 5 impounded river segments were modified with stationary river FTABLES.

Reservoir	River Segment
T. Nelson Elliott, Potomac River in Occoquan Watershed	PL0_5141_5140
Jennings Randolph, Potomac River	PU3_4450_4440
Savage River, Potomac River	PU1_4190_4300
Stony River, Potomac River	PU1_4840_4760
Tridelphia, Patuxent River	XU2_4070_4330
Rocky Gorge, Patuxent River	XU2_4330_4480
Upper Occoquan, Potomac River	PL3_5250_0001

4.1.2 Withdrawal Removal Modification to Phase 5

Washington metropolitan withdrawals were removed from the Phase 5 model, to later be replaced by PRRISM's more detailed withdrawal estimates. This removal is similar to the process the USGS uses to create its time series called "adjusted" flow at Little Falls (USGS Site 01646502). This flow is published by the USGS and is an estimate of daily flow that would be observed at Little Falls in the absence of water supply withdrawals by the WMA suppliers as well as flow diversions for the C&O Canal at Violet's Lock. Table 4-3 summarizes the withdrawals used in the Little Falls adjusted flow estimate and the corresponding river segment associated with those diversions in the Phase 5 model.

Table 4-3: Withdrawals and corresponding river segments for creating the adjusted flow time series at the USGS gage on the Potomac River at Little Falls near Washington, D.C. (USGS Site 01646502).

Withdrawal Location	River Segment
Fairfax Water's Potomac River intake	PM7_4620_4580
Washington Aqueduct's Potomac River intake at Great Falls	PM7_4580_4820
Washington Aqueduct's Potomac River intake at Little Falls	PM7_4820_0001
WSSC's Potomac River intake	PM7_4580_4820
City of Rockville's Potomac River intake	PM7_4580_4820
City of Fairfax's Goose Creek intake	PM3_4660_4620
Flows diverted to the C&O Canal at Violet's Lock	PM1_4500_4580*

* Note: no withdrawals were documented in the Phase 5 model for this particular river segment.

4.1.3 Consumptive Use Modification Made Outside of Phase 5

Withdrawals from the Potomac River and its tributaries by upstream users have an impact on the amount of water available to meet demand in the WMA. Water withdrawn upstream is for the most part returned to the river via wastewater treatment plant discharges. However, a portion of this water is not returned to the river due to evaporation, transpiration, incorporation into products, consumption by humans or livestock, diversion to another basin, or other processes. The portion of a water withdrawal that is removed and is not available for downstream use is termed "consumptive use."

The effects of upstream consumptive use are included in the resource assessment by incorporating projections of future consumptive use into PRRISM. Potomac River flow inputs to PRRISM are modified to remove the effects of upstream consumptive use on historical flows, as described below. Then the effects of forecasted future upstream consumptive use are added back during PRRISM simulations.

The flow time series for the Potomac River at Little Falls was the only input that needed to be modified to represent flows without the effect of upstream consumptive use. For the 1988-1999 period of interest, the simulated stream flow record was adjusted by adding an amount that varies linearly from zero mgd in 1929 to 129 mgd in 2000, for June through August. Similarly, the simulated stream flow record was adjusted by adding an amount that varied linearly from zero mgd in 1929 to 42 mgd in 2000, for September through May. For more detailed information on assumptions and calculation methods for estimating consumptive use, refer to Section 6.10 of Part 1 of this study.

4.1.4 Stream Flow Postprocessor to Perform Bias Correction

One factor that can affect the quality of stream flow simulations is model bias. For example, the Phase 5 model has been found to systematically underestimate flows during low-flow conditions. A bias-correction method was applied to the simulated stream flow time series to help account for this underestimation. In order to do this, a post-processor was created that used a combination of quantile mapping and linear regression to bias correct simulated stream flow predictions. More information on quantile mapping is available from Seo *et al.* (2006) and Hashino *et al.* (2006).

Quantile mapping uses empirical probability distributions for observed and simulated flows to remove biases. The respective cumulative distribution functions (CDF), F_o and F_s , are estimated from historically observed stream flow, Q_i^o, and simulated stream flow, Q_i^s. These are used to map the simulated stream flow Q_i to the revised stream flow Q_i^* as follows:

$$Q_i^* = F_o^{-1}\big(F_s(Q_i)\big)$$ **Equation 4-1**

Quantile mapping converts a probability distribution for simulated stream flow into an adjusted probabilistic distribution that is statistically identical to that of the observed stream flow. Figure 4-2 is a graphical representation of this process.

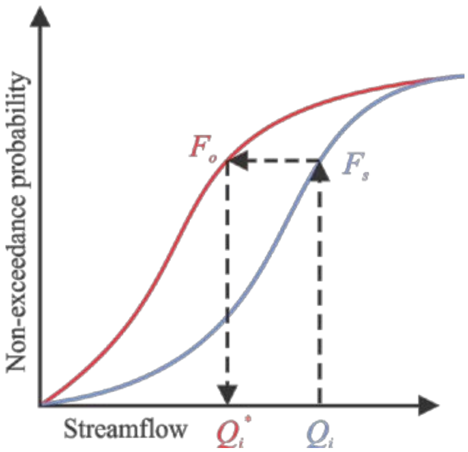


Figure 4-2: Quantile mapping concept, where F_s is the cumulative probability distribution for simulated stream flow, F_o is the cumulative probability distribution for observed stream flow, Q_i is the simulated stream flow, and Q_i^* is the simulated stream flow after being adjusted (image modified from Kim, 2009).

Additional steps were taken in order to use quantile mapping to bias correct stream flow projections for the climate scenarios. First, F_o and F_s were calculated using the PRRISM input time series developed from historical daily flow observations for the period, 1988-1999, and the Phase 5 “baseline” flow simulations for this same period, respectively. In order to avoid splitting the data by season or month, these CDFs were created using a 21-day period that crossed all available years and centered on the day belonging to the Q_i value of interest. The 21-day moving window was suggested to ICPRB by Riverside Technology, Inc., and was used by Riverside in their bias correction of climate-influenced stream flow simulations constructed for the climate change project led by HydroLogics (Jay Day and Marc Baldo, personal communication, July 7, 2012). This resulted in a set of 365 (or 366 if it was leap-year) paired CDFs per year. For example, the same set of CDFs was used for February 5 of each year and then a new set of CDFs were generated for the next day. The curves that were developed from the base simulation were then used to bias-correct flows for the future climate change scenarios.

Regression equations were used in the two cases in which the simulated climate change flow fell outside of the range of simulated Phase 5 base condition flows used to create F_s. The regression equations took the following form:

$$Q_i^* = m\,Q_i \qquad \text{Equation 4-2}$$

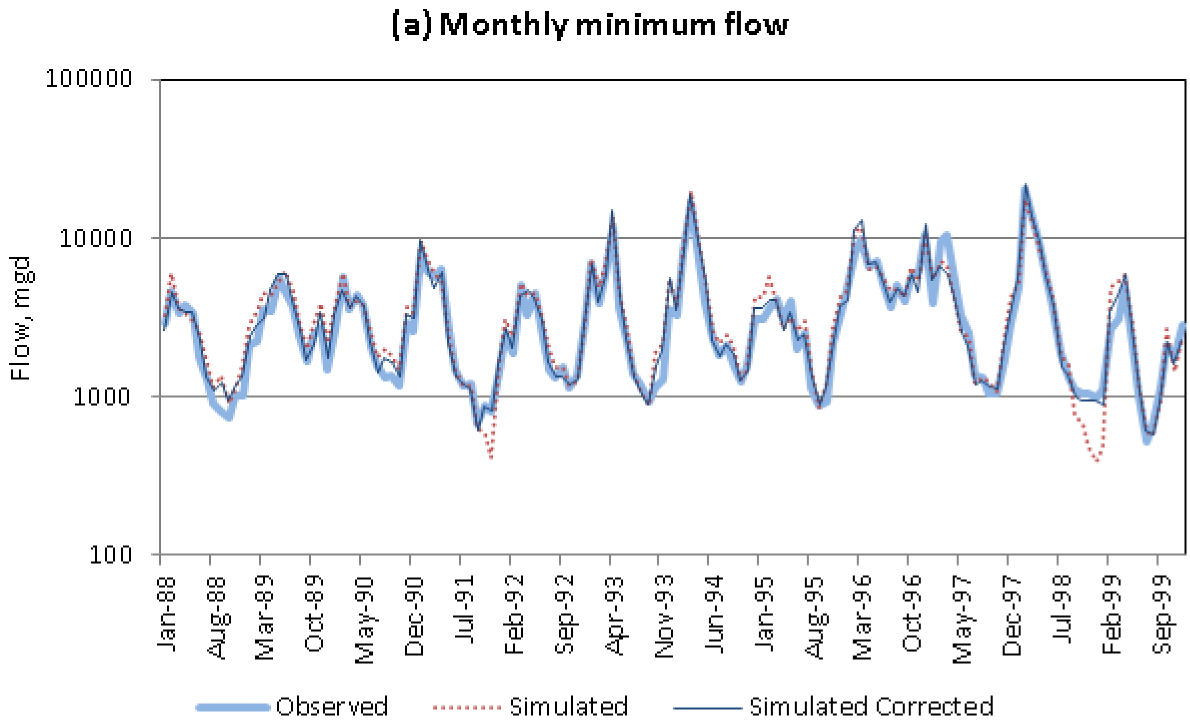
where, Q_i^* and Q_i were looked-up using their respective CDFs and an identical set of probabilities for either the upper or lower tail of the probabilistic distribution, and m was a slope coefficient that was fitted to the data.

The purpose of the bias-correction method was to improve low-flow estimation without significantly reducing the quality of the model’s mean or median flow estimation. The performance of the bias correction method was evaluated by computing the following “goodness-of-fit” statistics: (1) the ratio of uncorrected and corrected simulated flow to observed mean and median daily flows, expressed as a percentage (100% indicates perfect agreement); and (2) the coefficient of determination (R^2) between the observed flow and the uncorrected and corrected simulated daily, monthly mean, and monthly minimum flows (where R^2 = 1 indicates perfect agreement).

These statistics, which indicate the model's ability to accurately reproduce observed flows, are provided in Table 4-4. Most of the goodness-of-fit statistics for mean, median, and minimum flows are improved by the bias-correction procedure. Figure 4-3 illustrates how the bias-correction method was able to pull the simulated flows closer to the observed flows for both the minimum (graph a) and mean (graph b) monthly values of Potomac River flows at Little Falls.

Table 4-4: Goodness-of-fit statistics comparing observed data to simulated and bias-corrected simulated data.

PRRISM Input Description	Mean daily flow –percent of observed		Median daily flow –percent of observed		R^2 – daily flow		R^2 – monthly mean flow		R^2 – monthly minimum flow	
	simulated	corrected	simulated	corrected	simulated	corrected	simulated	corrected	simulated	corrected
Jennings Randolph Reservoir Inflows	85%	103%	78%	98%	0.54	0.58	0.89	0.91	0.90	0.93
Savage Reservoir Inflows	118%	100%	142%	94%	0.64	0.70	0.92	0.93	0.89	0.89
Little Seneca Reservoir Inflows	98%	103%	114%	111%	0.71	0.74	0.89	0.91	0.87	0.90
Occoquan Reservoir Inflows	98%	106%	113%	96%	0.54	0.57	0.94	0.95	0.87	0.85
Patuxent reservoir Inflows	92%	105%	95%	102%	0.70	0.72	0.94	0.96	0.88	0.92
Potomac River flows at Little Falls (adjusted to remove effects of WMA withdrawals, inflows from Jennings Randolph, Savage, & Little Seneca reservoir watersheds, and upstream consumptive use)	94%	101%	106%	100%	0.81	0.82	0.97	0.98	0.96	0.97



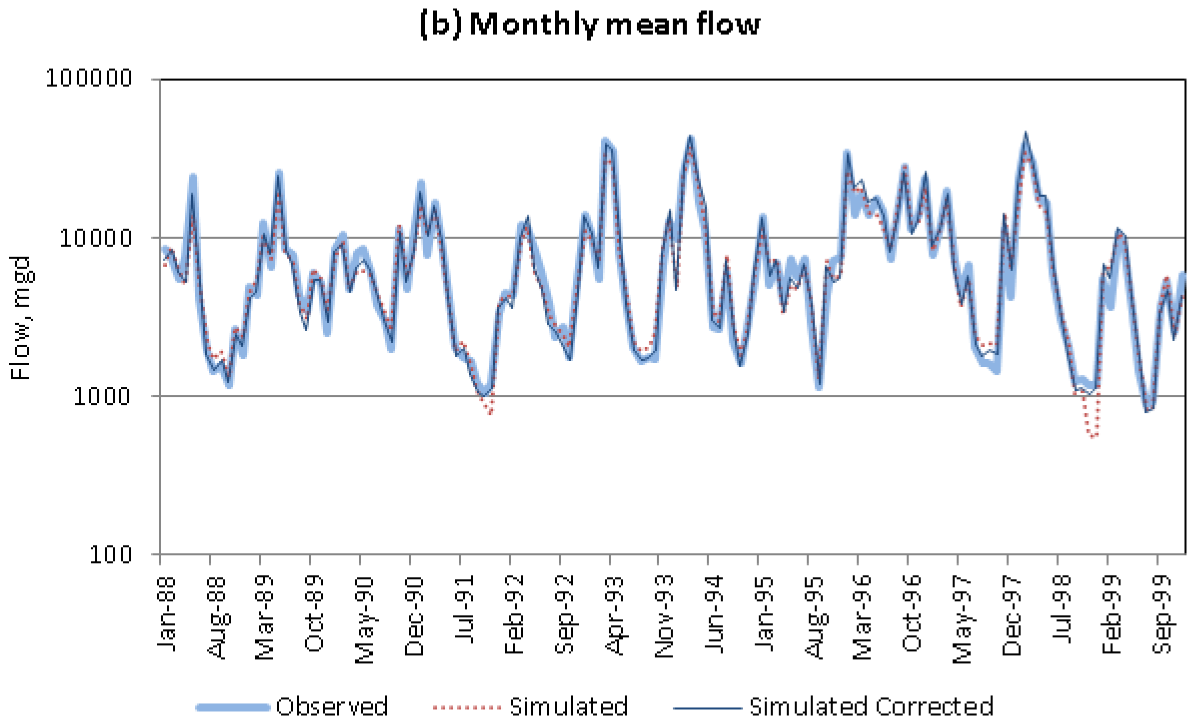


Figure 4-3: Observed, (uncorrected) simulated, and bias-corrected simulated Potomac River flow at Little Falls (with effects of WMA withdrawals, contributions from JR, S, and LS reservoir watersheds, and estimated upstream consumptive use removed).

4.2 Water Demand Model Inputs and Adjustments

4.2.1 Demand Model Inputs

The PRRISM simulates both restricted and unrestricted WMA water demands. "Unrestricted" refers to demands expected in the absence of water use restrictions. "Restricted" refers to demands under water use restrictions, which may be declared during times of drought and other water supply emergencies under a regional response plan, the *Metropolitan Washington Water Supply and Drought Awareness Response Plan: Potomac River System* (MWCOG, 2000).

Forecasts of daily unrestricted demands are based on meteorological conditions and on the day of the week. Each water supplier was assigned a daily precipitation time series based on Phase 5 land segments for each of the 18 climate scenarios. These land segments were identified based on proximity to previously selected NCDC weather stations identified in Part 1 of this study (Ahmed *et al.,* 2010). Table 4-5 summarizes the Phase 5 model land segment and corresponding NCDC weather observation station for each WMA water supplier.

Table 4-5: Precipitation projections and associated Phase 5 land segments.

Water Supplier	Land Segment	NCDC Station Name	NCDC Station ID
Washington Aqueduct	A11001	Washington Reagan Airport	448906
WSSC	A24033	College Park	181995
Fairfax Water	A51059	Vienna	448737

One daily temperature time series was generated for each climate scenario based on the temperature projection corresponding to land segment A11001 (Washington Reagan Airport, NCDC COOP-ID 448906). Temperature is only used in PRRISM's daily water demand model, which assumes that all three water suppliers are influenced by the same regional temperature.

To model the response of WMA water demands to temperature and precipitation, nonlinearity considerations documented in Section 5.6.4 of Part 1 of this study were applied to each of the climate projections. Temperature was broken into piece-wise linear segments at the 90^{o}F breakpoint so that different regression coefficients could be applied to temperatures greater than and less than 90^{o}F. For temperatures lagged by more than one day, no piece-wise partition was used. Precipitation greater than 0.2 inches was assigned a value of 0.2 inches for input to the regression model for WSSC, and any precipitation greater than 0.3 inches was assigned a value of 0.3 inches for Washington Aqueduct and for Fairfax Water. No additional modifications were made to these time series. For more explanation on why this modification was made to the climate inputs, refer to Section 5.6.4 of Part 1 of this study.

4.2.2 Demand Model Adjustments

Four modifications were made to the daily water demand model structure documented in Part 1, Chapter 5 of this study. These modifications included:

1) elimination of the Palmer Hydrological Drought Index (PHDI) as a predictor for variation in daily water demands;
2) adjustment of the remaining predictor variables' coefficients;
3) addition of a spring daily variation equation; and
4) an update of the CO-OP summer autoregressive integrated moving average (ARIMA) model based on the modified daily water demands.

These modifications were necessary in order to remove model dependencies on historical data and to allow the greatest possible flexibility in evaluating seasonal influences on daily water demand.

In PRRISM, daily water demand is a function of:

- simulation year,
- month,
- season,
- climate conditions,
- day of the week, and
- a daily error term based on an ARIMA process. (The ARIMA process was developed to capture the non-random component of the water demand model error.)

Daily demand for each of the three WMA water suppliers is simulated by first computing monthly average demand, which is the product of annual demand and monthly production factors. Second, daily demand is estimated by adding daily variation forecasts in demand to the monthly average demand. Regression models used to forecast daily variations in demand are based on weather and other variables. These models explain the differences seen between daily demand and monthly average conditions. A generic form of a regression equation is given as follows:

$$Y_t = b_0 + b_1 X_{1,t} + \ldots + b_k X_{k,t} + N_t \quad \text{Equation 4-3}$$

where the criterion variable Y_t is the forecast of daily variations in demand, which is modeled as a function of the k predictor variables $X_{1,t}, \ldots, X_{k,t}$. The residual (error) term in this equation is N_t, and the coefficients $b_0, \ldots, b_k$, describe the fixed coefficients that modify the predictor variables. Equation 4-3 is calibrated for each water supplier and can have a different set of coefficients for each season of the year.

The first modification made to Equation 4-3 was the removal of the PHDI. Although, the PHDI is an excellent measure of wet and dry conditions, it was not included as a predictor of daily variation in water demands for the climate change assessment because the index is based on historical data. The PHDI time series, used in Part 1 of this study, was obtained from the NCDC where it was calculated based on precipitation and temperature data, as well as the local available water content of the soil. From these inputs, all the basic terms of the water balance equation can be determined, including evapotranspiration, soil recharge, runoff, and moisture loss from the surface layer. Human impacts on the water balance, such as irrigation, are not considered by the index. While this index has a wealth of information, the historical data could not be easily modified to match projected temperature and precipitation data used to model future climate conditions.

The second modification made to Equation 4-3 was necessary because the PHDI is correlated with other predictors considered in modeling variation in daily demands. Backward stepwise regression methods were therefore used to determine new coefficients with minimal change in model prediction capabilities. Predictors were selected from temperature, both forecasted and lagged by one to five days; precipitation, both forecasted and lagged by one to five days; day of the week (Sunday, Monday, Tuesday…etc.); and the number of days in a row without significant rainfall (defined as less than 0.15 inches).

The third modification expanded the set of seasonal regression models to include a version of Equation 4-3 that simulates spring (March, April, and May) daily water demand. This is in contrast to Part 1 of this study, which only modeled summer (June, July, and August) and fall (September, October, November) daily water demand. In the past, spring daily water demands were not modeled because it is more difficult to fit Equation 4-3 to the spring data. A regression equation was attempted but a meaningful relationship could not be found for the winter season.

Table 4-6, Table 4-7, and Table 4-8 summarize the different coefficients used in Equation 4-3 for the respective spring, summer, and fall seasons for this study.

Table 4-6: Regression coefficients developed for WMA water suppliers (spring months March, April, May).

Independent variable	Water supplier		
	WSSC	Washington Aqueduct	Fairfax Water
Intercept, b_0	-5.70	-14.70	-5.55
Maximum daily temperature		0.08	0.10
Maximum daily temperature, one day prior		0.15	
Maximum daily temperature, two days prior	0.08		
Daily precipitation, one-day forecast	-1.75		-4.20
Daily precipitation, actual	-2.61		-4.11
Daily precipitation, one days prior	-4.54	-4.75	-2.74
Daily precipitation, two days prior	-2.79		-2.41
Daily precipitation, three days prior	-1.75		-3.41
Daily precipitation, four days prior	-2.24		-3.31
Daily precipitation, five days prior	-2.42		-3.02
Day of week – Monday	1.83	-3.49	2.37
Day of week – Thursday	-1.63		
Day of week – Saturday		-3.36	
Day of week – Sunday	3.81	-7.56	3.60
Number of days in a row without significant precipitation	0.40	0.21	0.56
Standard Error of Estimate	9.44	13.36	11.43
Standard Deviation of Criterion Series	10.56	14.10	12.85
Coefficient of Determination (R^2)	0.21	0.11	0.22

Table 4-7: Regression coefficients developed for WMA water suppliers (summer months June, July, August).

Independent variable	Water supplier		
	WSSC	Washington Aqueduct	Fairfax Water
Intercept, b_0	-76.33	-84.07	-71.90
Maximum daily temperature >90	0.43	0.41	0.71
Maximum daily temperature <90	0.36	0.38	0.61
Maximum daily temperature >90, one day prior	0.47	0.42	0.26
Maximum daily temperature <90, one day prior	0.44	0.35	0.21
Maximum daily temperature, two days prior		0.27	
Daily precipitation, one-day forecast			-19.22
Daily Precipitation, actual			-44.21
Daily precipitation, one day prior	-27.81	-17.82	-29.66
Daily precipitation, two days prior	-12.19	-15.37	-20.14
Daily precipitation, three days prior			-16.70
Daily precipitation, four days prior			-3.84
Daily precipitation, five-days prior			-5.02
Day of week – Monday		-6.14	
Day of week – Tuesday			-5.47
Day of week – Thursday			-3.35
Day of week – Saturday		-4.66	
Day of week – Sunday	2.17	-12.02	
Number of days in a row without significant precipitation	1.25	0.54	0.73
Standard Error of Estimate	12.20	14.11	17.55
Standard Deviation of Criterion Series	17.15	19.43	24.43
Coefficient of Determination (R^2)	0.50	0.42	0.47

Table 4-8: Regression coefficients developed for WMA water suppliers (fall months September, October, November).

Independent variable	Water supplier		
	WSSC	Washington Aqueduct	Fairfax Water
Intercept, b_0	-17.28	-18.91	-23.11
Maximum daily temperature	0.10		0.28
Maximum daily temperature, one day prior	0.11	0.28	
Daily precipitation, one-day forecast			-2.94
Daily precipitation, actual	-1.83	-4.20	-4.16
Daily precipitation, one day prior	-3.10		-3.13
Daily precipitation, two days prior	-1.33		-2.93
Daily precipitation, three days prior	-1.84		-2.66
Daily precipitation, four days prior	-1.63		-2.93
Daily precipitation, five days prior	-1.64		-1.97
Day of week – Monday	6.58	-3.62	5.24
Day of week – Saturday		-5.98	
Day of week – Sunday	6.40	-7.03	5.70
Number of days in a row without significant precipitation	0.36	0.43	0.58
Standard Error of Estimate	9.60	12.76	13.76
Standard Deviation of Criterion Series	11.41	14.31	16.24
Coefficient of Determination (R^2)	0.30	0.21	0.29

Figure 4-4 compares estimates of total WMA demands from the regression equations before and after the changes described above with actual demands for the years 1999 through 2002. Demand from the regression model of Part 1 (red) is calculated using the PHDI as a predictor variable. Demand from the model in Part 2 (blue), calculated using the coefficients in Table 4-6 through Table 4-8, is calculated without using the PHDI as a predictor variable. The observed record is shown in black.

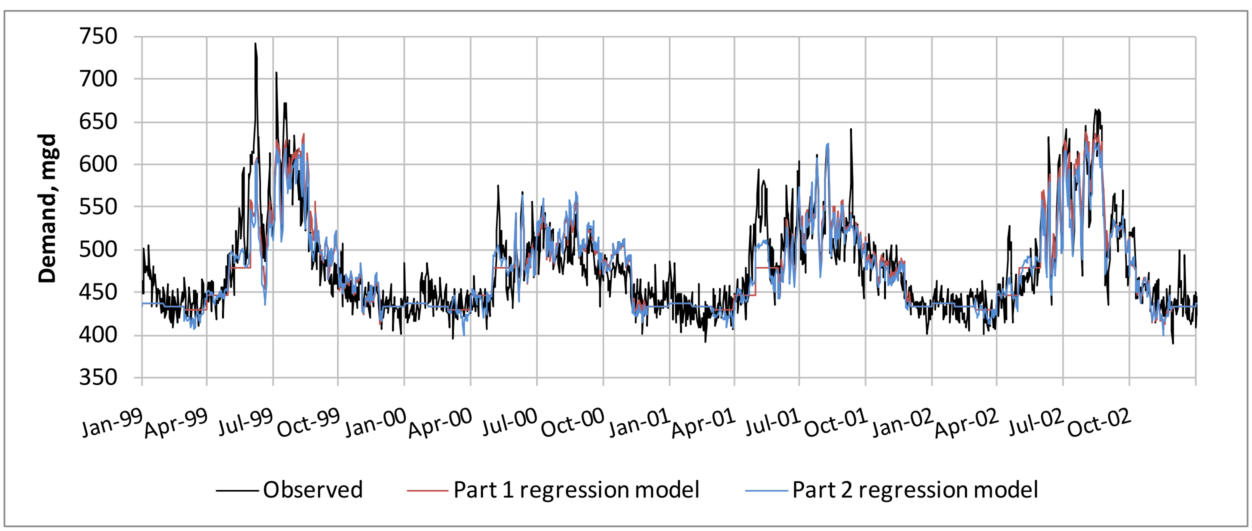


Figure 4-4: Comparison of total daily WMA demands predicted by the Part 1 (red) and Part 2 (blue) regression models for the period 1999-2002. The observed record is shown in black.

The forth modification to the daily demand model was made to the ARIMA modeling process, which is used to separate the error term, N_t, from Equation 4-3 into random and non-random components:

$$N_t = ARIMA_t + random_t \quad \text{Equation 4-4}$$

where $ARIMA_t$ is the non-random portion of N_t calculated by the ARIMA process at time t, and $random_t$ is the random component of N_t at time t. The non-random portion of the error term, N_t, is based on the ARIMA model for the CO-OP system as a whole, apportioned to the three suppliers based on relative demand.

The ARIMA models for the individual suppliers were not used in the simulation because of the correlation in these error terms, which would result in a dampening of total error if they were summed. Table 4-9 summarizes the updated CO-OP system ARIMA model. A random number generator was used for the random component of N_t, assuming a normal distribution, mean of zero, and the standard deviation of 22.66 mgd.

Table 4-9: Coefficient estimates of the ARIMA residual model and statistics.

	ARIMA	Coefficient	Coefficient value	Coefficient standard error of estimate	Coefficient T-ratio
CO-OP Summer	(1,0,1)	AR1 MA1	0.916 0.497	0.027 0.046	33.926 10.804
Model Chai-squared	11.28				
Model standard deviation	32.69				
Model standard error of estimate	22.66				

The coefficient of determination (R^2) between observed and modeled demand is given in Table 4-10. This is a measure of how well the combined regression and ARIMA models perform in estimating demand. Statistics are provided for the Part 1 and Part 2 model calibrations period 1995 through 2008. They are primarily provided for the summer model for each supplier, as that is the time period of highest demand and greatest interest. The closeness of the R^2 values between the two studies suggests that the model performance is similar between Part 1 and Part 2 model calibrations. However, the PHDI does seem to provide some benefit to the Part 1 demand model.

Table 4-10: Regression plus ARIMA coefficients of determination.

	2010 Part 1 R^2	2010 Part 2 R^2
Fairfax Water Summer	0.89	0.81
WSSC Summer	0.72	0.67
Washington Aqueduct Summer	0.59	0.53
WMA Summer	0.85	0.81
WMA Fall	0.87	0.80
WMA Spring	NA	0.59

4.3 Reservoirs

PRRISM estimates net evaporative losses from system reservoirs based on daily precipitation and monthly pan evaporation time series. (Net evaporative losses equal precipitation entering a reservoir minus the evaporation from the reservoir.) The precipitation time series used in these calculations, listed in Table 4-5, were assigned as follows: Occoquan assumed the same precipitation used for Fairfax Water and Patuxent, Seneca, Jennings Randolph, and Savage assumed the same precipitation used for WSSC. The pan evaporation time series were based on historical data and were not updated to reflect the impact of climate change.

4.4 Reference Conditions for Comparison with Climate Change Results

In the following chapters, projections of meteorological and hydrologic conditions under climate change are compared with conditions in the 12-year period from 1988 to 1999, using two different reference scenarios: a “base” condition, with stream flows simulated by the Phase 5 model, and an “observed” condition, with stream flows as measured at USGS gage stations. The impact of climate change on WMA system reliability is most appropriately evaluated by comparing climate change and base condition results. This is because although bias correction was applied, some model error is still present in the simulated flows. Because the Phase 5 simulations of flow under climate change are likely to reflect similar model errors, changes under climate change are likely more accurately predicted by differences in climate change and base condition results than by differences in climate change and observed condition results.

The successive changes made to PRRISM model assumptions to develop the observed and base conditions are listed below:

Pre-modified observed: CO-OP daily water supply demand forecasts are implemented as presented in Chapter 5 of Part 1 of this study. PRRISM flow time series inputs are computed from USGS observed flows.

Observed: CO-OP daily water supply demand forecasts are modified so that the PHDI is excluded as a predictor variable. This includes modifications to the demand regression equations, the random number generator, and the ARIMA model described above. PRRISM flow time series inputs are computed from USGS observed flows.

Base: Includes modified daily demand forecasts as described in “Observed.” PRRISM flow time series inputs are computed from Phase 5 simulated flows for the period from 1988 to 1999.

A comparison of PRRISM simulation results for WMA system reliability using the pre-modified observed, observed, and base scenarios is given later in this report in Table 6-4.

5 Comparison of Current and Projected Future Conditions

Each climate scenario provides a unique interpretation of what the future might hold in terms of temperature, precipitation, potential evapotranspiration, stream flows, and water supply demands. All of these factors help determine the reliability of the WMA water supply system and are important PRRISM inputs. This chapter describes predicted changes under this study's 18 climate change scenarios that could affect water demand and availability.

Conditions under climate change are compared with observed and base conditions, both of which are approximate representations of current conditions. However, the base scenario is probably the best basis for comparison with the climate scenarios because it reflects similar model limitations and has been bias corrected using the same method. For more explanation on climate change scenario abbreviations used in figure legends, refer back to Table 3-1 and Table 3-2 in Section 3.3.

5.1 Temperature and Precipitation

Both temperature and precipitation patterns are expected to change in the future. Projected changes in monthly average temperature and precipitation in the Potomac basin above Little Falls are shown in Figure 5-1. Temperature changes are reported as the difference between the climate scenario projection and the base value, in degrees Celsius. Precipitation changes are reported as a percent difference: the difference between the climate scenario projection and the base value, divided by the base value and multiplied by 100. The graphs in Figure 5-1 show basin-wide averages, obtained from Phase 5 temperature and precipitation time series by computing area-weighted means of values for individual model land segments.

In the 18 climate scenarios the increase in annual average temperature by the year 2040 ranges from 0.7 to 2.3 ^{o}C, with an average over all scenarios of 1.5 ^{o}C (see Table 5-1). The monthly average temperatures also show a strong tendency to increase, as shown in Figure 5-1. In a few cases, however, there are slight decreases in monthly average temperature, mainly in the winter months.

Future precipitation in the Potomac basin is also likely to change, but model projections differ on whether precipitation will decrease or increase. The 18 climate scenarios used in this study are approximately evenly split; the projected change in total annual precipitation, in comparison with the base value of 42.2 inches, ranges from -4.0 to +3.9 inches, or minus nine percent to plus nine percent (see Table 5-1). There are also considerable differences in the monthly projections, as shown in Figure 5-1.

Figure 5-1 shows the variation in each of the GCM's monthly temperature and precipitation projections by greenhouse gas emission scenario (A2-"high" emissions scenario, A1B-"medium," and B1-"low"). The differences in global temperature change projections for these three scenarios, as indicated in Figure 3-2, are significant toward the latter part of the 21st century. They are less pronounced in the year 2040, which is consistent with results in Figure 5-1.

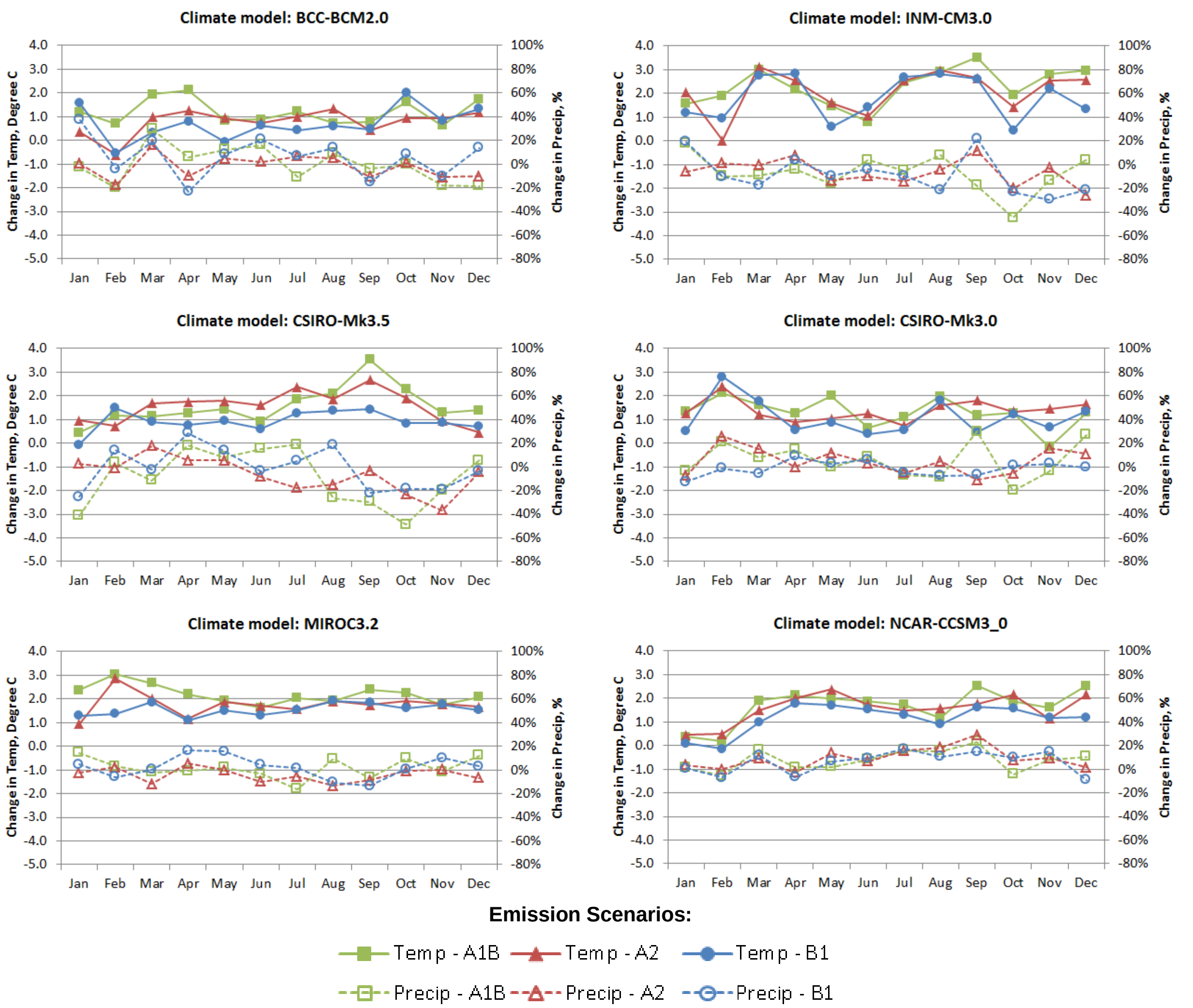


Figure 5-1: Change in basinwide monthly average air temperature (°C) and monthly total precipitation (%) for different climate models and emission scenarios.

5.1.1 Temperature Extremes

Figure 5-2 compares the number of days per year that daily maximum temperature for Phase 5 land segment A11001 (which includes Washington Reagan Airport, NCDC COOP-ID 448906) qualifies as an extreme event for current and projected future conditions. Extreme temperature events are defined as days with maximum temperatures above 32.2°C (90°F). Extreme temperature events may increase in the future. These events occur mostly during the spring, summer, and fall months, particularly during the months of July and August. Increases in these events may increase water supply demands by increasing outdoor water use. (See Section 4.2.2 for more details on how PRRISM responds to temperature changes.)

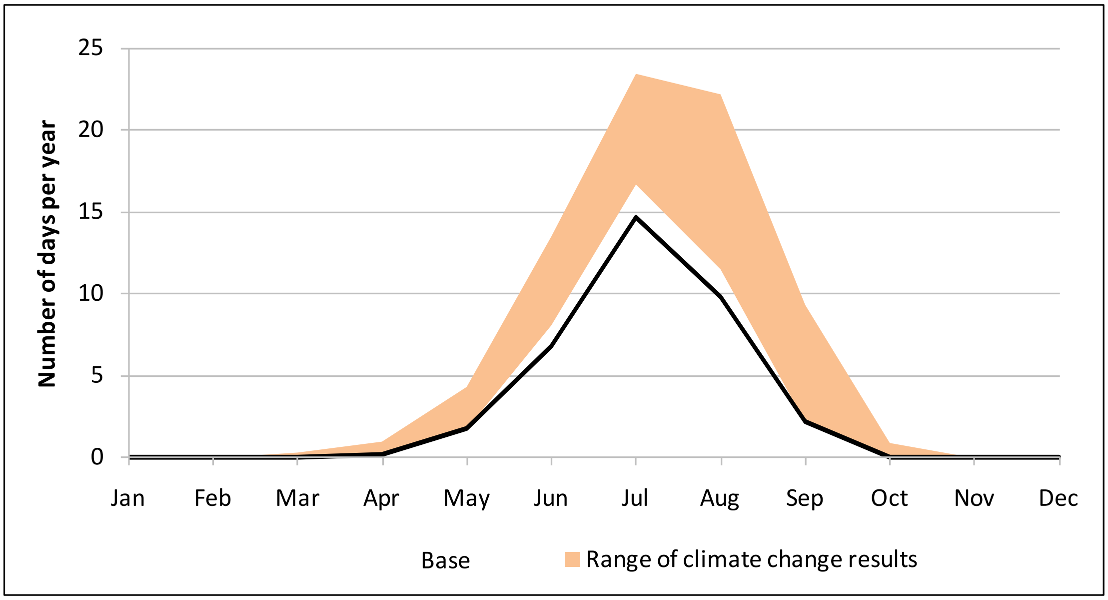


Figure 5-2: Average number of days per year with maximum temperatures above 32.2°C (90°F). Data is for land segment A11001 (which includes Washington Reagan Airport, NCDC Station ID 448906).

5.1.2 Precipitation Extremes

Due to limitations in the precipitation projections used in this study, extreme patterns in precipitation data are not reported. As discussed in Section 3.4, this study uses climate change projections for precipitation that are based on monthly change factors. Although, extreme precipitation events from the observed record are more or less severe depending on the change factor that is applied, no additional adjustments were made to account for possible changes in the frequency or duration of extreme precipitation events at the daily or hourly time step. Additionally, these events cannot influence simulated water supply withdrawals because one of the PRRISM modeling assumptions is that precipitation above a certain threshold does not affect demand. (See the nonlinearity discussion at the end of Section 4.2.1.)

5.2 Stream Flow

As discussed in Chapter 1, this study's climate change scenarios were constructed by first combining GCM projections of mean monthly temperature and precipitation in the Potomac basin in the year 2040 with historical data from the 12-year period from 1988 through 1999. These data were then used to simulate basin stream flows. The resulting sets of daily stream flow simulations are 12 years in length, with each year representing potential conditions in 2040. The statistics reported below are computed over this 12-year simulation period.

5.2.1 Potomac River Flow at Little Falls

Figure 5-3 shows that the tendency for natural Potomac River flow at Little Falls to drop below 700 mgd in a given month may increase due to climate change. At this flow level water supply releases from Jennings Randolph and Little Seneca reservoirs may occur. Natural Little Falls flow is defined as observed flow at the Little Falls gage (USGS site 01646500) with adjustments made to remove the effects of WMA withdrawals and North Branch reservoir releases. Little Falls is also the location of the most downstream metropolitan area water supply intake and has a minimum environmental flow recommendation of 100 mgd (MD DNR, 1981; U.S. Army Corps of Engineers *et al.*, 2012).

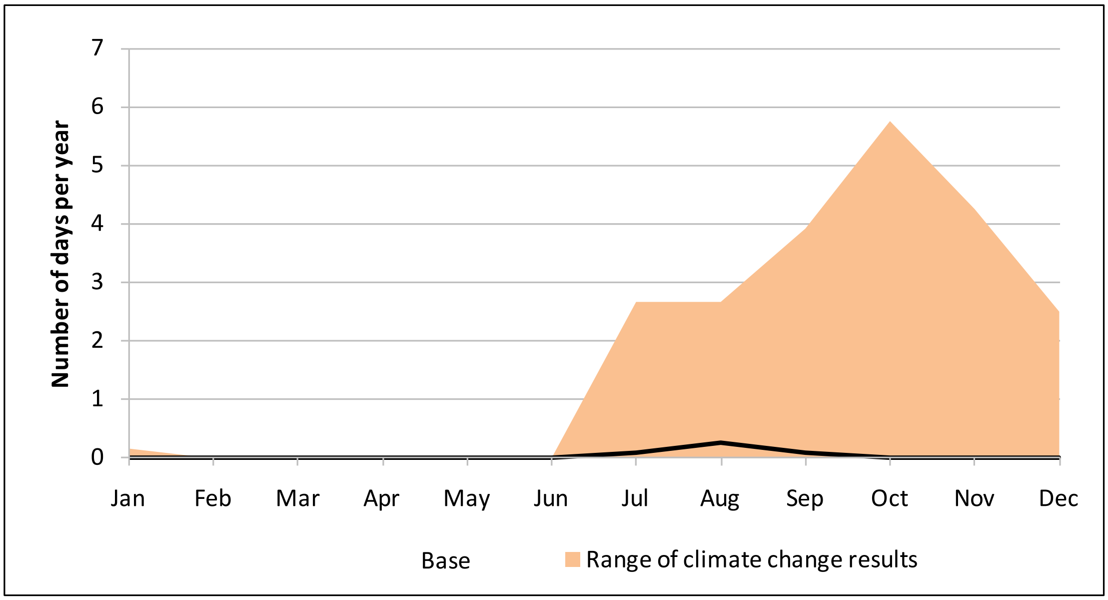
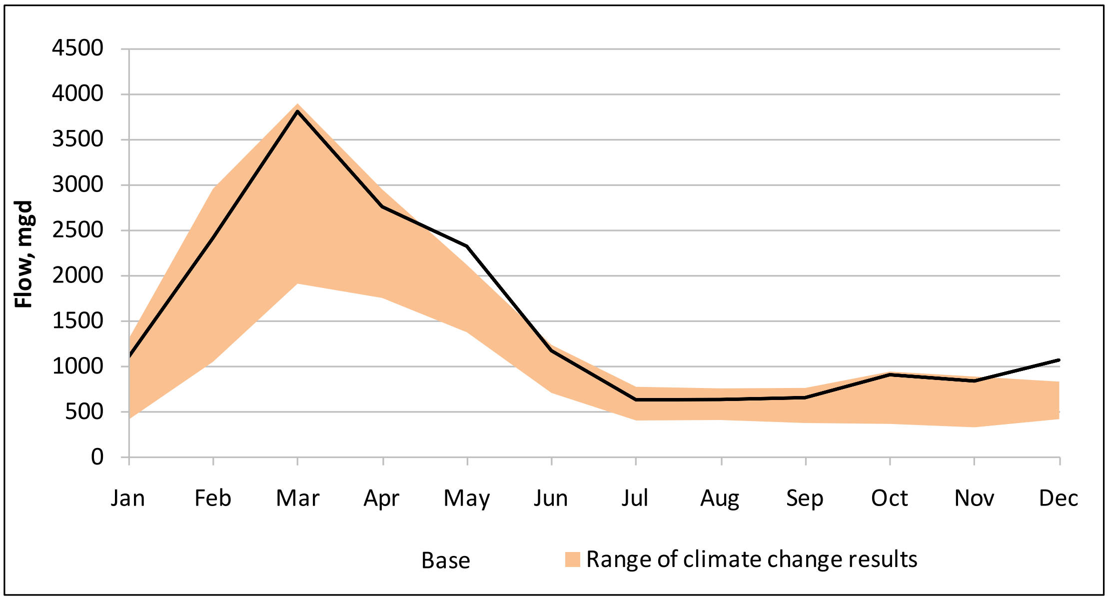


Figure 5-3: Average number of days per year that natural Potomac River flow at Little Falls fell below 700 mgd.

Figure 5-4 supports results in Figure 5-3 in that it shows that both median and minimum natural flow at Little Falls may decrease under climate change. The graphs respectively show the lowest daily flow and the median daily flow for each month of the year over the 12-year simulation period. These graphs shows that that flows in the Potomac River decrease in most of the 18 climate change scenarios considered in this study. Only a few of the future climate scenarios show shifts towards higher than base scenario flows. Scenario B_B1 in Figure 5-4 is the strongest example of this.



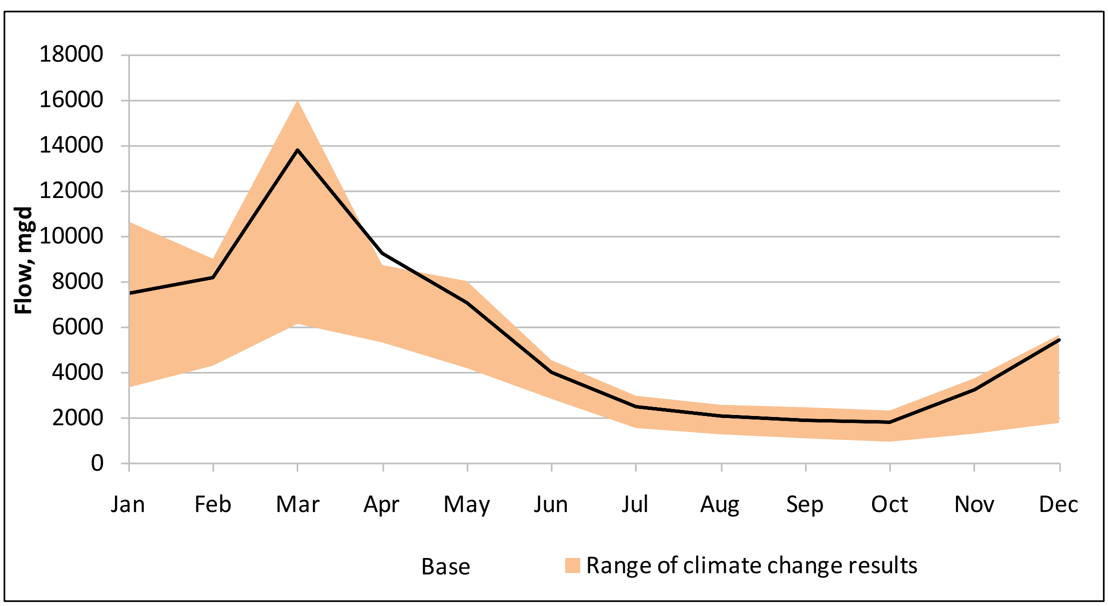


Figure 5-4: Monthly minimum (top graph) and median (bottom graph) natural Potomac River flow at Little Falls.

5.2.2 Reservoir Inflows

Figure 5-5 through Figure 5-9 show that projected total monthly reservoir inflows, averaged over the 12-year simulation period, are in some cases greater and in some cases smaller than historically observed inflows. A reduction in total monthly inflows, which occurs in the majority of the scenarios, means a reduction in the amount of water available to replenish reservoir storage.

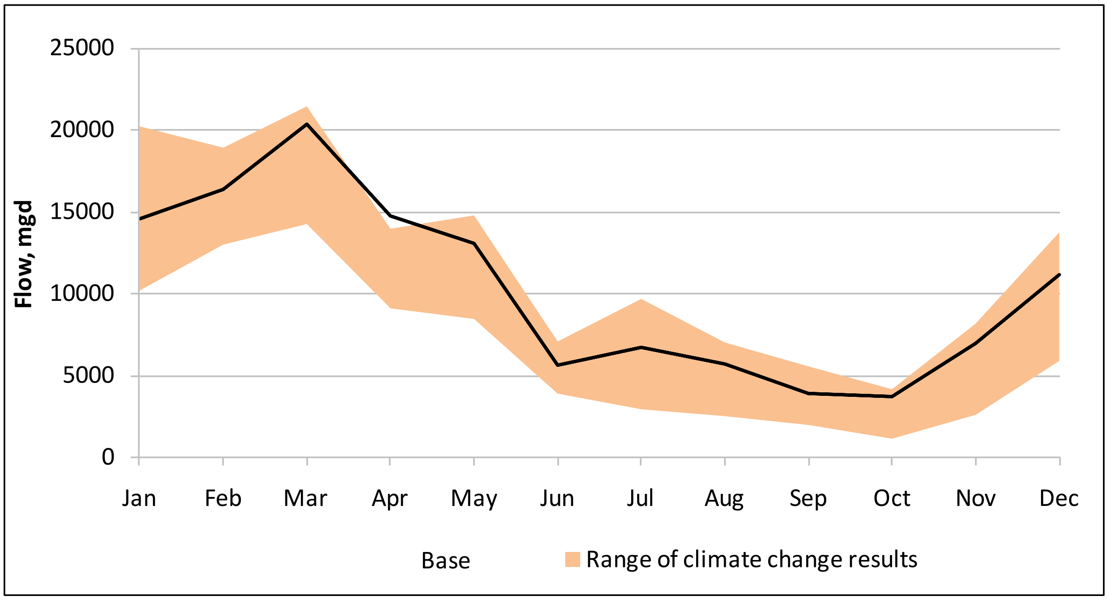


Figure 5-5: Jennings Randolph Reservoir total monthly inflows averaged over the 12-year simulation period.

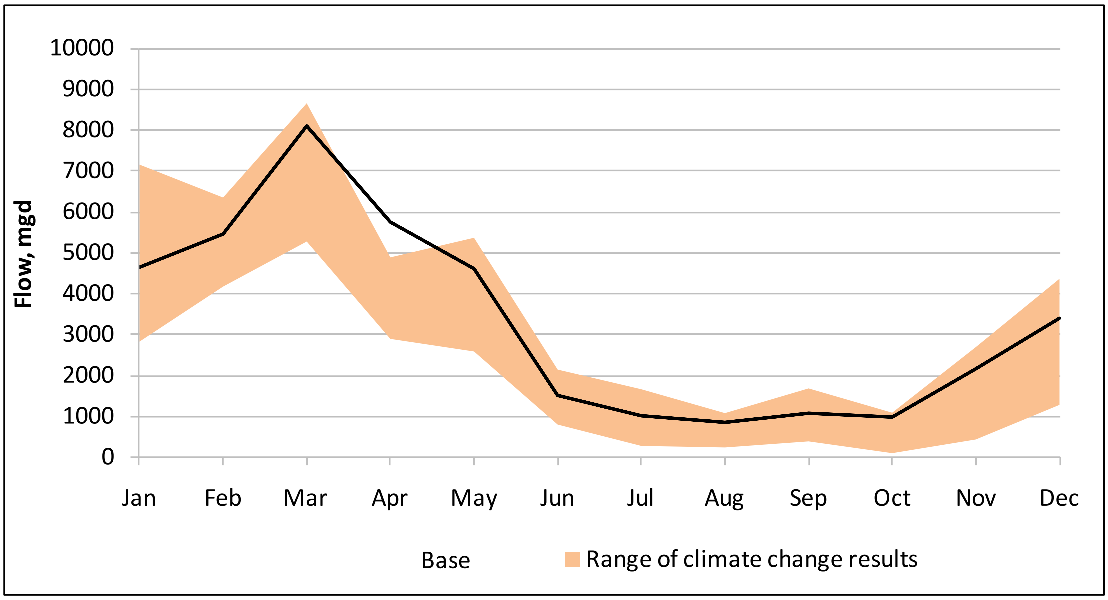


Figure 5-6: Savage Reservoir total monthly inflows averaged over the 12-year simulation period.

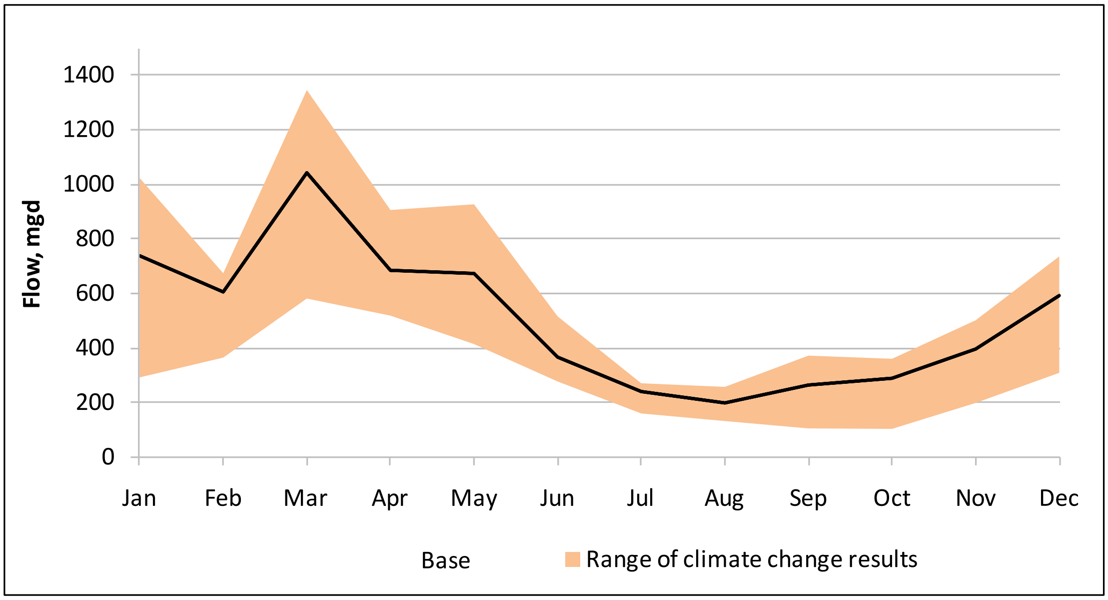


Figure 5-7: Little Seneca Reservoir total monthly inflows averaged over the 12-year simulation period.

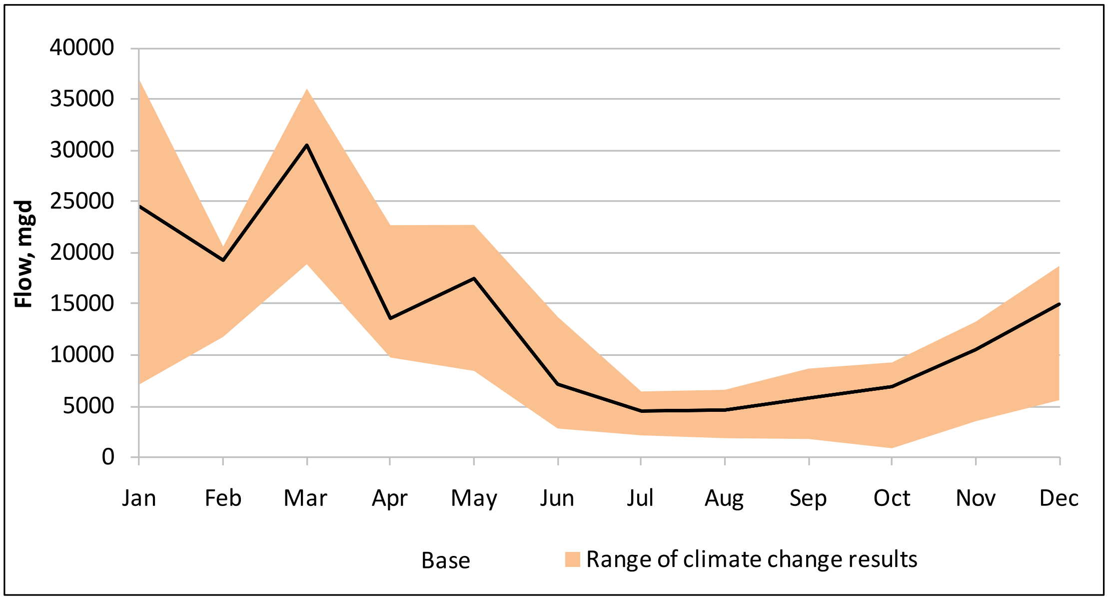


Figure 5-8: Occoquan Reservoir total monthly inflows averaged over the 12-year simulation period.

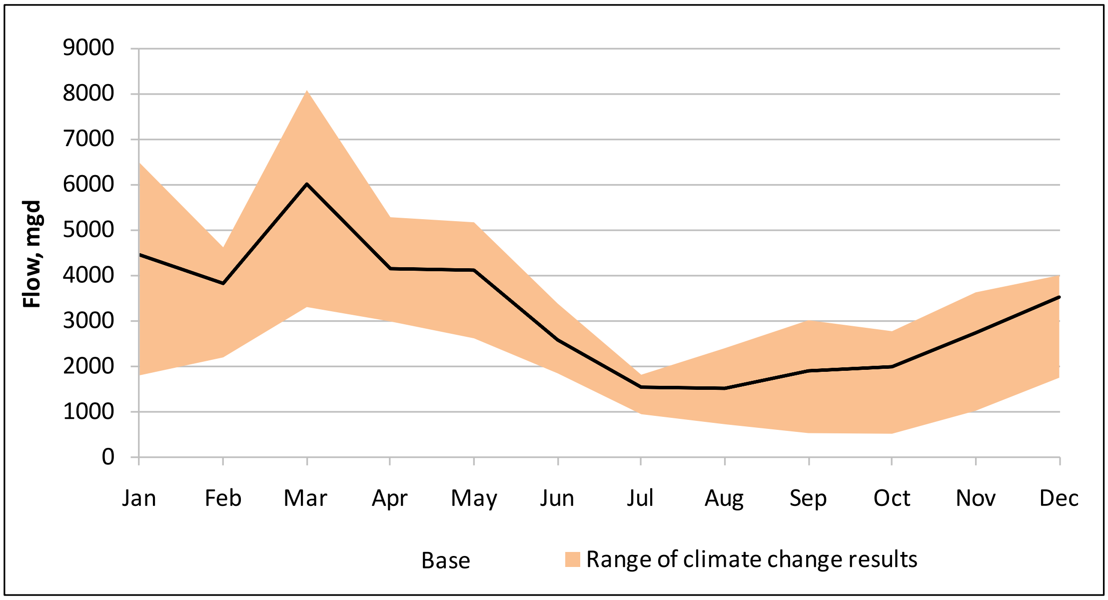


Figure 5-9: Patuxent reservoirs (Tridelphia and Rocky Gorge) total monthly inflows averaged over the 12-year simulation period.

5.3 Basin-wide Water Budget

Climate change will affect stream flows in the Potomac basin via a number of interrelated processes which are sensitive to changes in both temperature and precipitation. As discussed in Chapter 2, it is believed by many scientists, based on current global model results, that precipitation will increase in the Potomac region. Increased precipitation is likely to lead to more surface runoff to streams during rain events and potentially to increased recharge to groundwater aquifers. Groundwater is generally the primary source of stream flow during dry weather periods. However, rising temperatures will cause more precipitation to be lost to evaporation from the soil, streams, and other surfaces in the basin and will increase transpiration, that is, the water released to the atmosphere by plants. These increases in evapotranspiration will tend to decrease flow in basin streams.

Results presented in the previous sections show that though there is increased precipitation in half of the 18 climate change scenarios, both minimum and median monthly flows in the Potomac River decrease in most scenarios. To better understand how projected changes in temperature and precipitation affect stream flows, it is worthwhile to examine more closely their effects on watershed processes. The Phase 5 model, used to generate stream flows in this study, is based on the Hydrologic Simulation Program – FORTRAN model (HSPF). It was used in this study to generate a number of additional HSPF outputs to help characterize annual and monthly basin-wide water budget components.

HSPF estimates of annual basin-wide evapotranspiration, stormflow, and baseflow were computed for each of the climate scenarios. These quantities are related by the simple water budget equation:

$$P = ET + Q_{SF} + Q_{BF} \qquad \text{Equation 5-1}$$

where here P represents total water from precipitation entering stream flow, ET is total evapotranspiration from the watershed, Q_{SF} is the stormflow component of stream flow, and Q_{BF} is the baseflow component of stream flow. Baseflow is defined as the component of stream flow that is groundwater discharged from surrounding aquifers. Stormflow is defined in this study as the difference between total stream flow and baseflow. It is computed in HSPF as the sum of overland flow and interflow. Overland flow is the runoff of precipitation from the land surfaces. Interflow is the portion of water from a storm event that infiltrates through the ground's surface and travels laterally through unsaturated upper zone soil layers before discharging to streams.

Table 5-1 contains basin-wide averages of annual precipitation, evapotranspiration, stormflow, and baseflow for the base scenario and for the 18 climate scenarios. These values were obtained by computing area-weighted averages of annual water budget components for each Potomac basin land segment, available in the HSPF output files. The calculations were restricted to areas of the upper portion of the Potomac watershed, upstream of the USGS gage on the Potomac River at Little Falls near Washington, D.C. Results show that though average precipitation increases in the Potomac basin in nine out of the 18 climate change scenarios, evapotranspiration increases in all climate change scenarios due to higher temperatures. As a result, basin-wide averages of total stream flow decrease by as much as 35 percent in 14 out of the 18 scenarios. Average annual baseflow, which is particularly important to water supply because it constitutes the majority of stream flow during dry weather periods, decreases in the basin in 16 out of the 18 scenarios, by as much as 34 percent.

Table 5-2 and Table 5-3 contain the Phase 5 model's estimates of basin-wide mean monthly inflow to and outflow from groundwater storage, that is, recharge and baseflow. Table 5-2 indicates that according to the Phase 5 model estimates, the seasonal pattern of groundwater recharge does not change significantly under climate change, with January, February and March remaining the months of greatest recharge, and June, July, August, September, and October remaining the months of least recharge. The last column of Table 5-2 shows that mean annual groundwater recharge decreases in the Potomac basin under all but three climate scenarios. Average monthly baseflows in Table 5-3 are significantly less than base scenario values for many of the climate change scenarios, with the percent decrease in baseflow being greatest in the months of September through November.

In the last column of Table 5-1, the climate scenarios are ranked by total stream flow. The scenario with the greatest total stream flow, B_B1, is ranked as 1, and the scenario with the least total stream flow, I_A1B, is ranked as 18. By this ranking, the six climate scenarios with the most severe impact on stream flow (with ranks of 13 to 18) are C3.5_A1B, C3.5_A2, I_A1B, I_A2, I_B1, and M_A2. In these six scenarios, total annual precipitation decreases by 2.4 to 4.0 inches, or six to nine percent, compared with current conditions. Temperature increases by 1.6 to 2.3 ^{o}C. Evapotranspiration increases by five to eight percent. Baseflow and total stream flow fall by 24 to 34 percent and by 26 to 35 percent, respectively. A review of results in Table 5-3 for these six scenarios shows that reductions in mean monthly baseflows in August and September are in some cases even more severe, ranging from 20 to 51 percent.

Table 5-1: Basin-wide mean annual water budget for the base scenario and for the 18 climate change scenarios.

Scenario	Temperature change	Precipitation	Evapotranspiration	Stormflow	Baseflow	Total stream flow	Precipitation	Evapotranspiration	Stormflow	Baseflow	Total stream flow	Rank
	(°C)	(inches)	(inches)	(inches)	(inches)	(inches)	(percent)	(percent)	(percent)	(percent)	(percent)	
Base	0.00	42.2	27.3	6.4	8.6	15.0						
B_A1B	1.2	42.2	29.0	5.9	7.5	13.4	100%	106%	93%	87%	89%	8
B_A2	0.8	41.7	28.5	5.8	7.5	13.3	99%	104%	90%	88%	89%	9
B_B1	0.7	45.0	28.5	7.7	8.9	16.6	107%	105%	120%	104%	111%	1
C3.0_A1B	1.3	44.0	29.2	6.7	8.2	14.9	104%	107%	104%	96%	99%	5
C3.0_A2	1.4	43.7	29.2	6.5	8.1	14.6	103%	107%	102%	94%	98%	6
C3.0_B1	1.1	41.0	28.5	5.3	7.3	12.6	97%	105%	83%	85%	84%	11
C3.5_A1B	1.6	38.2	28.9	4.0	5.7	9.7	91%	106%	63%	66%	65%	17
C3.5_A2	1.6	39.6	28.7	4.7	6.4	11.1	94%	105%	74%	75%	74%	13
C3.5_B1	0.9	41.3	28.7	5.6	7.2	12.8	98%	105%	87%	84%	86%	10
I_A1B	2.3	38.9	29.5	3.8	5.9	9.7	92%	108%	59%	68%	65%	18
I_A2	2.1	39.1	29.2	4.1	6.0	10.1	93%	107%	64%	70%	67%	15
I_B1	1.8	38.6	28.9	4.0	5.9	9.9	91%	106%	62%	69%	66%	16
M_A1B	2.2	42.1	29.9	5.3	7.1	12.4	100%	110%	83%	83%	83%	12
M_A2	1.8	39.8	29.0	4.5	6.5	11.0	94%	106%	70%	76%	73%	14
M_B1	1.6	42.8	29.4	6.0	7.5	13.5	101%	108%	93%	88%	90%	7
N_A1B	1.7	45.5	30.2	7.0	8.3	15.3	108%	111%	109%	97%	102%	4
N_A2	1.6	46.1	30.2	7.4	8.6	15.9	109%	111%	115%	100%	106%	2
N_B1	1.2	45.1	29.5	7.3	8.3	15.6	107%	108%	113%	97%	104%	3
Average of 18 climate change scenarios	1.5	41.9	29.2	5.6	7.3	12.9	99%	107%	88%	85%	86%	

Table 5-2: Basin-wide mean monthly inflow to groundwater storage (recharge) for the 18 climate change scenarios (inches and percentage of base).

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total annual
Base	1.31	1.28	1.69	0.67	0.81	0.42	0.44	0.34	0.44	0.46	0.70	0.90	9.46
B_A1B	1.21	0.86	1.75	0.65	0.83	0.47	0.33	0.34	0.36	0.38	0.51	0.72	8.41
	92%	*68%*	*103%*	*96%*	*103%*	*111%*	*75%*	*100%*	*82%*	*83%*	*73%*	*80%*	89%
B_A2	1.23	0.96	1.73	0.58	0.77	0.40	0.42	0.34	0.33	0.39	0.54	0.81	8.49
	94%	*75%*	*102%*	*87%*	*95%*	*94%*	*95%*	*98%*	*75%*	*84%*	*77%*	*90%*	90%
B_B1	1.74	1.11	1.87	0.53	0.80	0.50	0.45	0.41	0.35	0.43	0.60	1.05	9.84
	133%	87%	111%	79%	99%	117%	103%	119%	79%	94%	86%	117%	104%
C3.0_A1B	1.35	1.19	1.59	0.71	0.72	0.43	0.35	0.27	0.50	0.34	0.62	1.15	9.19
	103%	93%	94%	105%	89%	101%	79%	78%	114%	73%	89%	128%	97%
C3.0_A2	1.25	1.19	1.69	0.65	0.83	0.40	0.36	0.33	0.31	0.34	0.66	1.01	9.03
	95%	93%	100%	96%	103%	95%	83%	96%	71%	74%	96%	113%	95%
C3.0_B1	1.15	0.99	1.36	0.68	0.77	0.42	0.36	0.27	0.32	0.37	0.61	0.91	8.22
	88%	78%	80%	100%	95%	99%	82%	79%	74%	81%	88%	101%	87%
C3.5_A1B	1.27	0.92	1.22	0.55	0.56	0.38	0.31	0.28	0.23	0.13	0.33	0.68	6.87
	97%	72%	72%	81%	69%	89%	70%	82%	52%	29%	47%	76%	73%
C3.5_A2	1.06	0.94	1.36	0.63	0.59	0.31	0.26	0.22	0.34	0.25	0.46	0.56	6.99
	81%	74%	80%	94%	73%	74%	59%	65%	77%	55%	66%	62%	74%
C3.5_B1	1.27	0.96	1.16	0.57	0.63	0.34	0.28	0.17	0.37	0.26	0.32	0.56	6.90
	97%	76%	68%	85%	78%	81%	64%	50%	84%	55%	47%	62%	73%
I_A1B	1.43	0.98	1.36	0.58	0.72	0.36	0.27	0.30	0.29	0.36	0.53	0.94	8.12
	109%	77%	80%	86%	89%	85%	61%	86%	66%	79%	77%	104%	86%
I_A2	1.17	1.00	1.25	0.63	0.71	0.32	0.31	0.22	0.27	0.31	0.51	0.76	7.46
	89%	79%	74%	94%	88%	76%	71%	64%	61%	67%	73%	84%	79%
I_B1	1.33	0.99	1.46	0.71	0.86	0.41	0.39	0.26	0.28	0.34	0.60	0.91	8.53
	101%	78%	86%	106%	106%	96%	88%	75%	63%	74%	87%	101%	90%
M_A1B	1.29	1.09	1.69	0.63	0.72	0.41	0.46	0.39	0.50	0.41	0.69	1.04	9.32
	99%	85%	100%	93%	90%	98%	105%	112%	113%	89%	99%	116%	99%
M_A2	1.34	1.14	1.64	0.60	0.80	0.42	0.47	0.40	0.55	0.48	0.75	0.99	9.56
	102%	89%	97%	89%	99%	98%	106%	116%	124%	104%	107%	111%	101%
M_B1	1.24	1.05	1.70	0.60	0.77	0.43	0.48	0.38	0.47	0.47	0.78	0.93	9.31
	94%	83%	101%	90%	95%	101%	110%	110%	108%	103%	112%	104%	98%
N_A1B	1.29	1.09	1.69	0.63	0.72	0.41	0.46	0.39	0.50	0.41	0.69	1.04	9.32
	99%	85%	100%	93%	90%	98%	105%	112%	113%	89%	99%	116%	99%
N_A2	1.34	1.14	1.64	0.60	0.80	0.42	0.47	0.40	0.55	0.48	0.75	0.99	9.56
	102%	89%	97%	89%	99%	98%	106%	116%	124%	104%	107%	111%	101%
N_B1	1.24	1.05	1.70	0.60	0.77	0.43	0.48	0.38	0.47	0.47	0.78	0.93	9.31
	94%	83%	101%	90%	95%	101%	110%	110%	108%	103%	112%	104%	98%

Table 5-3: Basin-wide mean monthly stream baseflow, in inches and as a percentage of base condition, for the 18 climate change scenarios (inches and percentage of base).

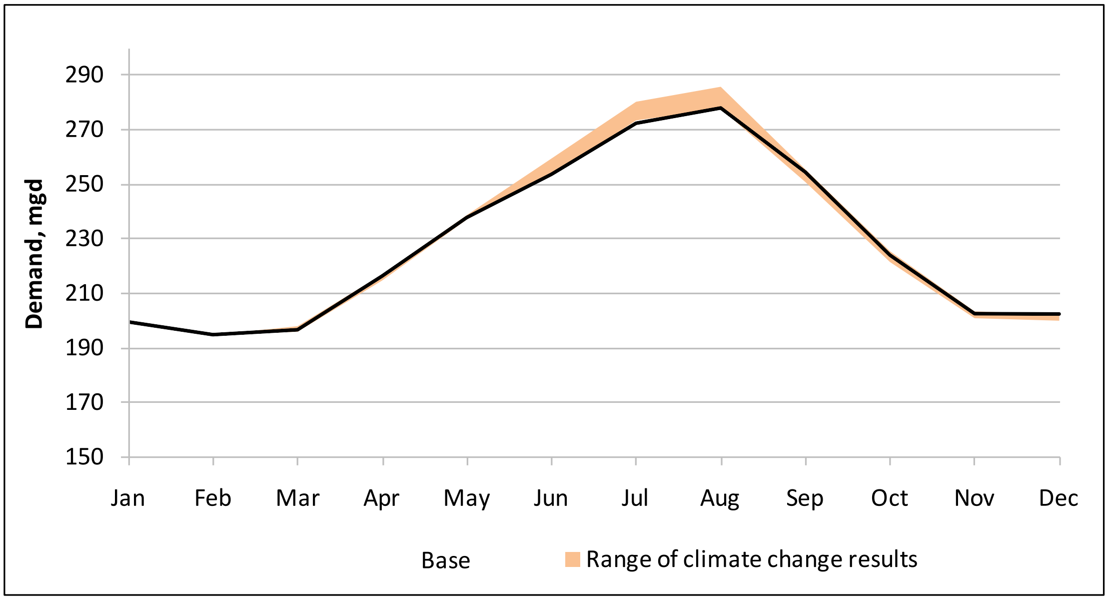
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Base	0.93	1.09	1.45	1.14	0.86	0.55	0.38	0.33	0.30	0.37	0.47	0.69
B_A1B	0.79	0.87	1.27	1.08	0.82	0.56	0.35	0.29	0.25	0.30	0.35	0.52
	85%	*80%*	*87%*	*94%*	*96%*	*102%*	*91%*	*88%*	*82%*	*81%*	*76%*	*76%*
B_A2	0.84	0.93	1.31	1.06	0.78	0.50	0.35	0.30	0.24	0.29	0.37	0.58
	90%	*85%*	*91%*	*93%*	*90%*	*92%*	*90%*	*93%*	*79%*	*78%*	*78%*	*84%*
B_B1	1.15	1.20	1.53	1.15	0.81	0.57	0.41	0.37	0.28	0.33	0.41	0.70
	124%	*110%*	*105%*	*101%*	*94%*	*105%*	*107%*	*112%*	*93%*	*89%*	*89%*	*102%*
C3.0_A1B	1.02	1.08	1.38	1.09	0.80	0.51	0.33	0.25	0.26	0.33	0.38	0.74
	110%	99%	95%	96%	94%	93%	86%	77%	87%	88%	82%	108%
C3.0_A2	0.93	1.03	1.40	1.11	0.84	0.54	0.34	0.29	0.23	0.26	0.39	0.69
	100%	95%	96%	97%	98%	99%	89%	88%	75%	71%	83%	100%
C3.0_B1	0.84	0.92	1.15	0.96	0.78	0.51	0.33	0.26	0.21	0.27	0.38	0.63
	90%	85%	79%	84%	91%	93%	87%	79%	70%	73%	81%	92%
C3.5_A1B	0.53	0.63	0.96	0.87	0.75	0.50	0.36	0.26	0.15	0.12	0.16	0.37
	57%	58%	66%	76%	87%	92%	94%	80%	49%	32%	33%	54%
C3.5_A2	0.68	0.85	1.24	1.03	0.78	0.46	0.25	0.18	0.16	0.18	0.19	0.37
	73%	78%	85%	91%	91%	85%	66%	56%	53%	50%	40%	53%
C3.5_B1	0.71	0.86	1.20	1.06	0.88	0.55	0.35	0.32	0.24	0.24	0.29	0.52
	76%	79%	83%	93%	103%	100%	91%	99%	79%	64%	63%	75%
I_A1B	0.73	0.89	1.05	0.82	0.60	0.39	0.26	0.22	0.16	0.14	0.18	0.39
	79%	82%	73%	72%	70%	72%	67%	66%	54%	39%	38%	57%
I_A2	0.64	0.80	1.11	0.89	0.65	0.39	0.23	0.18	0.18	0.22	0.27	0.42
	69%	73%	76%	78%	76%	71%	60%	55%	59%	58%	59%	61%
I_B1	0.69	0.89	1.05	0.80	0.64	0.40	0.24	0.17	0.18	0.23	0.23	0.37
	75%	82%	72%	70%	74%	73%	64%	53%	60%	62%	49%	54%
M_A1B	0.95	1.00	1.18	0.92	0.72	0.45	0.26	0.22	0.19	0.25	0.34	0.60
	103%	91%	81%	81%	84%	83%	68%	68%	64%	67%	72%	87%
M_A2	0.77	0.91	1.10	0.88	0.71	0.43	0.26	0.20	0.17	0.22	0.31	0.52
	83%	83%	75%	77%	83%	78%	68%	63%	56%	59%	65%	76%
M_B1	0.90	0.98	1.22	1.01	0.85	0.54	0.34	0.26	0.20	0.24	0.36	0.62
	97%	89%	84%	89%	99%	99%	90%	81%	65%	66%	76%	90%
N_A1B	0.96	1.04	1.39	1.08	0.78	0.50	0.35	0.33	0.31	0.37	0.44	0.74
	104%	95%	96%	94%	90%	90%	93%	103%	102%	100%	95%	107%
N_A2	0.98	1.07	1.39	1.06	0.80	0.52	0.37	0.35	0.33	0.42	0.50	0.76
	105%	98%	96%	93%	93%	95%	96%	106%	110%	113%	106%	110%
N_B1	0.91	1.00	1.35	1.08	0.79	0.52	0.38	0.35	0.31	0.39	0.51	0.73
	98%	91%	93%	95%	93%	95%	98%	107%	101%	105%	108%	106%

5.4 Demands

As discussed in Section 4.2, summertime water demands are sensitive to temperature and precipitation conditions. To account for this, PRRISM simulates daily WMA demands based on temperature and precipitation time series. Figure 5-10 through Figure 5-12 show simulated 2040 unrestricted WMA water supply demands during moderate drought conditions under climate change (from single a PRRISM run based on 2040 likely demands). These graphs show that summertime demands under climate change tend to be greater than base scenario demands for both monthly average and maximum values. The plotted demands are from a single PRRISM model run based on forecasted 2040 likely average annual demand from Part 1 of this study (Ahmed *et al.*, 2010). The monthly averages are calculated across all years in the 12-year simulation period. The monthly maximums are selected as the highest single-day withdrawal over the simulation period for each month. Demands for December, January, and February are not expected to show much change because of the limited ability of the PRRISM demand model to simulate wintertime demands (see Section 4.2). The results shown in these figures are summarized below in Table 5-4.

Table 5-4: Projecteded 2040 July and August water demands used in base and climate change scenarios.

	Fairfax Water	Washington Aqueduct	WSSC
Average annual – base	228	179	204
Average annual – climate change	228 – 229	179 – 180	204 – 205
Average Jul-Aug – base	275	206	227
Average Jul-Aug – climate change	274 – 286	206 – 213	234 – 236
Max Jul-Aug – base	321	243	243
Max Jul-Aug – climate change	322 – 326	244 – 249	244 – 249



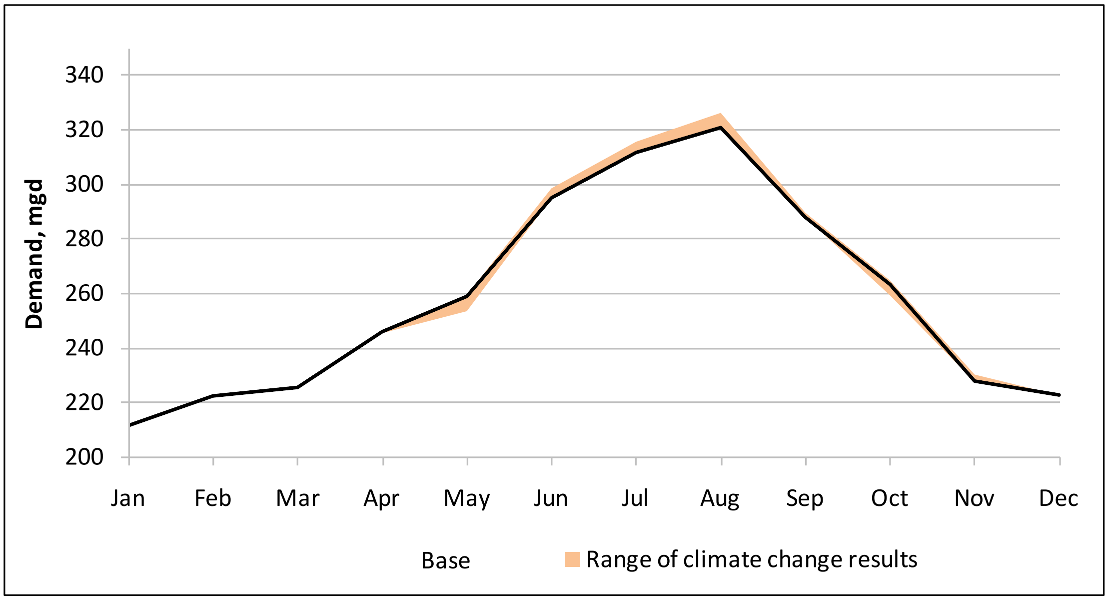
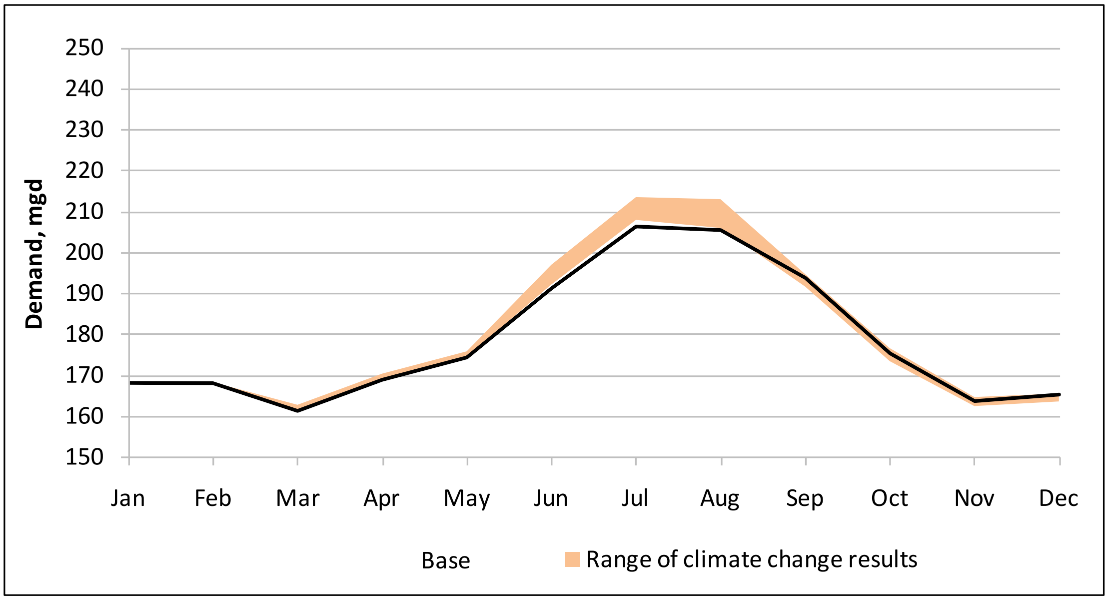


Figure 5-10: Fairfax Water 2040 average day (top) and maximum day (bottom) monthly unrestricted water supply demands.



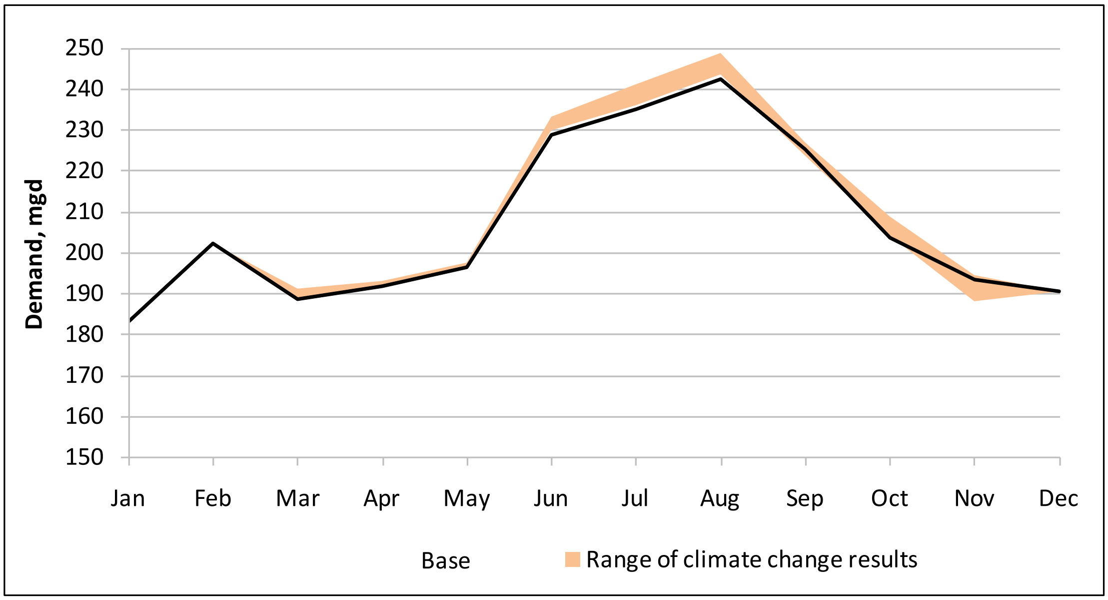
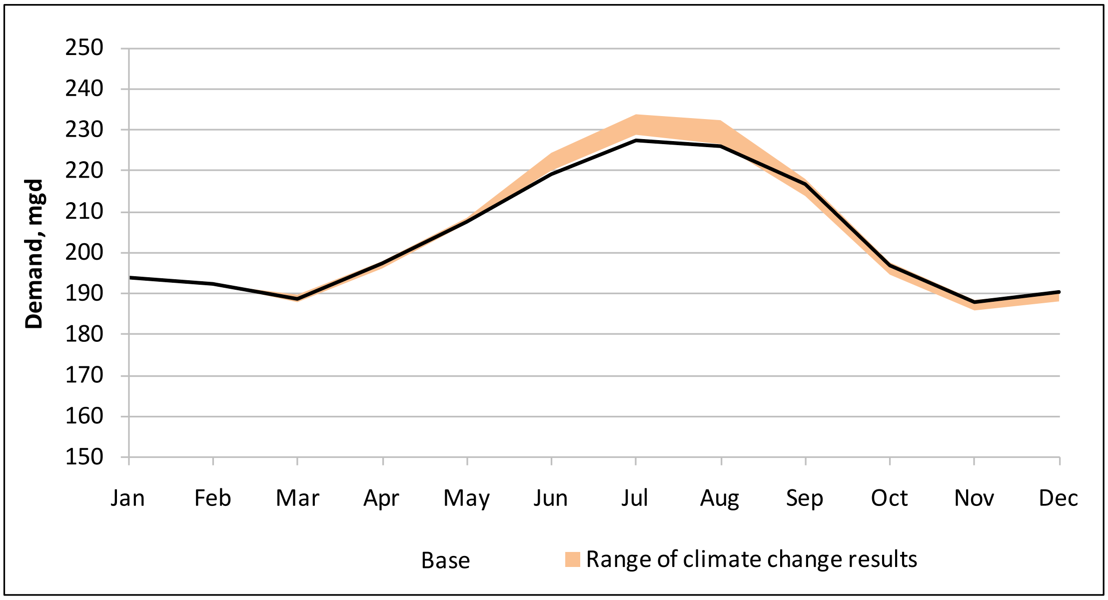


Figure 5-11: Washington Aqueduct 2040 average day (top) and maximum day (bottom) monthly unrestricted water supply demands.



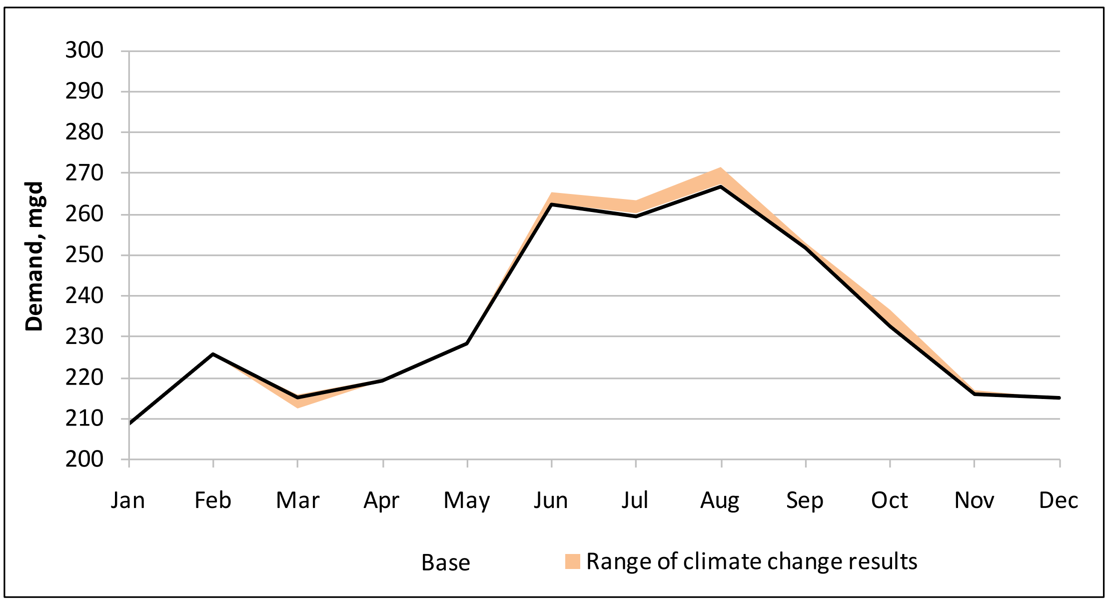


Figure 5-12: WSSC 2040 average day (top) and maximum day (bottom) monthly unrestricted water supply demands.

6 System Performance

The performance of the current WMA water supply system in 2040 under potential climate change conditions was evaluated using PRRISM, which simulates the daily processes that govern water supply and demand in the WMA. These include flows in the Potomac River, releases from system reservoirs, and water withdrawals by the three major water suppliers. Daily WMA water withdrawals were simulated for each of the 18 climate scenarios based on forecasts of average annual demands from Part 1 of this study and modified estimates of seasonal and daily variations discussed above in Section 4.2. Projected flows from the Phase 5 model were used to develop "natural" daily Potomac River flows and reservoir inflows for input into PRRISM. These represent flows that would be expected in absence of withdrawals, diversions, or reservoir regulations. Outflows to the Potomac River from Jennings Randolph and Savage reservoirs were based on PRRISM's representation of the current reservoir operating rules. These rules were developed in close coordination with the Baltimore District of the Army Corps of Engineers. Reservoir water supply releases from Jennings Randolph, Savage, and Little Seneca reservoirs were simulated to meet the recommended minimum flow at Little Falls, plus a margin of safety, taking into account projected flows and withdrawals.

This chapter contains results from the analysis of overall system performance. A summary of the system operations simulated by PRRISM and the model's primary inputs and outputs is provided in Table 6-1. Unless otherwise noted, all scenarios were run using the PRRISM input parameters given in Appendix A. PRRISM inputs are identical for Part 1 and Part 2 of this study, with the exception of the minimum allowed production rate for the Patuxent water treatment plant, which has been changed from 27 mgd to 30 mgd (Karen Wright, personal communication). In addition, to help preserve Patuxent storage during severe long-term droughts, an emergency production rate of 20 mgd has been assumed when storage falls below 10 percent of capacity.

Table 6-1: Summary of PRRISM's simulated operations, inputs, and outputs.

Simulated System Operations	Model Inputs	Model Outputs
Reservoirs: • Jennings Randolph water quality releases • Jennings Randolph water supply releases • Savage Reservoir releases • Little Seneca Reservoir water supply releases *Water withdrawals:* • WMA suppliers Potomac River withdrawals • City of Rockville Potomac River withdrawals • Fairfax Water's Occoquan Reservoir withdrawals • WSSC's Patuxent reservoir withdrawals	*Projected daily stream flows:* • Potomac River flows • Reservoir inflows *Forecasted daily water demand:* • Washington Aqueduct • Fairfax Water • Washington Suburban Sanitary Commission • City of Rockville *Other inputs:* • Forecast year: 2040 • Water use restriction triggers and percent reductions • Upstream wastewater treatment plant discharges • Upstream consumptive use	*WMA system performance measures:* • Magnitude and frequency of reservoir storage shortfalls (vulnerability) • Number of days of releases • Magnitude and frequency of Potomac River low flows downstream of the water supply intakes • Magnitude and frequency of demand deficit (reliability, resiliency, and vulnerability) *Model performance checks:* • Model water balance

6.1 Scenarios

Model results are for the average annual "likely" demand for year 2040 from Part 1 of this study. This forecast was computed using current water use patterns and demographic projections from the Metropolitan Washington Council of Governments (MWCOG), under the assumption that household unit use rates would decrease slightly throughout the forecast period due to the effects of the Energy Policy Act of 1992. The inputs for temperature, precipitation, stream flow, and average annual demand used to generate the observed, base, and 18 climate scenarios are summarized in Table 6-2 below.

Table 6-2: Summary of model run inputs for resource analysis under changed climate conditions.

Scenario ID	Temperature and Precipitation Inputs		Stream Flow Input	Average Annual Demand Input	Year
	Climate Model	Emissions Model			
Observed	NCDC observed	Inherent in observed data	USGS observed	Likely average annual demands (from Part 1 of this study): MWCOG Round 7.2 growth forecasts and assuming future unit use reductions for both single family households and multi-family households (e.g. apartment buildings)	2040
Base			Simulated using the Chesapeake Bay Program Office's Phase 5 watershed model		
B_A1B	BCC-BCM2.0	A1B emissions (medium): High population growth, slow economic development & slow technological change			
C3.0_A1B	CSIRO-Mk3.0				
C3.5_A1B	CSIRO-Mk3.5				
I_A1B	INM-CM3.0				
M_A1B	MIROC3.2(medres)				
N_A1B	NCAR-CCSM3_0				
B_A2	BCC-BCM2.0	A2 emissions (high): Very rapid economic growth & and technological change, population peak mid-century, balance of energy sources			
C3.0_A2	CSIRO-Mk3.0				
C3.5_A2	CSIRO-Mk3.5				
I_A2	INM-CM3.0				
M_A2	MIROC3.2(medres)				
N_A2	NCAR-CCSM3_0				
B_B1	BCC-BCM2.0	B1 emissions (low): Similar to A1B, but change toward service & information economy			
C3.0_B1	CSIRO-Mk3.0				
C3.5_B1	CSIRO-Mk3.5				
I_B1	INM-CM3.0				
M_B1_likely	MIROC3.2(medres)				
N_B1_likely	NCAR-CCSM3_0				

As discussed in Section 4.2.2, PRRISM's simulated daily WMA water supply demand includes a randomly generated component. This represents the observed variability in demand for a given set of temperature and precipitation conditions. Therefore, every model run has slightly different estimates of daily demand and slightly different system performance results. To capture the effects of this variability on system performance, the model was run 20 times for each scenario. Average values of system performance metrics over these 20 runs are reported along with the associated standard deviation. The metrics used to evaluate system performance are discussed below.

6.2 Measures of Performance

Model run results are expressed in terms that define the reliability, vulnerability, and resiliency of the Potomac system (Hashimoto *et al.*, 1982). Reservoir reliability is represented as the probability of meeting a given demand and is expressed as a percentage of time that demand can be met. Vulnerability is a measure of the magnitude or significance of a failure and can be defined as the largest shortfall during a model run. Resiliency gauges the ability of the system to recover from system failure and can be defined as the maximum number of consecutive periods of shortage during a model run (Wurbs, 1996).

These concepts are addressed by multiple performance metrics in PRRISM as described below. All percentages and other statistics are computed over the 12-year simulation period.

Reliability metrics:

- *Percentage of years with no Potomac shortfalls:* Percentage of years in which Potomac River flow is insufficient to meet all demand plus the 100 mgd flow-by at Little Falls.
- *Percentage of years with voluntary, mandatory, and emergency restrictions:* Percentage of years in which water use restrictions are implemented. (The approximation that PRRISM uses for WMA water use restrictions triggers and reductions are summarized in Table 6-3. See Part 1 of this study for more discussion of WMA restrictions.)

Table 6-3: PRRISM approximations of WMA water use restriction triggers and assumed demand reductions.

PRRISM Restriction Status	Restriction trigger	Percent reduction in system demand, June through September	Percent reduction in system demand, October through May
Voluntary	Combined storage in Jennings Randolph and Little Seneca less than 60 percent full	5%	3%
Mandatory	Jennings Randolph or Little Seneca storage of less than 25 percent full	9.2%	5%
Emergency	Jennings Randolph or Little Seneca storage empty	15%	15%

Resiliency metric:

- *Maximum number of days in a row of Potomac shortfalls:* expressed as the maximum number of consecutive days in which demand cannot be met during the 12-year simulation period.

Vulnerability metrics:

- *Total number of days in which Potomac shortfalls must be allocated:* Total number of days over the simulation period in which flow is insufficient to meet water supply needs and the 100 mgd flow-by at Little Falls.
- *Maximum amount of Potomac shortfall allocated in a single day, mgd:* Expressed as the maximum total Potomac shortfall for all three WMA water suppliers on any single day.
- *Average amount of Potomac shortfall allocated, mgd:* Expressed as the average amount of Potomac shortfall that must be allocated to the water suppliers.
- *Total amount of Potomac shortfall allocated, mg:* Expressed as the total amount of a shortfall over the simulation period.

- *Total number of days with Patuxent water supply shortfalls:* Expressed as the number of days where the Patuxent withdrawal is below the emergency storage request of 20 mgd.
- *Total number of days with Occoquan water supply shortfalls:* Expressed as the number of days where the Occoquan withdrawal is below the minimum demand of 45 mgd for Occoquan's area served.

<u>Other model run metrics:</u>

- *Minimum storages in Jennings Randolph Reservoir water supply account and Little Seneca, Occoquan, and Patuxent reservoirs, billion gallons (bg).*
- *Minimum combined storage in Little Seneca Reservoir and Jennings Randolph Reservoir water supply account, bg.*
- *Minimum combined storage in Patuxent, Occoquan, and Little Seneca reservoirs and Jennings Randolph Reservoir water supply account, bg.*
- *Average annual demand, mgd:* This reports the average demand simulated by the model given the projected meteorological conditions in 2040, as reduced by simulated water use restrictions.
- *Minimum average natural summer Potomac River flow (moderate drought year), mgd:* This metric is the minimum, over the simulation period, of the average natural flow at Little Falls in June, July, and August. Natural flow refers to the flow that would have occurred without upstream reservoir regulation, consumptive use, return flows from wastewater treatment plants, or WMA withdrawals.
- *Minimum average natural autumn Potomac River flow (moderate drought year), mgd:* This metric is the minimum, over the simulation period, of the average natural flow at Little Falls in September, October, and November.
- *Minimum average summer Potomac River flow (moderate drought year), mgd:* This metric is the minimum, over the simulation period, of the average flow at Little Falls in June, July, and August. This represents the modeled flow, including all upstream augmentation, withdrawals, and consumptive use. Little Falls is downstream of the WMA water supply intakes.
- *Minimum average fall Potomac River flow (moderate drought year), mgd:* This metric is the minimum, over the simulation period, of the average flow at Little Falls in September, October, and November.

6.3 Comparison of PRRISM Reference Scenario Results

In Section 4.4, the steps taken to construct a "base" condition are described. The base condition provides a current-day reference scenario with which the climate change results can be compared. Table 6-4 compares PRRISM reliability metrics for the base condition and the two other reference scenarios defined in Section 4.4. The "pre-modified observed" condition is identical to that used in Part 1 of this study to evaluate system performance using the historical hydrologic record, except for the changes to Patuxent minimum withdrawals discussed in the beginning of this chapter. The model run results in Table 6-4 used stream flows from the time period, January 1, 1988 to December 31, 1999, and simulated 2040 likely demands. The differences between "pre-modified observed" and "observed" results in Table 6-4 show that the modification that was made to the demand model does not significantly change system performance, supporting the results of Section 4.2. However, simulated system performance is better for the observed condition, which used historical stream flow data, than for the base condition, which used Phase 5's simulated stream flows. Although bias correction was applied to the simulated flows, there are still some differences between observed and simulated flows. Because these same model errors are likely present in the Phase 5 flow projections for the climate change condition, it is more appropriate to compare the climate change scenario results with base rather than with observed scenario results.

Table 6-4: Comparable simulations documenting effects of model changes (single run) for the 1999 drought using 2040 likely demands.

Measures of Performance (over 12-year simulation period)	Pre-modified observed	Observed	Base
Percentage of years with no Potomac shortfalls	100.0%	100.0%	100.0%
Maximum number of days in a row of Potomac shortfalls	0	0	0
Total number of days in which Potomac shortfalls must be allocated	0	0	0
Maximum amount of Potomac shortfall allocated in a single day, mgd	0	0	0
Average amount of Potomac shortfall allocated, mgd	0.0	0.0	0.0
Total amount of Potomac shortfall allocated, mg	0	0	0
Total number of days with Patuxent water supply shortfalls	0	0	0
Total number of days with Occoquan water supply shortfalls	0	0	0
Percentage of years with restrictions voluntary restrictions	0.0%	0.0%	8.3%
Percentage of years with restrictions mandatory restrictions	0.0%	0.0%	0.0%
Percentage of years with restrictions emergency restrictions	0.0%	0.0%	0.0%
Little Seneca Reservoir minimum storage, bg	2.9	3.0	2.8
Jennings Randolph water supply account minimum storage, bg	5.5	5.5	5.2
Jennings Randolph water quality account minimum storage, bg	1.2	1.2	0.8
Patuxent reservoirs minimum storage, bg	2.9	2.9	2.5
Occoquan Reservoir minimum storage, bg	4.0	4.0	4.2
Savage Reservoir minimum storage, bg	0.7	0.7	0.6
Little Seneca Reservoir and Jennings Randolph water supply account minimum combined storage, bg	8.4	8.5	8.1
Patuxent, Occoquan, and Little Seneca reservoirs and Jennings Randolph water supply minimum combined storage, bg	17.8	18.0	17.7
Number of years in simulation	12	12	12
Average annual demand, moderate drought year, mgd	611	607	607
Minimum average natural summer Potomac River flow (moderate drought year), mgd	1,146	1,146	1,189
Minimum average natural fall Potomac River flow (moderate drought year), mgd	1,194	1,194	1,099
Minimum average summer Potomac River flow (moderate drought year), mgd	524	538	583
Minimum average fall Potomac River flow (moderate drought year), mgd	758	769	669

6.4 Climate Change Scenario Results

PRRISM predictions of WMA water supply system performance in the year 2040 under the 18 climate scenarios appear in Table 6-5 through Table 6-7. Results are categorized by impact on system performance. Table 6-5 shows system performance metrics for the six climate change scenarios that have only a minor impact on the system, Table 6-6 shows results for the six scenarios that have a moderate impact, and Table 6-7 shows results for the six scenarios that have a major impact. The results for the base scenario are provided in each table for comparison.

The results are to a large degree determined by conditions that occurred during a single year of the 12-year simulation period – the year that is based on historical data from 1999. As discussed in Chapter 1, the drought of 1999 required the first ever water supply releases from the Jennings Randolph and Little Seneca reservoirs since their completion in the early 1980s. The drought of 1999 is considered to be moderate in its severity, because, unlike the 1930 drought of record, forecasted 2040 demands are not predicted to deplete system reservoir storage if hydrologic conditions similar to those experienced in 1999 were to re-occur. However, the following tables show that this might change under future climate conditions. Results below indicate potential system performance in 2040 if a moderately severe drought similar in likelihood to the drought of 1999 were to occur.

6.4.1 Minor Impact Scenarios

Six of the climate change scenarios have little impact on the WMA water supply system during a moderate drought: B A1B, B A2, B B1, N A1B, N A2, and N B1. System performance metrics for these scenarios are given in Table 6-5. System performance deteriorates to some degree in five of the six scenarios, but actually improves in one of the scenarios, B B1. No water supply shortfalls and no mandatory or emergency water use restrictions occur under any of these scenarios, and in scenario, B B1, the percentage of years with voluntary restrictions fall to zero. Minimum combined storage in Little Seneca Reservoir and in the Jennings Randolph Reservoir water supply account ranges from 4.7 to 10.0 bg, compared with 8.0 bg in the base case. Minimum combined system storage ranges from 13.7 to 20.5 bg, compared with 17.7 for the base case.

6.4.2 Moderate Impact Scenarios

Under six of the climate change scenarios the WMA experiences more frequent and stricter water use restrictions but no water supply shortages during a moderate drought. Table 6-6 gives performance metrics for the "moderate impact" scenarios: C3.0 A1B, C3.0 A2, C3.0 B1, C3.5 B1, M A1B, and M B1. These results show that over the 12-year simulation period, the percentage of years with mandatory water use restrictions ranges from 1.7 to 8.3 percent, compared with no mandatory restrictions in the base case, and in one of the scenarios emergency restrictions are required. In these scenarios, climate change has a significant impact on reservoir storage during a moderate drought. Minimum combined storage in Little Seneca Reservoir and in the Jennings Randolph Reservoir water supply account falls to the range, 0.6 to 4.5 bg, compared with 8.0 bg in the base case. Minimum combined system storage falls to 7.5 to 13.1 bg, compared with 17.7 for the base case.

6.4.3 Major Impact Scenarios

Table 6-7 gives results for the six climate change scenarios that have a major impact on the WMA system: C3.5 A1B, C3.5 A2, I A1B, I B1, and M A2. These are the same six scenarios that ranked highest in predicted reduction in mean annual stream flow, as shown in the last column of Table 5-1. Under these scenarios the system, in the absence of operational and/or structural changes, would experience water supply shortages in the event that a moderate occurred in 2040.

In these scenarios during such a drought, both mandatory and emergency water use restrictions are in place and most system reservoirs become empty or close to empty. The exception is Occoquan Reservoir, which only experiences a slight reduction in minimum storage during a moderate drought. However, it should be noted that the operating rules for the Occoquan Reservoir used in this analysis were developed by Fairfax Water for a specific modeling scenario with 2010 water demands. It is likely that operating rules modified for 2040 conditions would draw down the reservoir further than occurs in the simulations shown. It is important to note that operating rules are sensitive to hydrologic changes, which may be impacted by increased wastewater return flows in the future, as well as reservoir storage, which may change over time due to impacts of sedimentation. An update of the Occoquan reservoir operating rules was beyond the scope of this project, but will take place prior to the next WMA water demand and resource availability study.

Table 6-5: System performance metrics for year 2040 minor impact scenarios.

Measures of Performance (over 12-year simulation period)	Base		B A1B		B A2		B B1		N_A1B		N_A2		N_B1	
	Avg.	Std.	Avg.	Std.	Avg.	Std.	Avg.	Std.	Avg.	Std.	Avg.	Std.	Avg.	Std.
Reliability, Vulnerability, Resiliency														
Percentage of years with no Potomac shortfalls	100%	0.0%	100%	0.0%	100%	0.0%	100%	0.0%	100%	0.0%	100%	0.0%	100%	0.0%
Max number of days in a row with Potomac shortfalls	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Total number of days with Potomac shortfalls	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Max Potomac shortfall allocated in a single day, mgd	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Average amount of Potomac shortfall allocated, mgd	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Total amount of shortfall allocated, mg	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Total number of Patuxent shortfalls, days	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Total number of Occoquan shortfalls, days	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Percentage of years with restrictions														
Voluntary restrictions	6.3%	3.7%	8.3%	0.0%	8.3%	0.0%	0.0%	0.0%	8.3%	0.0%	8.3%	0.0%	8.3%	0.0%
Mandatory restrictions	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Emergency restrictions	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Minimum reservoir storage, bg														
Little Seneca Reservoir	2.8	0.11	1.7	0.16	1.7	0.19	3.1	0.04	2.0	0.10	2.4	0.17	2.4	0.14
Jennings Randolph water supply account	5.2	0.04	2.9	0.08	3.0	0.10	6.8	0.04	4.1	0.09	4.7	0.13	4.7	0.10
Jennings Randolph water quality account	0.8	0.00	0.4	0.00	0.9	0.00	1.0	0.00	1.0	0.00	1.0	0.00	0.9	0.00
Patuxent reservoirs	2.5	0.00	2.0	0.00	2.0	0.00	2.4	0.00	2.4	0.00	2.5	0.00	2.5	0.00
Occoquan Reservoir	4.2	0.06	4.0	0.05	4.1	0.05	4.2	0.05	4.0	0.08	4.2	0.06	4.2	0.05
Savage Reservoir	0.6	0.00	0.7	0.00	0.6	0.00	0.7	0.00	0.7	0.00	0.7	0.00	0.7	0.00
Little Seneca Reservoir and Jennings Randolph water supply account, combined	8.0	0.14	4.7	0.21	4.7	0.25	10.0	0.06	6.2	0.17	7.2	0.29	7.1	0.22
Patuxent, Occoquan, and Little Seneca reservoirs and Jennings Randolph water supply account, combined	17.7	0.28	13.9	0.34	13.7	0.43	20.5	0.18	15.7	0.27	16.7	0.44	16.4	0.38
Miscellaneous														
Number of years in simulation	12	-	12	-	12	-	12	-	12	-	12	-	12	-
Average annual demand in moderate drought year, mgd	614	6	612	4	611	5	616	6	613	6	615	7	617	5
Minimum average flow (moderate drought year)														
Min average natural summer Potomac River flow, mgd	1,189	0	1,050	0	1,002	0	1,251	0	1,032	0	1,076	0	1,064	0
Min average natural autumn Potomac River flow, mgd	1,099	0	946	0	930	0	1,039	0	1,106	0	1,184	0	1,174	0
Min average summer Potomac River flow, mgd	574	10	479	5	424	7	619	10	441	8	473	9	454	8
Min average autumn Potomac River flow, mgd			484	11	474	10	586	7	692	12	787	6	765	8

Note: Avg. = average, Std. = standard deviation

Table 6-6: System performance metrics for year 2040 moderate impact scenarios.

Measures of Performance (over 12-year simulation period)	Base		C3.0 A1B		C3.0 A2		C3.0 B1		C3.5 B1		M A1B		M B1	
	Avg.	Std.	Avg.	Std.	Avg.	Std.	Avg.	Std.	Avg.	Std.	Avg.	Std.	Avg.	Std.
Reliability, Vulnerability, Resiliency														
Percentage of years with no Potomac shortfalls	100%	0.0%	100%	0.0%	100%	0.0%	100%	0.0%	100%	0.0%	100%	0.0%	100%	0.0%
Max number of days in a row with Potomac shortfalls	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Total number of days with Potomac shortfalls	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Max Potomac shortfall allocated in a single day, mgd	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Average amount of Potomac shortfall allocated, mgd	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Total amount of shortfall allocated, mg	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Total number of Patuxent shortfalls, days	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Total number of Occoquan shortfalls, days	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Percentage of years with restrictions														
Voluntary restrictions	6.3%	3.7%	8.3%	0.0%	8.3%	0.0%	8.3%	0.0%	8.3%	0.0%	8.3%	0.0%	8.3%	0.0%
Mandatory restrictions	0.0%	0.0%	8.3%	0.0%	5.4%	4.1%	8.3%	0.0%	1.7%	3.4%	8.3%	0.0%	8.3%	0.0%
Emergency restrictions	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	8.3%	0.0%	0.0%	0.0%
Minimum reservoir storage, bg														
Little Seneca Reservoir	2.8	0.11	1.5	0.23	1.4	0.18	0.9	0.18	1.8	0.13	0.6	0.30	1.5	0.22
Jennings Randolph water supply account	5.2	0.04	2.2	0.09	2.5	0.11	1.0	0.08	2.7	0.09	0.0	0.00	1.9	0.08
Jennings Randolph water quality account	0.8	0.00	1.0	0.00	1.0	0.00	0.9	0.00	0.7	0.00	0.8	0.00	0.9	0.00
Patuxent reservoirs	2.5	0.00	2.3	0.00	2.2	0.01	2.0	0.04	1.9	0.00	1.9	0.04	2.2	0.02
Occoquan Reservoir	4.2	0.06	3.8	0.06	3.9	0.05	4.0	0.05	3.9	0.05	4.1	0.10	4.1	0.04
Savage Reservoir	0.6	0.00	0.7	0.00	0.6	0.00	0.7	0.00	0.7	0.00	0.6	0.00	0.6	0.01
Little Seneca Reservoir and Jennings Randolph water supply account, combined	8.0	0.14	3.7	0.30	4.0	0.27	1.9	0.25	4.5	0.21	0.6	0.30	3.5	0.29
Patuxent, Occoquan, and Little Seneca reservoirs and Jennings Randolph water supply account, combined	17.7	0.28	12.0	0.59	13.1	0.42	8.6	0.46	12.6	0.32	7.5	0.52	11.7	0.53
Miscellaneous														
Number of years in simulation	12	-	12	-	12	-	12	-	12	-	12	-	12	-
Average annual demand, moderate drought year, mgd	614	6	608	6	608	6	606	5	607	3	596	5	604	7
Minimum average flow (moderate drought year)														
Min average natural summer Potomac River flow, mgd	1,189	0	993	0	1,034	0	938	0	1,055	21	827	0	1,008	0
Min average natural autumn Potomac River flow, mgd	1,099	0	978	0	949	0	913	0	924	63	878	0	890	0
Min average summer Potomac River flow, mgd	574	10	428	8	472	10	394	5	477	13	324	6	447	7
Min average autumn Potomac River flow, mgd			520	8	492	8	463	10	476	70	427	8	443	11

Note: Avg. = average, Std. = standard deviation

Table 6-7: System performance metrics for year 2040 major impact scenarios.

Measures of Performance (over 12-year simulation period)	Base		C3.5 A1B		C3.5 A2		I A1B		I A2		I B1		M A2	
	Avg.	Std.	Avg.	Std.	Avg.	Std.	Avg.	Std.	Avg.	Std.	Avg.	Std.	Avg.	Std.
Reliability, Vulnerability, Resiliency														
Percentage of years with no Potomac shortfalls	100%	0.0%	91.3%	1.9%	99.2%	2.6%	93.8%	3.7%	91.7%	0.0%	93.8%	3.7%	97.1%	4.1%
Max number of days in a row with Potomac shortfalls	0	0	6	3	0	0	4	4	14	3	4	3	1	2
Total number of days with Potomac shortfalls	0	0	11	4	0	0	5	4	14	4	6	4	1	2
Max Potomac shortfall allocated in a single day, mgd	0	0	-182	63	-2	8	-142	90	-323	26	-124	88	-40	69
Average amount of Potomac shortfall allocated, mgd	0	0	-66	14	-1	6	-62	39	-162	20	-55	36	-22	36
Total amount of shortfall allocated, mg	0	0	-763	348	-3	12	-434	389	-2303	478	-432	392	-81	145
Total number of Patuxent shortfalls, days	0	0	73	3	0	0	32	4	14	6	0	0	0	0
Total number of Occoquan shortfalls, days	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Percentage of years with restrictions														
Voluntary restrictions	6.3%	3.7%	23.8%	3.1%	16.7%	0.0%	23.8%	3.1%	22.5%	3.9%	24.6%	1.9%	15.8%	2.6%
Mandatory restrictions	0.0%	0.0%	15.0%	5.8%	8.3%	0.0%	11.7%	5.7%	8.3%	0.0%	8.3%	0.0%	8.3%	0.0%
Emergency restrictions	0.0%	0.0%	8.8%	1.9%	8.3%	0.0%	9.2%	2.6%	8.3%	0.0%	8.3%	0.0%	8.3%	0.0%
Minimum reservoir storage, bg														
Little Seneca Reservoir	2.8	0.11	0.0	0.00	0.5	0.29	0.1	0.14	0.0	0.00	0.1	0.16	0.3	0.27
Jennings Randolph water supply account	5.2	0.04	0.0	0.00	0.0	0.00	0.0	0.00	0.0	0.00	0.0	0.00	0.0	0.00
Jennings Randolph water quality account	0.8	0.00	1.0	0.01	0.1	0.00	0.9	0.06	0.0	0.00	0.0	0.01	0.6	0.00
Patuxent reservoirs	2.5	0.00	0.0	0.00	0.6	0.12	0.0	0.00	0.0	0.00	0.4	0.05	0.7	0.04
Occoquan Reservoir	4.2	0.06	3.1	0.06	3.5	0.23	3.2	0.19	3.6	0.15	3.5	0.16	4.0	0.05
Savage Reservoir	0.6	0.00	0.4	0.03	0.6	0.00	0.3	0.02	0.5	0.01	0.5	0.01	0.6	0.00
Little Seneca Reservoir and Jennings Randolph water supply account, combined	8.0	0.14	0.0	0.00	0.5	0.29	0.1	0.14	0.0	0.00	0.1	0.16	0.3	0.27
Patuxent, Occoquan, and Little Seneca reservoirs and Jennings Randolph water supply account, combined	17.7	0.28	4.9	0.09	6.5	0.53	4.5	0.20	4.1	0.15	4.6	0.22	5.2	0.34
Miscellaneous														
Number of years in simulation	12	-	12	-	12	-	12	-	12	-	12	-	12	-
Average annual demand, moderate drought year, mgd	614	6	586	6	591	6	586	6	591	7	592	6	588	4
Minimum average flow (moderate drought year)														
Min average natural summer Potomac River flow, mgd	1,189	0	822	0	806	0	753	0	703	0	760	0	763	0
Min average natural autumn Potomac River flow, mgd	1,099	0	552	0	716	0	632	0	771	0	781	0	805	0
Min average summer Potomac River flow, mgd	574	10	295	10	311	7	252	9	208	10	263	9	270	7
Min average autumn Potomac River flow, mgd	655	9	216	4	297	10	257	4	354	6	363	6	377	8

Note: Avg. = average, Std. = standard deviation

6.5 Reasons for System Performance Differences

This study assumes that differences in system performance brought on by climate change may be a result of increased water supply demand, reduced water supply availability, or a combination of both. In order to better understand the results presented in the previous section, Figure 6-1 through Figure 6-20 display the range of PRRISM simulation time series for the 18 climate scenarios compared with results for the base scenario. All of the plots are for a single year of the 12-year simulation period, representing a moderate drought occurring in the year 2040. All plots show averages of the 20 model runs.

Growing water supply demand is not a cause of system failure under the climate change scenarios. Although the water supply demand model in PRRISM projects generally higher unrestricted demands under the climate scenarios, as discussed in Section 5.4, Figure 6-1 shows that because of water use restrictions that would be triggered by falling reservoir levels, demand during the later portions of the drought tends to drop under the climate scenarios.

The key model input that influences system performance is “natural” Potomac River flow at Little Falls, which is flow that would have occurred without augmentation by reservoir releases and without WMA withdrawals. Figure 6-2 shows that natural Potomac River flow for the climate scenarios tends to be significantly less than flow in the base scenario, especially during low-flow periods. Figure 6-3 shows Potomac River flow at Little Falls taking into account the effects of reservoir releases and WMA withdrawals. The graph shows that flow is also lower than the base case under the climate change scenarios, except during a portion of the lowest flow period. This exception is due to flow augmentation from reservoir releases.

Reduced flow at Little Falls results in greater reliance on system reservoirs (Figure 6-9 through Figure 6-14). For the six climate scenarios with the most significant impact on basin hydrology, storage in most system reservoirs is almost completely depleted during a moderate drought in 2040. This is particularly the case for Jennings Randolph water supply, Little Seneca Reservoir, and the Patuxent reservoirs. When Jennings Randolph water supply and Little Seneca Reservoir storages drop to zero (Figure 6-9 and Figure 6-14, respectively), the system fails. That is, Potomac shortfalls occur (Figure 6-20). In addition to the increased releases from these two reservoirs (Figure 6-15 and Figure 6-17), production at both the Occoquan and Patuxent reservoirs is higher (Figure 6-19 and Figure 6-19, respectively) due to load shifting to these off-Potomac resources. The three most severe climate scenarios cause storage in the Patuxent reservoirs to be completely depleted during a moderate drought.

It is important to note that the reservoir operations simulated by PRRISM are based on current operations and do not reflect a number of changes likely to occur by the year 2040. PRRISM simulates estimated losses of reservoir capacity due to sedimentation, and the “rule curves” used to simulate reservoir release and withdrawal rates have not been revised to reflect operational changes that would likely be implemented if this sedimentation does occur. Rule curves have not been updated to reflect the impact of future changes in upstream wastewater treatment plant discharges, which are significant in the case of the Occoquan Reservoir. Finally, if future evaluations indicate that basin hydrology is changing in a manner similar to that predicted by the more severe scenarios considered in the current study, reservoir operating rules would be adjusted. For example, though Figure 6-10 shows Jennings Randolph water quality storage falling to zero during the month of January in some climate scenarios, the operator of this reservoir, the U.S. Army Corps of Engineers, would most certainly be operating with a new set of winter refill targets.

In the case of the Occoquan Reservoir, though Figure 6-13 indicates that significant storage is unused during the simulated drought, the rule curves that were used were developed by Fairfax Water for a specific project for 2010 demands, and it is likely that rules modified for 2040 conditions would draw down the reservoir further than the simulations shown. Conversely, though the Patuxent reservoir system fails several times under some of the climate scenarios (Figure 6-12), WSSC's use of these reservoirs would undoubtedly change in response to altered hydrological conditions in the basin.

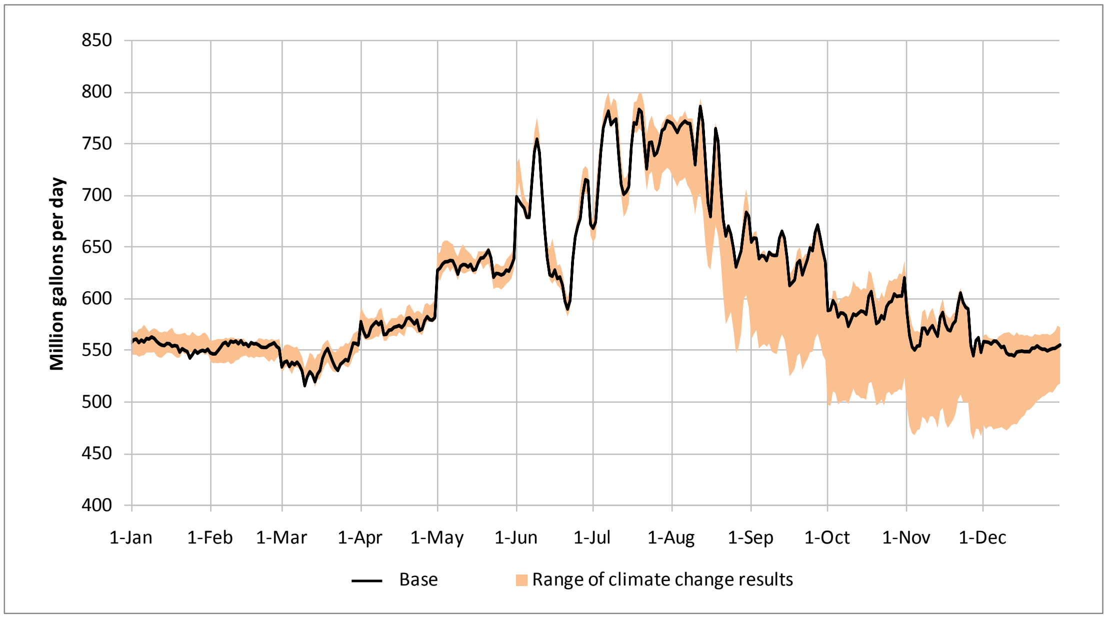


Figure 6-1: Total system demand (restricted) in the year 2040 in the event of a moderate drought.

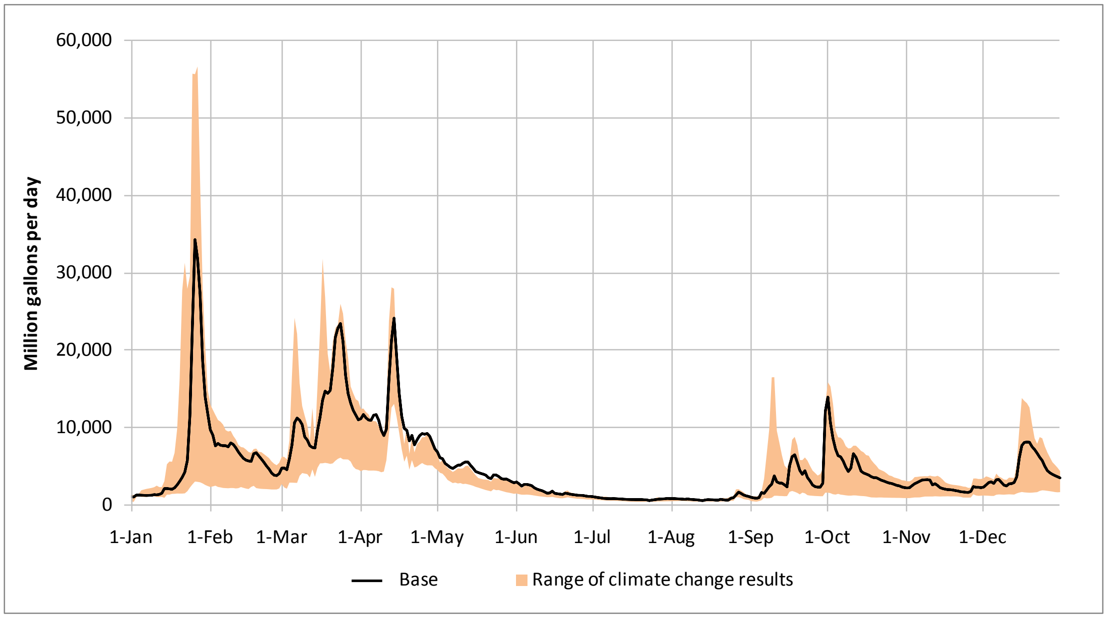


Figure 6-2: "Natural" Potomac River flow at Little Falls in the year 2040 in the event of a moderate drought.

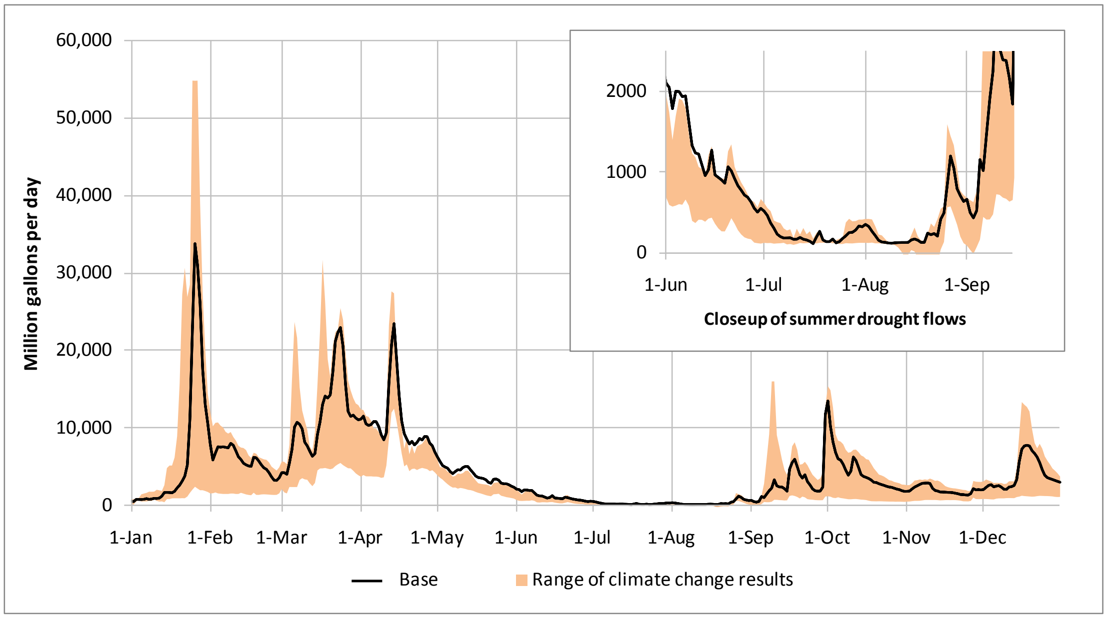


Figure 6-3: Potomac River flow at Little Falls in the year 2040 in the event of a moderate drought.

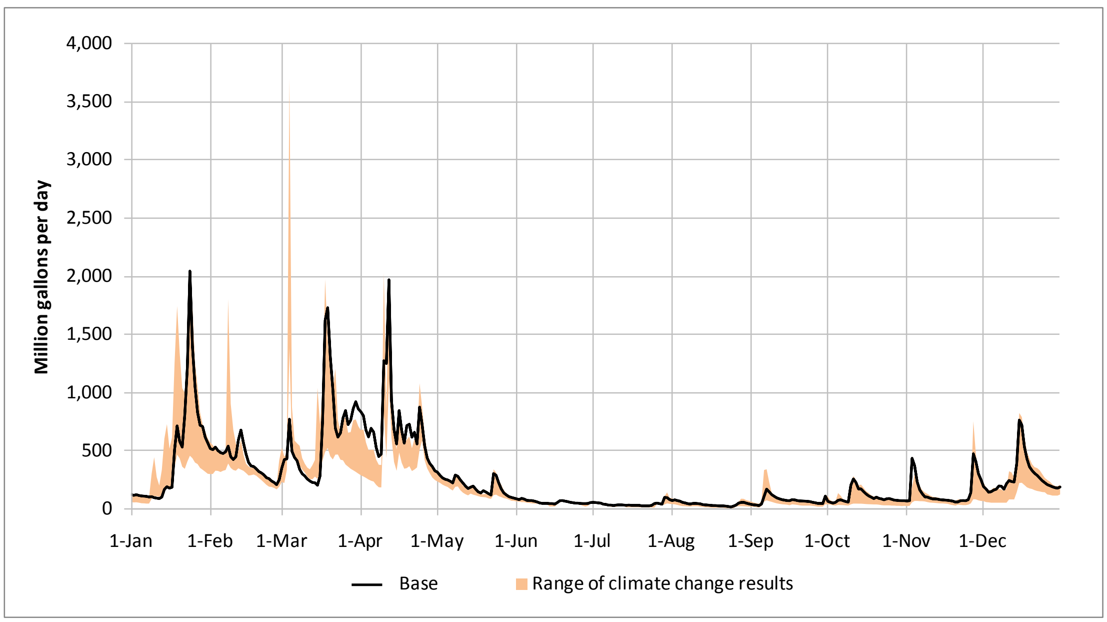


Figure 6-4: Jennings Randolph Reservoir inflow in the year 2040 in the event of a moderate drought.

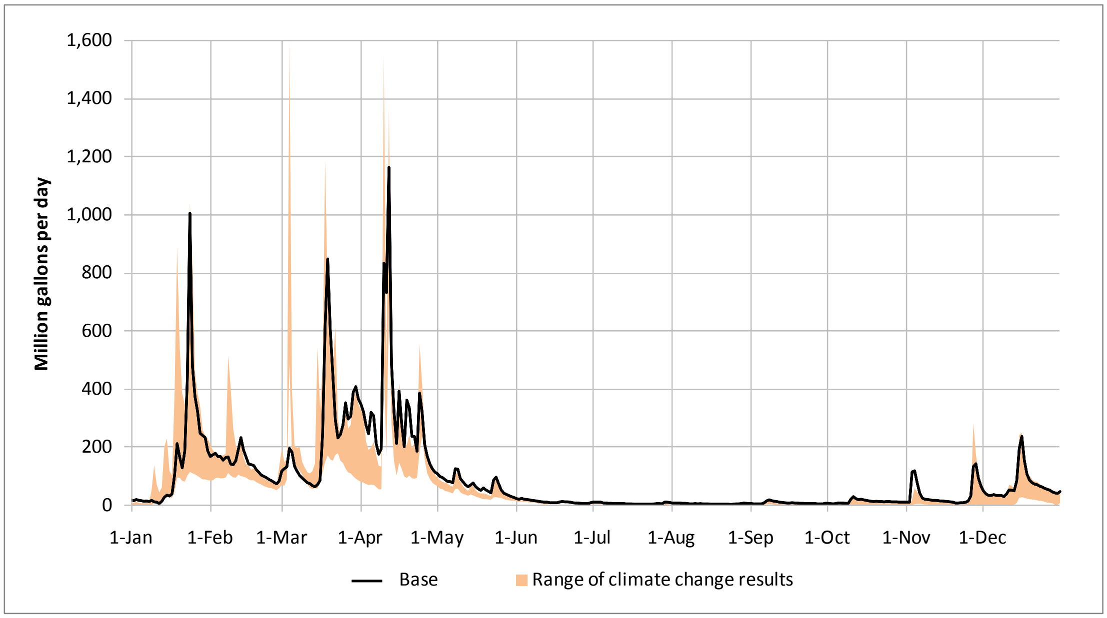


Figure 6-5: Savage Reservoir inflow in the year 2040 in the event of a moderate drought.

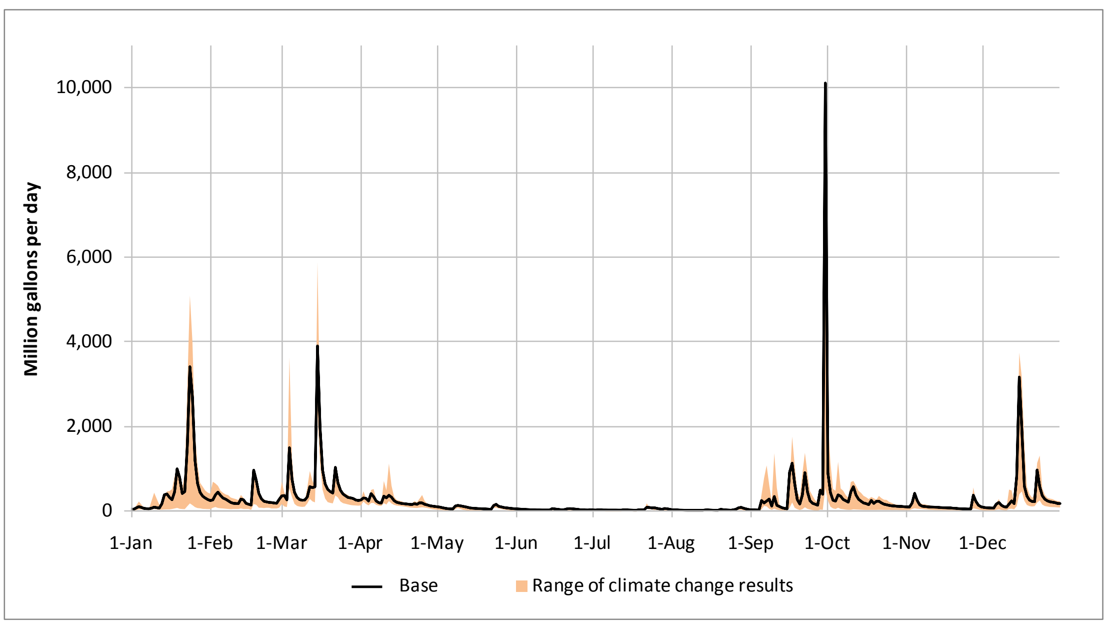


Figure 6-6: Occoquan Reservoir inflow in the year 2040 in the event of a moderate drought.

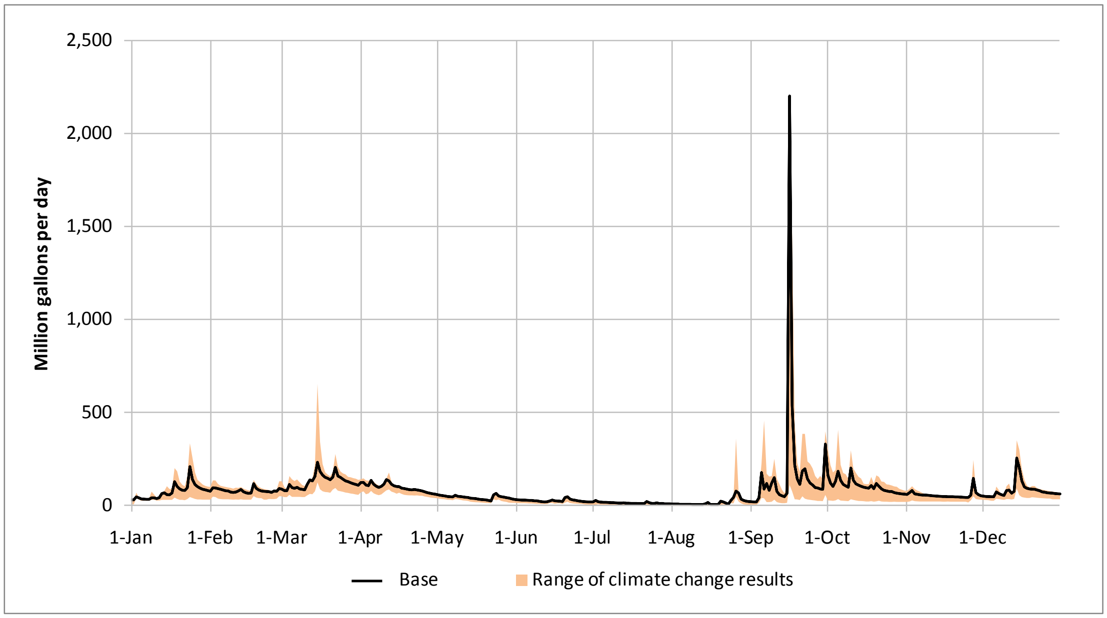


Figure 6-7: Patuxent reservoirs inflow in the year 2040 in the event of a moderate drought.

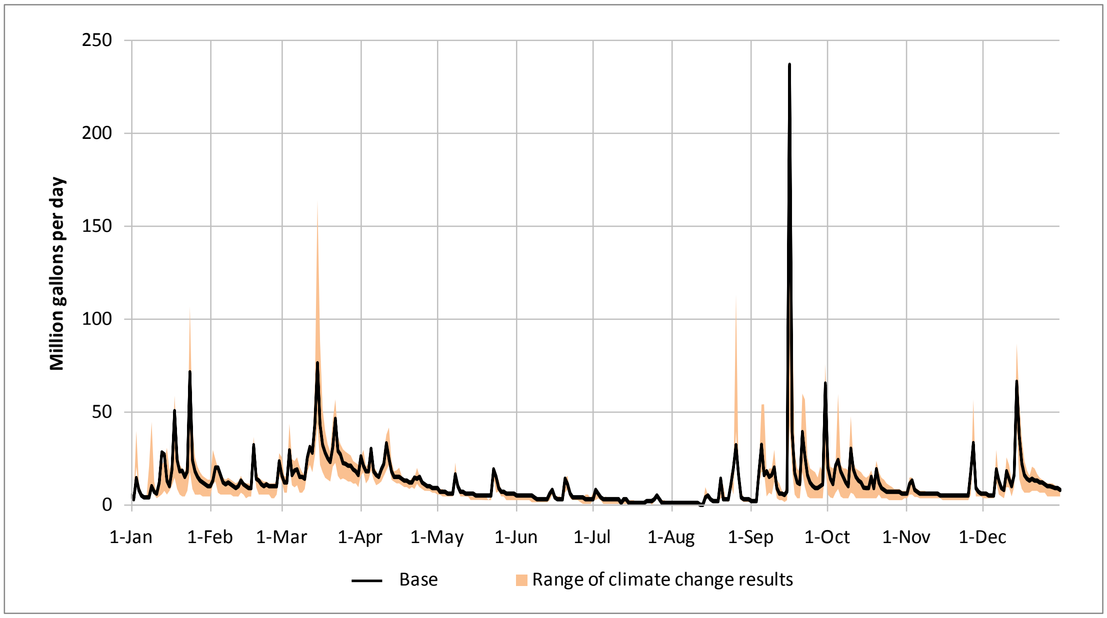


Figure 6-8: Little Seneca Reservoir inflow in the year 2040 in the event of a moderate drought.

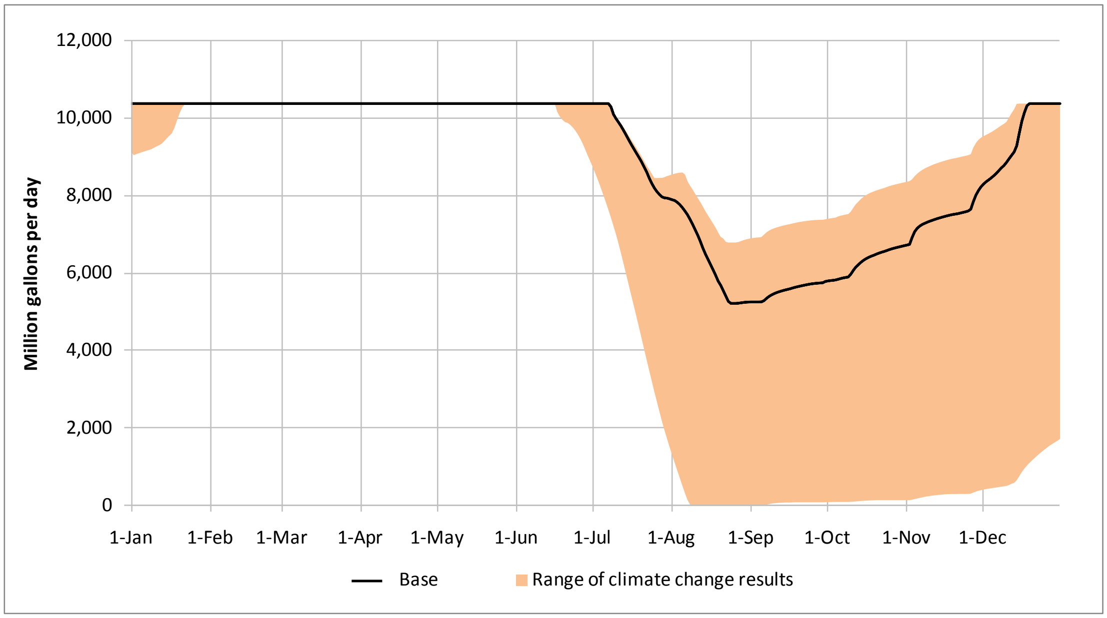


Figure 6-9: Jennings Randolph Reservoir water supply storage in the year 2040 in the event of a moderate drought.

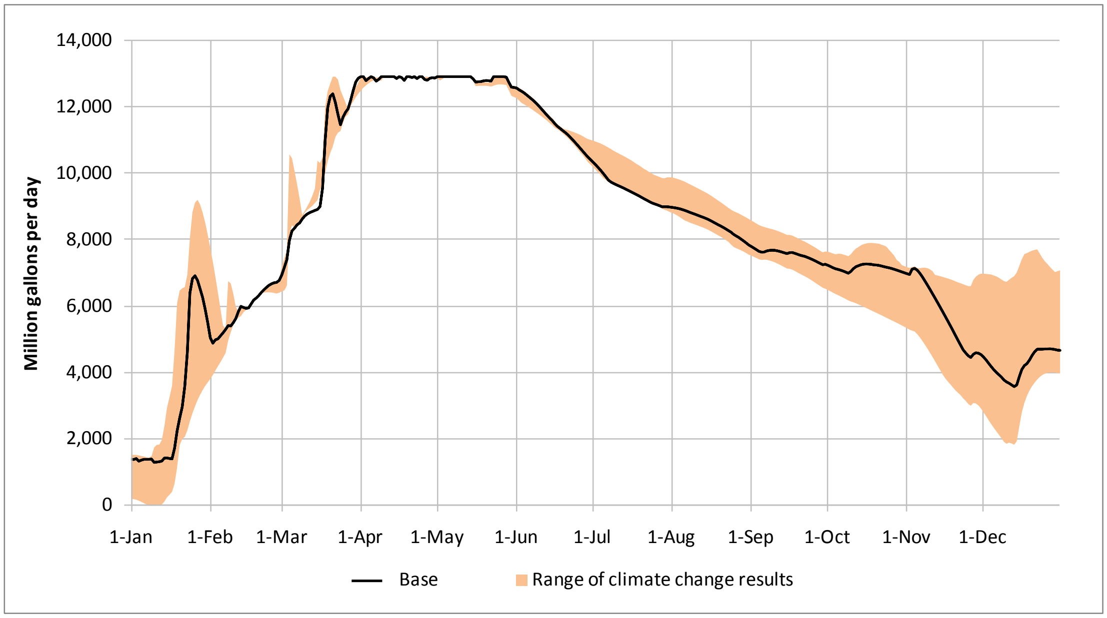


Figure 6-10: Jennings Randolph Reservoir water quality storage in the year 2040 in the event of a moderate drought.

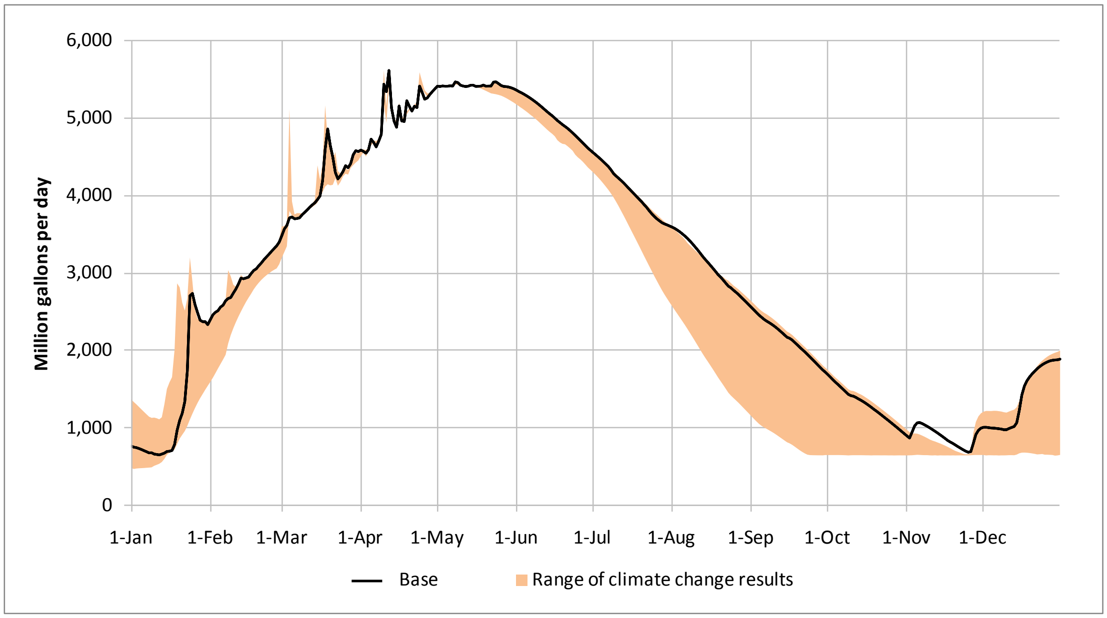


Figure 6-11: Savage Reservoir storage in the year 2040 in the event of a moderate drought.

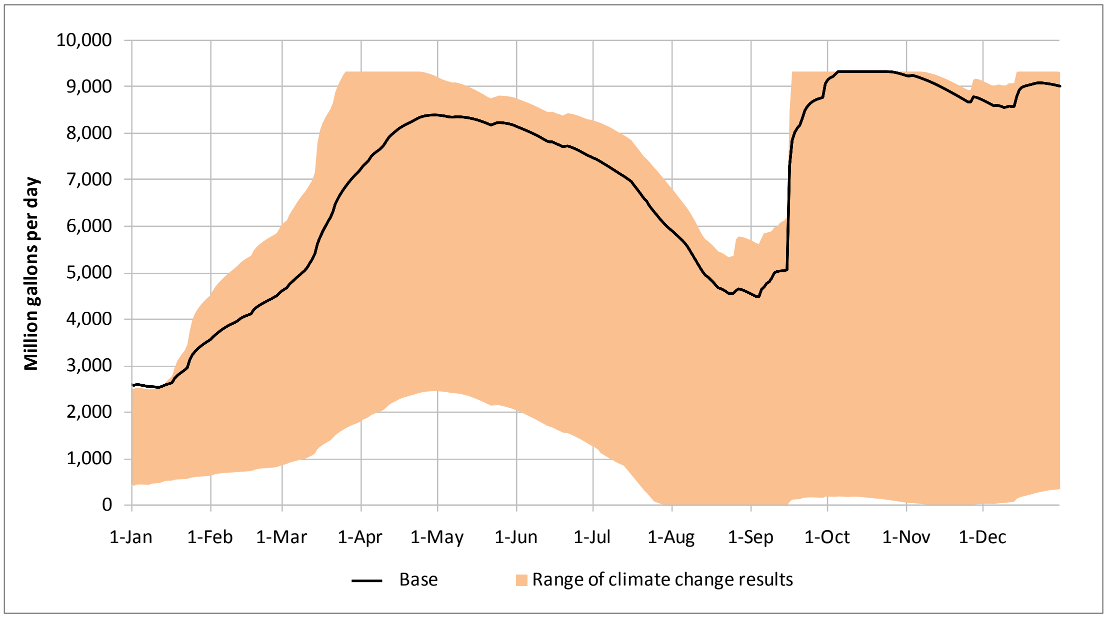


Figure 6-12: Combined Patuxent reservoirs (Tridelphia and Rocky Gorge) storage in the year 2040 in the event of a moderate drought.

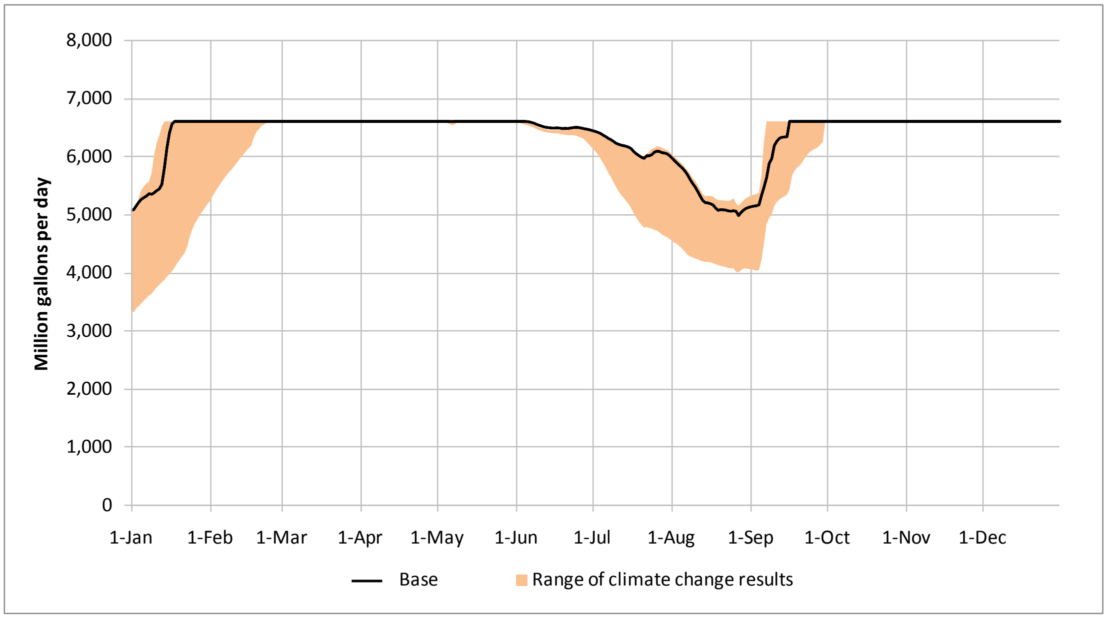


Figure 6-13: Occoquan Reservoir storage in the year 2040 in the event of a moderate drought.

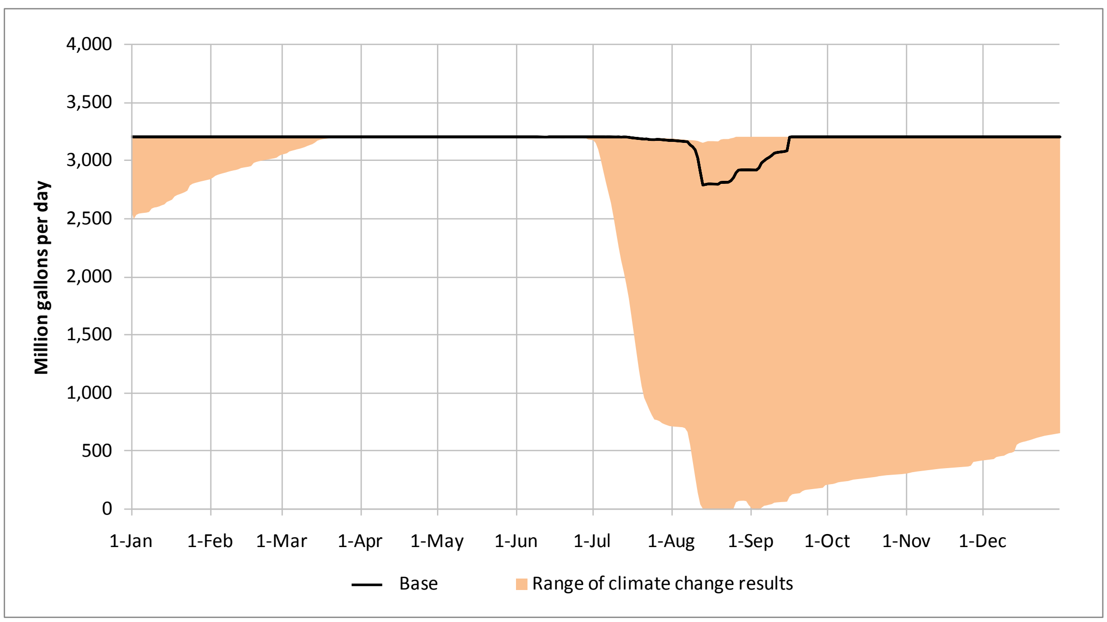


Figure 6-14: Little Seneca storage in the year 2040 in the event of a moderate drought.

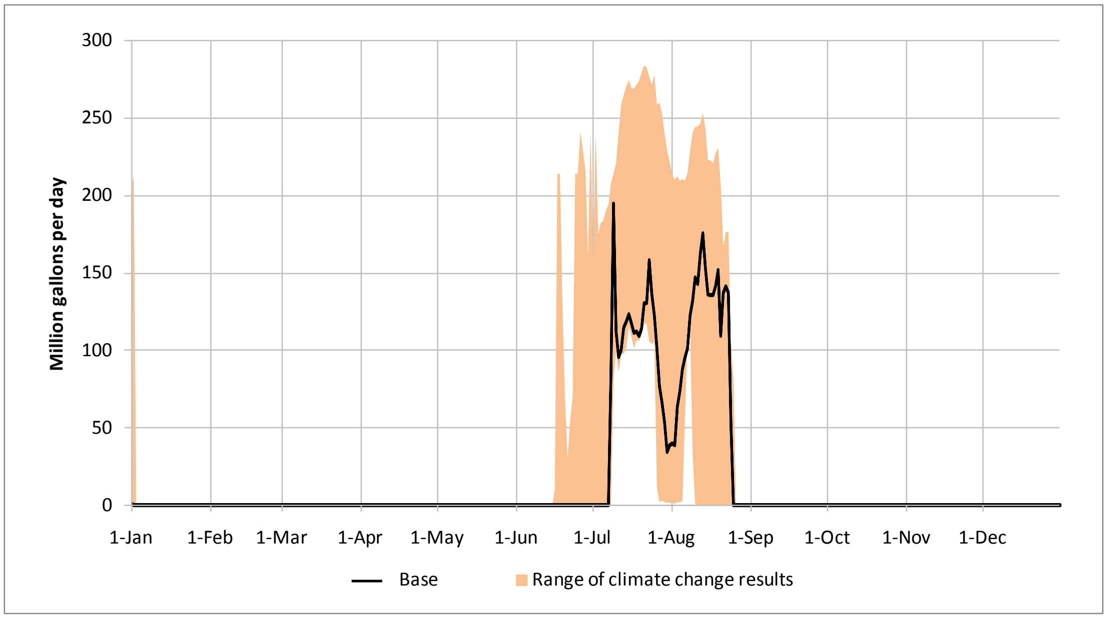


Figure 6-15: Jennings water supply releases in the year 2040 in the event of a moderate drought.

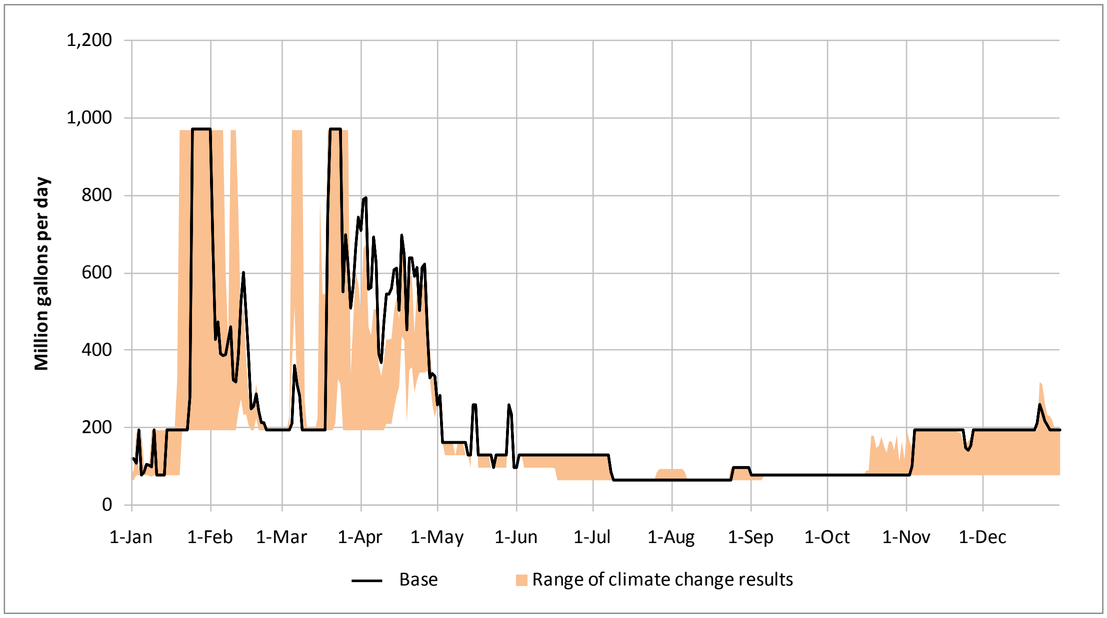


Figure 6-16: Jennings Randolph water quality releases in the year 2040 in the event of a moderate drought.

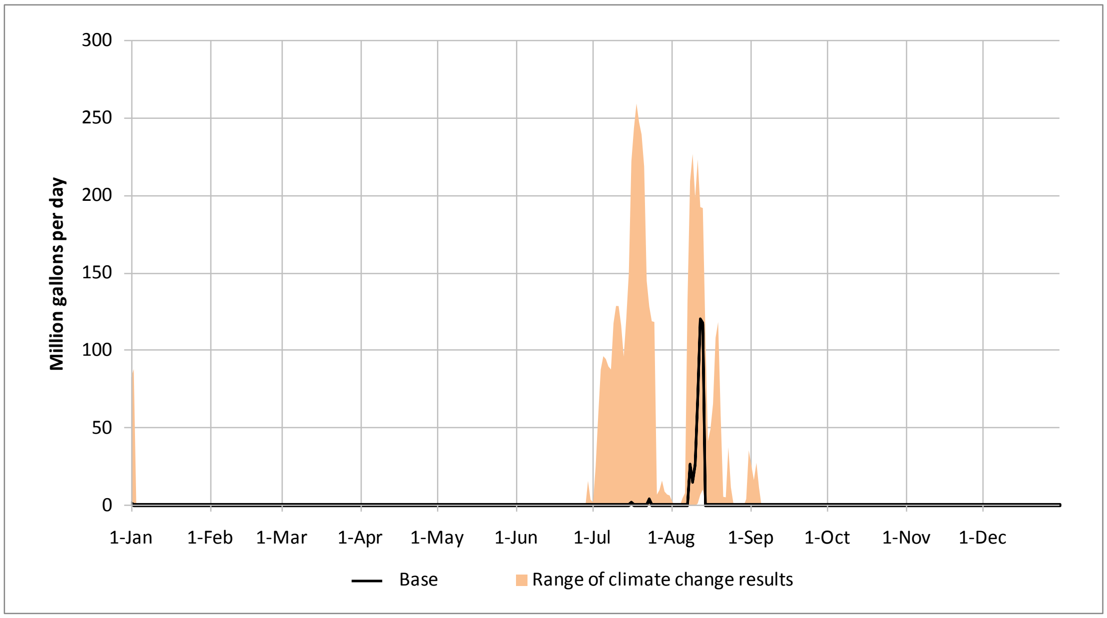


Figure 6-17: Little Seneca releases in the year 2040 in the event of a moderate drought.

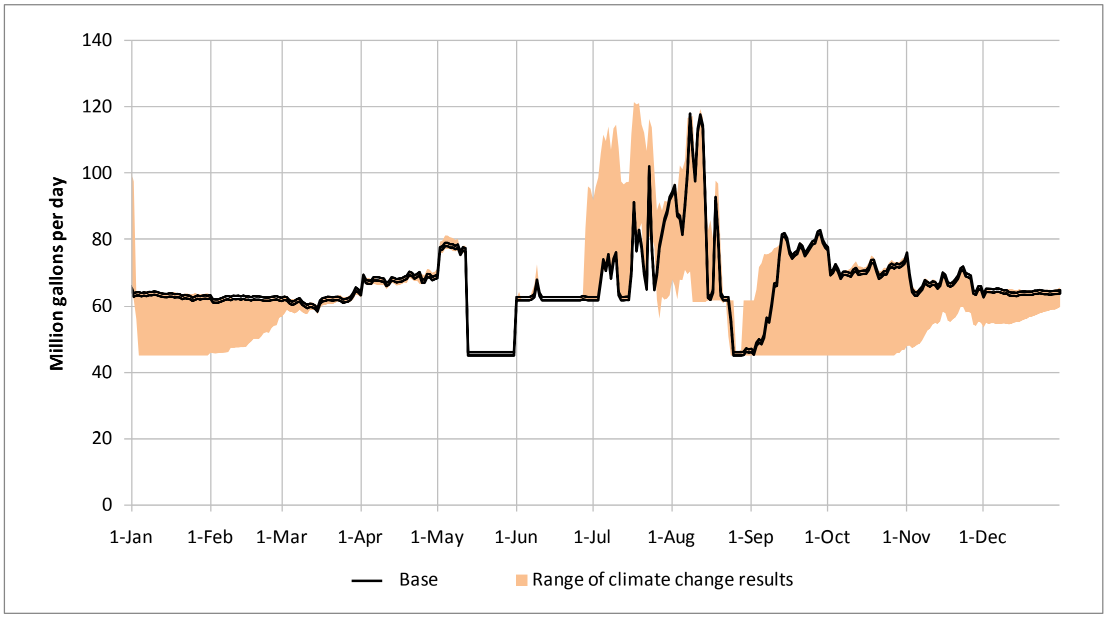


Figure 6-18: Occoquan production in the year 2040 in the event of a moderate drought.

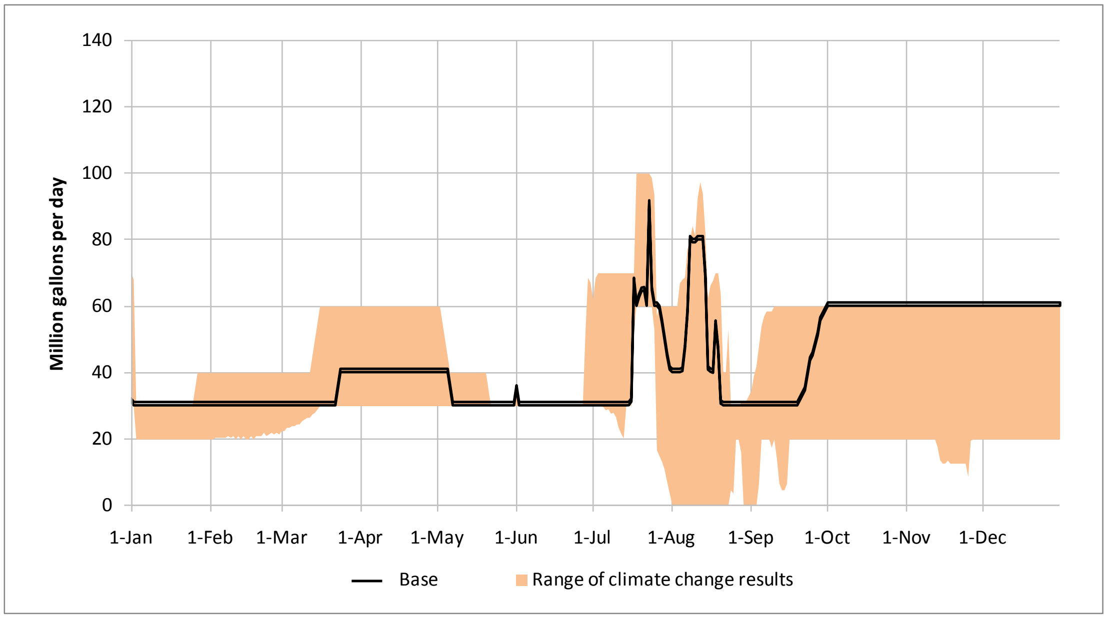


Figure 6-19: Patuxent production in the year 2040 in the event of a moderate drought.

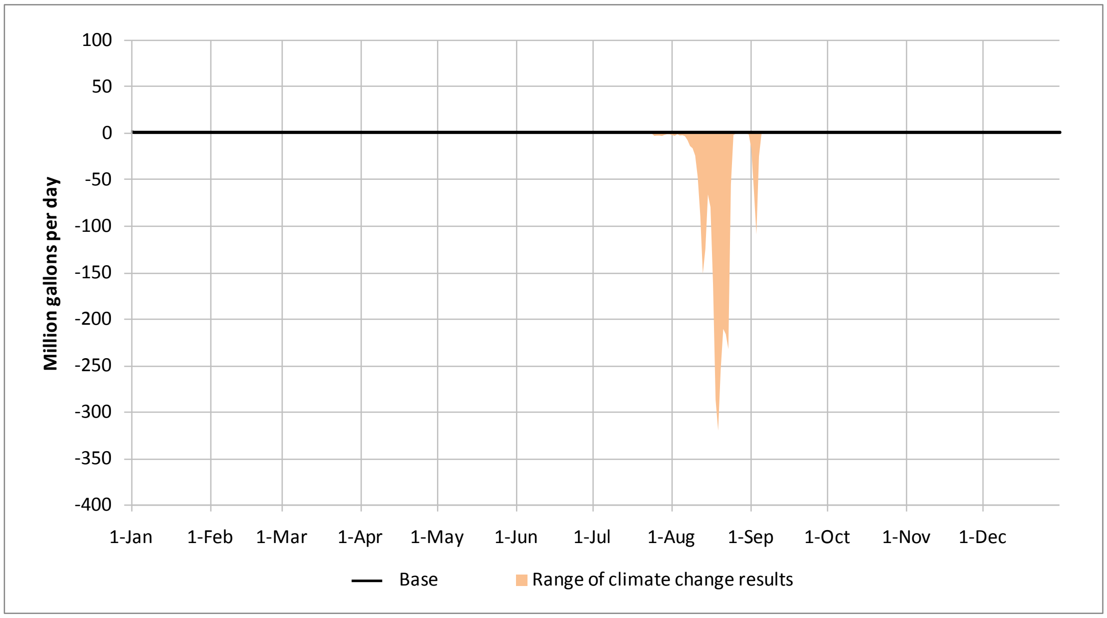


Figure 6-20: Potomac shortfalls in the year 2040 in the event of a moderate drought.

7 Conclusions

7.1 Key Results

Climate change may have a significant impact on current Washington metropolitan area water supplies. Though it is uncertain whether precipitation will increase or decrease in our region, study results indicate that higher temperatures may raise rates of evapotranspiration to a significant degree. Higher evapotranspiration rates are predicted to reduce the amount of water available to recharge basin aquifers and to decrease flows in the Potomac River and in the streams that fill and replenish system reservoirs. Study simulations produced a wide range of effects. However, under the assumption that no changes are made to the WMA water supply system, results indicate that in a basin altered by climate change a moderate drought occurring in 2040 may cause the imposition of emergency water use restrictions, nearly empty reservoirs, and water supply shortages.

This study was based on 18 climate change scenarios for the Potomac River basin for the year 2040, that is, 18 separate projections of how future temperatures, precipitation, and stream flows might be altered under climate change. ICPRB's long-term water supply planning model, PRRISM, was used to evaluate the impact of these changes on the performance of the Washington metropolitan area's water supply system, in comparison with a base scenario which assumed no climate change. Results fell evenly into three categories:

1) <u>Minor impact scenarios</u>: Six of the scenarios indicate that climate change will have a relatively minor impact on the system during a moderate drought, with water demands being met without mandatory water use restrictions and no severe depletion of system reservoir levels.
2) <u>Moderate impact scenarios</u>: Under six of the scenarios, the region experiences more frequent and stricter water use restrictions during a moderate drought, including mandatory restrictions, and significantly lower reservoir levels.
3) <u>Major impact scenarios</u>: The remaining six scenarios indicate that, in the absence of operational or structural changes to the water supply system, a moderate drought would cause the imposition of mandatory and emergency water use restrictions and the near emptying of most system reservoirs. In addition, water supply shortfalls would occur on some days of the drought.

7.2 Uncertainties

There is still a great deal of uncertainty associated with projections of future climate. There is no way to determine which of the 18 climate scenarios used in this study provides a closer approximation to actual conditions that will occur in the year 2040. Users of global model projections are cautioned against simple probabilistic interpretations of output from multiple models. Results in this report should be interpreted with the following uncertainties and study limitations in mind:

- Global climate model projections of temperature and precipitation changes vary widely.
- There is less confidence in projections at the regional scale, and in particular, global models differ on whether average precipitation will increase or decrease in the Potomac River basin.
- The Chesapeake Bay Program's watershed model was used to predict how altered climate would affect stream flows in the basin. These results are sensitive to estimates of evapotranspiration rates, which are subject to uncertainty due to the complexity of this process.

- Observed variability over a short historical time period, 1988-1999, was used to represent the range of potential conditions that might occur in 2040 under climate change. Results give an indication of how climate change may alter the effects of a moderate drought, comparable to the drought that occurred in 1999, but not a severe and prolonged drought.

7.3 Future Steps

Water supply planners and managers must ensure that resources are sufficient to meet the needs of the communities they serve as well as the requirements of aquatic ecosystems that depend on them. It is therefore important that they keep abreast of developments in climate science and regularly review and assess local trends and projections of how hydrologic conditions might change in the coming decades. Under the set of cooperative agreements which govern water supply planning and drought management in the Washington metropolitan area, the area's three main water suppliers are committed to conducting regular forecasts of future demands and resources. For the past 15 years this has included assessments of the potential impact of climate change.

Climate change will likely add additional stress to a system facing the challenge of population growth. The region's suppliers are committed by cooperative agreements to funding structural and/or operational means of increasing water availability if assessments determine that there is a need. Studies have been conducted on alternatives to increase water supplies (see Ahmed *et al.*, 2010 for a summary of past work). These alternatives have included use of the Potomac and Occoquan estuaries as supplies and retired quarries as storage facilities. Other measures that could improve system performance under climate change include:

1) increased flexibility in shifting between the system's Potomac and off-Potomac resources,
2) improved stream flow forecasts to inform reservoir release decisions, and
3) earlier and stricter water use restrictions.

Based on the results of this study, we recommend that future assessments and efforts related to the WMA system consider the following:

1) The results of the current study on climate change were determined to a large degree by predicted increases in evapotranspiration rates. Confidence in results would be increased by an investigation of the sensitivity of stream flows to changes in the model used to simulate evapotranspiration.
2) The current study was limited by the relatively short time series used to represent potential variations in future climate, which was based on historical data from 1988 through 1999. The construction of a long-term time series of historical Potomac basin meteorological and land use data, extending back to the year 1930, would allow for the simulation of conditions similar to the drought of record in a basin altered by climate change.
3) The next WMA water supply reliability study is scheduled for completion in 2015. This will provide an opportunity for an updated assessment of the relative benefits of selected options for increasing future water supplies.
4) The current cooperative approach to water supply planning and management has served the Washington metropolitan region well over the past 30 years. Impacts of climate change will be felt not just locally, but in communities throughout the Potomac basin. An extension of cooperative water supply management to other areas of the basin may be an additional aid in managing resources to meet the challenges of the future.

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Appendix A PRRISM Inputs

Model Input	Part 1 of 2010 Study	Part 2 of 2010 Study
General		
Potomac River historical flow time series (mgd)	Little Falls, 1929-2002	Little Falls, 1929-2007
Great Falls/Little Falls flow-bys (mgd)	300/100	300/100
Flow-by safety buffer (mgd)	30	30
Little Falls 9-day future flow predictions	Mainstem regression equation	Mainstem regression equation
Load shifting to Occoquan & Patuxent	Yes	Yes
Buffer for balance N Br/L Seneca releases	150	150
Random number seed for single runs	4426	4426
North Branch reservoirs		
JR usable capacity, WS + WQ (MG)	12,803 + 15,929 as of year 1997	12,803 + 15,929 as of year 1997
JR sedimentation rate (MG/yr)	127 (distributed) as of year 1997	127 (distributed) as of year 1997
Savage usable capacity in 2000 (MG)	6331 as of year 2000	6331 as of year 2000
Savage sedimentation rate (MG/yr)	18	18
Savage match	Yes - 16% of JR release	Yes - 16% of JR release
Westernport withdrawal/cutbacks	1/No	1/No
North Branch Advisory Group Recommendations		
JR whitewater releases	Yes	Yes
Savage whitewater releases	Yes	Yes
Threshold for making Savage WW releases as percentage of Rule Curve B	95%	95%
Try to meet Luke flow target on non-WW weekends	No	No
Little Seneca Reservoir		
Usable capacity in (BG)	3,785 as of year 2000	3,785 as of year 2000
Sedimentation rate (MG/yr)	15	15
Occoquan Reservoir		
Usable capacity (MG)	8,004 as of year 2000	8,004 as of year 2005
Sedimentation rate (MG/yr)	40	40
Rule curve	70 mgd + UOSA; 70 mgd; 60 mgd; 50 mgd	70 mgd + UOSA; 70 mgd; 60 mgd; 50 mgd
Maximum treatment rate (mgd)	120 in 2010; to 140 in 2018; to 160 in 2040	120 in 2010; to 140 in 2018; to 160 in 2040
Delta load shift (mgd)	35	35
Treatment plant water loss rate (percentage)	12%	12%
Cut back Occoquan withdrawals Jun 1 to Jul 15?	No	No
Reset Occoquan?	No	No

Model Input	Part 1 of 2010 Study	Part 2 of 2010 Study
Patuxent reservoirs		
Usable capacity (MG)	10,080 as of year 2004	10,080 as of year 2004
Sedimentation rate (MG/yr)	24	24
Patuxent rule curve, mgd	30/40/60	30/40/60
Maximum treatment rate (mgd)	100	100
Minimum treatment rate (mgd)	27	30
Treatment rate at emergency (< 10%) storage (mgd)	Not applicable	20
Delta load shift (mgd)	40	40
Cut back Patuxent withdrawals Jun 1 – Jul 15?	Yes – to 27 mgd	Yes – to 30 mgd
Reset Patuxent reservoirs?	No	No
Consumptive Use & WWTP return flows (mgd)		
Upstream consumptive use for Jun-Aug (mgd)	Based on Steiner *et al*., (2000), plus 1 mgd for Mirant Dickerson	Based on Steiner *et al*., (2000), plus 1 mgd for Mirant Dickerson
Upstream consumptive use for Sep-May (mgd)	Based on Steiner *et al*., (2000), plus 1 mgd for Mirant Dickerson	Based on Steiner *et al*., (2000), plus 1 mgd for Mirant Dickerson
Broad Run WWTP return flows (mgd)	Based on estimated Loudoun Water wintertime demand and consumptive use estimate (see Section 6.5, Part 1)	Based on estimated Loudoun Water wintertime demand and consumptive use estimate (see Section 6.5, Part 1)
Seneca WWTP return flows (mgd)	2010, 2015, 2020, 2025, 2030, 2035, 2040: 18.82, 20.57, 22.13, 23.49, 24.58, 26.37, 27.86	2010, 2015, 2020, 2025, 2030, 2035, 2040: 18.82, 20.57, 22.13, 23.49, 24.58, 26.37, 27.86
UOSA WWTP return flows (mgd)	2010, 2015, 2020, 2025, 2030, 2035, 2040: 32.15, 36.35, 40.45, 44.45, 48.45, 52.45, 56.45	2010, 2015, 2020, 2025, 2030, 2035, 2040: 32.15, 36.35, 40.45, 44.45, 48.45, 52.45, 56.45
Water use restrictions		
Water use restrictions	Yes	Yes
Restriction triggers: JR and/or L Seneca storage <, Voluntary/Mandatory/Emergency	60%/25%/5%	60%/25%/5%
Assumed demand reduction, Jun-Sep, Voluntary/Mandatory/Emergency	5%/9.2%/15%	5%/9.2%/15%
Assumed demand reduction in other months, Voluntary/Mandatory/Emergency	3%/5%/15%	3%/5%/15%
Maximum change in demand reduction per time step	0.5%	0.5%