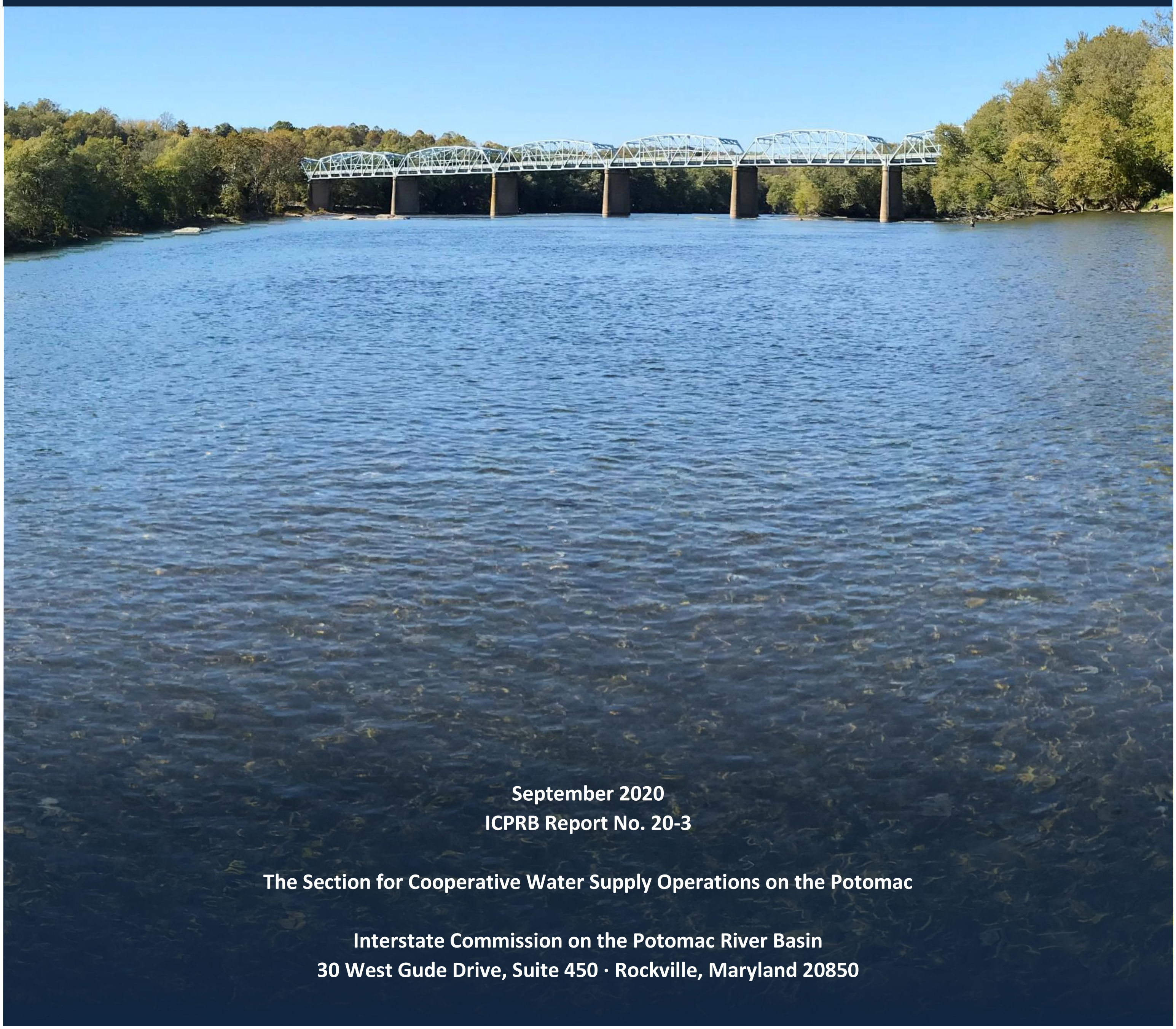
2020 Washington Metropolitan Area Water Supply Study

Demand and Resource Availability Forecast for the Year 2050

Prepared by S.N. Ahmed, H.L.N. Moltz, C.L. Schultz, and A. Seck



September 2020
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The Section for Cooperative Water Supply Operations on the Potomac

Interstate Commission on the Potomac River Basin
30 West Gude Drive, Suite 450 · Rockville, Maryland 20850

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Preface

This report was prepared by the Interstate Commission on the Potomac River Basin (ICPRB), Section for Cooperative Water Supply Operations on the Potomac (CO-OP) with funding provided by the three major Washington, DC, metropolitan area (WMA) water suppliers: Fairfax Water; the Washington Aqueduct Division of the U.S. Army Corps of Engineers; and WSSC Water. The Commission commends the work of CO-OP staff, in conjunction with experts from the regional water suppliers. This important study, the seventh in a series which began in 1990 to evaluate the ability of the WMA water supply system to meet future demands, supports infrastructure planning and decision-making to help provide a safer, more secure, sustainable and resilient water supply for the region for the coming decades. We encourage regional and federal stakeholders, planners and policymakers to take note of the report's findings. Specific details in the study may not in all instances reflect the official views or policies of ICPRB signatories or of the water suppliers.

Acknowledgements

This report would not have been possible without the many people who generously provided us with data and information. We thank the following individuals, as well as those whom we may have neglected to mention:

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Finally, we would like to express our appreciation to John Young of the USGS Leetown Science Center for providing us with the cover photo of the Potomac River at Point of Rocks.

List of Abbreviations/Glossary

°C	Degrees Celsius
°F	Degrees Fahrenheit
ac-ft	Acre-feet
ACS	American Community Survey
ARIMA	Autoregressive integrated moving average
BCSD	Bias-correction and spatial disaggregation
BG	Billion gallons
CBP	Chesapeake Bay Program
CDF	Cumulative distribution function
cfs	Cubic feet per second
CMIP5	Coupled Model Intercomparison Project Phase 5
CO-OP	Section for Cooperative Water Supply Operations on the Potomac
CO-OP suppliers	Fairfax Water, WSSC Water, and Washington Aqueduct
CU	Consumptive use
DC	District of Columbia
DC Water	District of Columbia Water and Sewer Authority
DES	Department of Environmental Services
DPW	Department of Public Works
DUR	Dwelling Unit Ratio
EMP	Employees
ESRI	Environmental Systems Research Institute
Fort Belvoir	United States Government (Fort Belvoir)
FW or Fairfax Water	Fairfax County Water Authority
GHCN	Global Historical Climatology Network
GHG	Greenhouse gas
GIS	Geographic Information Systems
gpd	Gallons per day
HH	Occupied households
HU	Housing units
ICPRB	Interstate Commission on the Potomac River Basin
IPCC	Intergovernmental Panel for Climate Change
Km	Kilometer

LFAA	Low Flow Allocation Agreement
LW	Loudoun Water
m	Meter
MAE	Mean absolute error
MDE	Maryland Department of Environment
ME	Mean error
MFH	Multi-family households
MG	Million gallons
MGD	Million gallons per day
MG/yr	Million gallons per year
MGS	Maryland Geological Survey
MSL	Mean sea level
MWCOG	Metropolitan Washington Council of Governments
NCA4	Fourth National Climate Assessment
NOAA	National Oceanographic and Atmospheric Administration
NCEI	National Centers for Environmental Information
NCICS	North Carolina Institute for Climate Studies
nClimGrid	Gridded 5km GHCN-Daily Temperature and Precipitation Dataset
NWIS	National Water Information System
PRISM	Parameter Regression on Independent Slopes Model
PRRISM	Potomac Reservoir and River Simulation Model
PWCSA	Prince William County Service Authority
PWD	Public Works Department
PWS	Public water supply
R^2	Coefficient of determination
RCP	Representative concentration pathway
RMSE	Root mean square error
SA	Service area
SE	Standard error
SD	Standard deviation
SFH	Single family households
TAZ	Traffic analysis zones
US	United States

USACE	U.S. Army Corps of Engineers
USEPA	U.S. Environmental Protection Agency
USGS	U.S. Geological Survey
UPRC	Upper Potomac River Commission
VADEQ	Virginia Department of Environmental Quality
VAWC	Virginia-American Water Company (VAWC or VAW)
WA	Washington Aqueduct
WMA	Washington Metropolitan Area, or Washington, DC., metropolitan area
WMA suppliers	CO-OP suppliers, Loudoun Water, and the City of Rockville
WSCA	Water Supply Coordination Agreement
WSSC Water	Washington Suburban Sanitary Commission
WRF	Water reclamation facility
WRRF	Wastewater resource recovery facility
WTP	Water treatment plant
WWTP	Wastewater treatment plant
WFP	Water filtration plant
WTF	Water treatment facility

Executive Summary

The Washington, DC, metropolitan area (WMA) is home to almost five million people and the place of employment for over three million. The region's water suppliers have an important responsibility: to meet water supply needs and reliably ensure that the functions of federal government, including Congress, the Pentagon, and key agencies, are not disrupted. The WMA has a unique, cooperative water supply system that was established more than 35 years ago by agreement among the Fairfax County Water Authority (Fairfax Water), the Washington Suburban Sanitary Commission (WSSC Water), the Washington Aqueduct Division of the U.S. Army Corps of Engineers (Washington Aqueduct), the District of Columbia, and the Interstate Commission on the Potomac River Basin (ICPRB). One of the requirements of the agreement is that every five years a study be conducted to evaluate whether available resources will be able to meet forecasted water demands. This is the seventh in the series of such studies. The objective of the current study is to provide decision-makers with the following:

- forecasts of water demands for the WMA throughout the planning horizon, 2050, taking into account projected demographic and societal changes that may affect future water use,
- forecasts of water availability, considering the potential impact of changes in climate and upstream water use on system resources, and
- an evaluation of the ability of current and planned system resources to meet the forecasted demands.

The current study has a fourth objective, and that is to assess the effectiveness of several options for enhancing the current system that were recommended in a special study conducted in 2017 (Schultz *et al*., 2017). This special study, which will be referred to as the 2017 alternatives study, evaluated and compared the ability of 10 proposed changes and additions to the WMA water supply system to meet the challenges of growing regional demand for water and the potential impacts of climate change.

Study Approach

This study includes several new elements: i) an estimate of the statistical uncertainties of the annual demand forecasts (Chapter 3, Section 3.5), ii) a new assessment of the impact of climate change on the variability of mean annual streamflows (Chapter 6), and iii) inclusion of the impact of state drought management on Potomac River flow (Chapter 7).

A scenario planning approach is used to investigate the performance of the WMA water supply system under a plausible range of future conditions. Scenario planning can inform decisions regarding new infrastructure, especially in the face of significant uncertainties. In the current study, scenarios are developed to represent ranges of uncertainty in future water demands and in the response of basin streamflows to future changes in climate. CO-OP's planning model, the Potomac Reservoir and River Simulation Model (PRRISM), is used to evaluate how well four potential future configurations of the WMA water supply system would perform under the various scenarios. The future system configurations are based on the recommended phased options presented in the 2017 alternatives study, but also take into account stakeholder efforts initiated since the publication of that study.

WMA Water Supply System

The WMA is defined in this study as the District of Columbia and the portions of the Maryland and Virginia suburbs that are supplied water, either directly or indirectly, by Fairfax Water, Washington Aqueduct, and WSSC Water (known collectively as the CO-OP suppliers) and by Loudoun Water and the City of Rockville. The areas served by these suppliers, along with current, planned, and proposed resources, are shown in Figure ES-1.

The Potomac River supplies, on average, just over three quarters of the WMA's water. The CO-OP suppliers provide funding for three upstream reservoirs: Jennings Randolph, Little Seneca, and Savage. Water in these reservoirs is released during drought to augment natural river flow. In addition, Fairfax Water and WSSC Water rely daily on reservoirs outside of the drainage area of the freshwater Potomac River, on the Occoquan River and the Patuxent River, respectively. Two additional resources are planned to be in place within the next 20 years: Loudoun Water's Milestone Reservoir, scheduled for completion in 2024, and Fairfax Water's Vulcan Quarry Phase 1, planned to be in place by 2040 to augment their Occoquan supply.

Two proposed reservoirs are also shown in Figure ES-1: Travilah Quarry, located in Montgomery County, Maryland, and Luck Stone Quarry B, in Loudoun County, Virginia.[1] Loudoun Water has a long-standing relationship with the Luck Stone Company and aims to have Quarry B available by 2040 for use as a regional resource. Travilah Quarry was found to be most effective in mitigating the risk to WMA water supply of a contaminant spill in the Potomac River (MWCOG, 2016) and was also found to be a highly effective resource for drought mitigation in the 2017 alternatives study (Schultz *et al.*, 2017). An effort is currently

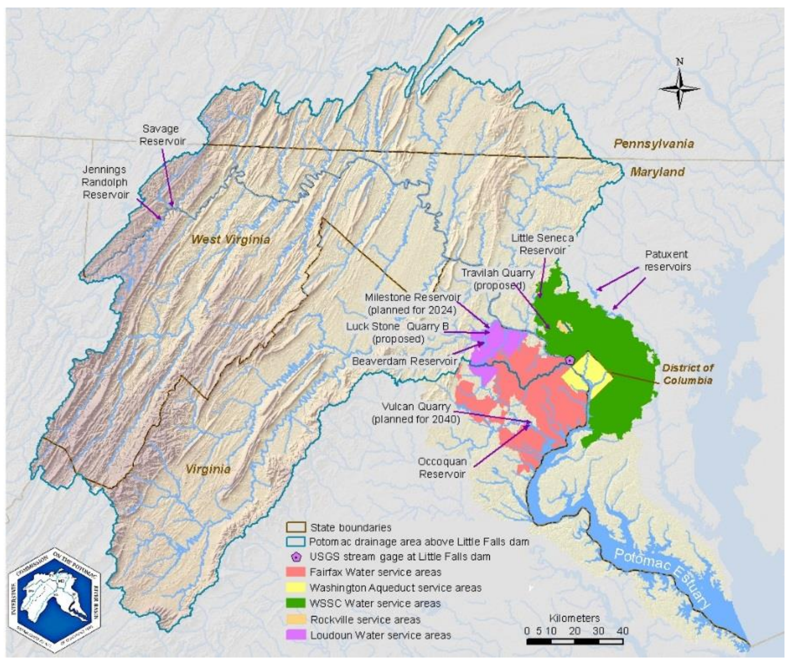

Figure ES-1: WMA water supply system service areas and current, planned, and proposed resources.

[1] At this time, neither of these resources are owned by the CO-OP suppliers and no agreements for regional use have been developed.

underway, led by the CO-OP water suppliers and supported by the ICPRB, to initiate the planning studies and stakeholder dialogs necessary to acquire and convert Travilah Quarry for use as a dual-purpose regional water supply resource.

Forecasts of Water Demand

Due to continuing improvements in efficiencies of household water fixtures and appliances, water use in the WMA has remained remarkably steady for almost three decades despite continuing population growth. Water demand averaged 453 million gallons per day (MGD) for the CO-OP suppliers during the most recent period for which data is available (2014-2018). Figure ES-2 shows total annual, summer, and winter water production, as well as annual peak-day production, from 1990-2018. Though the WMA population rose 41% over this period, from 3.4 to 4.8 million people, water demands have essentially remained constant due to falling per household and per employee use. This pattern of declining unit use is consistent with trends observed throughout the United States (DeOreo and Mayer, 2012).

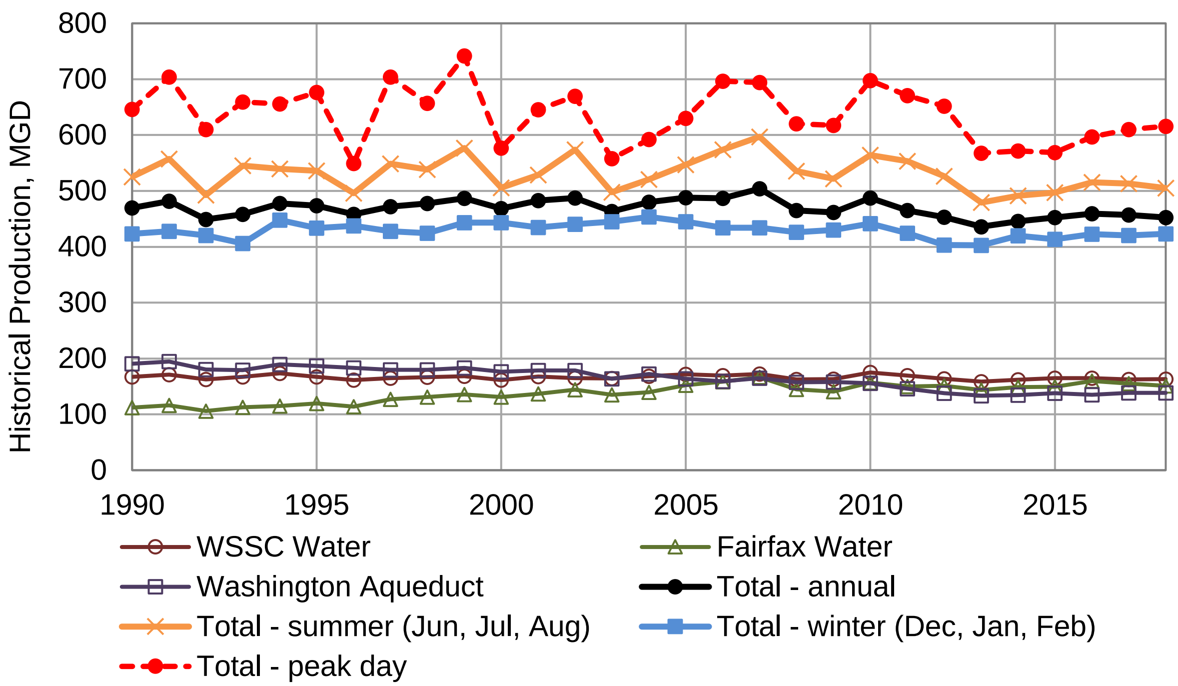

Figure ES-2: Historical CO-OP supplier water use, from supplier daily production data.

Forecasts of average annual water demand were developed by combining recent water use information derived from billing data provided by the WMA suppliers and their wholesale customers, information on the current and future extent of the areas served, and the most recent demographic forecasts (Round 9.1) from the Metropolitan Washington Council of Governments (MWCOG). Water use data was disaggregated into three categories for forecasting purposes: single family households, multi-family households (apartments and condominiums), and employees (including commercial, industrial, and institutional use). Extrapolations on the MWCOG Round 9.1 forecasts project that population in the WMA in 2050 will be 6.1 million, a 27% increase from 2018 levels.

Average annual demand in the WMA, including Rockville, was 455 MGD in 2018, and this is projected to increase to 501 MGD (10%) by 2040 and to 528 MGD (16%) by 2050. The estimated uncertainties (one standard error) in 2040 and 2050 are ±9.7% and ±10.4%, respectively. In Figure ES-3, the forecasted demands of the CO-OP suppliers are compared with results from past studies by ICPRB (Kame'enui *et al.*, 2005; Hagen and Steiner, 2000; Mullusky *et al.*, 1996; Holmes and Steiner, 1990; Ahmed *et al.*, 2010; Ahmed *et al.*, 2015), the U.S. Army Corps of Engineers (USACE) (1963; 1983), and MWCOG (as reported in USACE 1975). WMA demand forecasts have consistently fallen over time due to reductions in per household and per employee use. ICPRB's more recent WMA demand forecasts have included a model that predicts future reductions in household and employee use based on installation of water savings fixtures and appliances in new construction and assumed replacement rates for existing buildings. Nonetheless, new technologies may become available that are not envisioned by today's water planners, and this may result in further unanticipated reductions in unit use rates in future years.

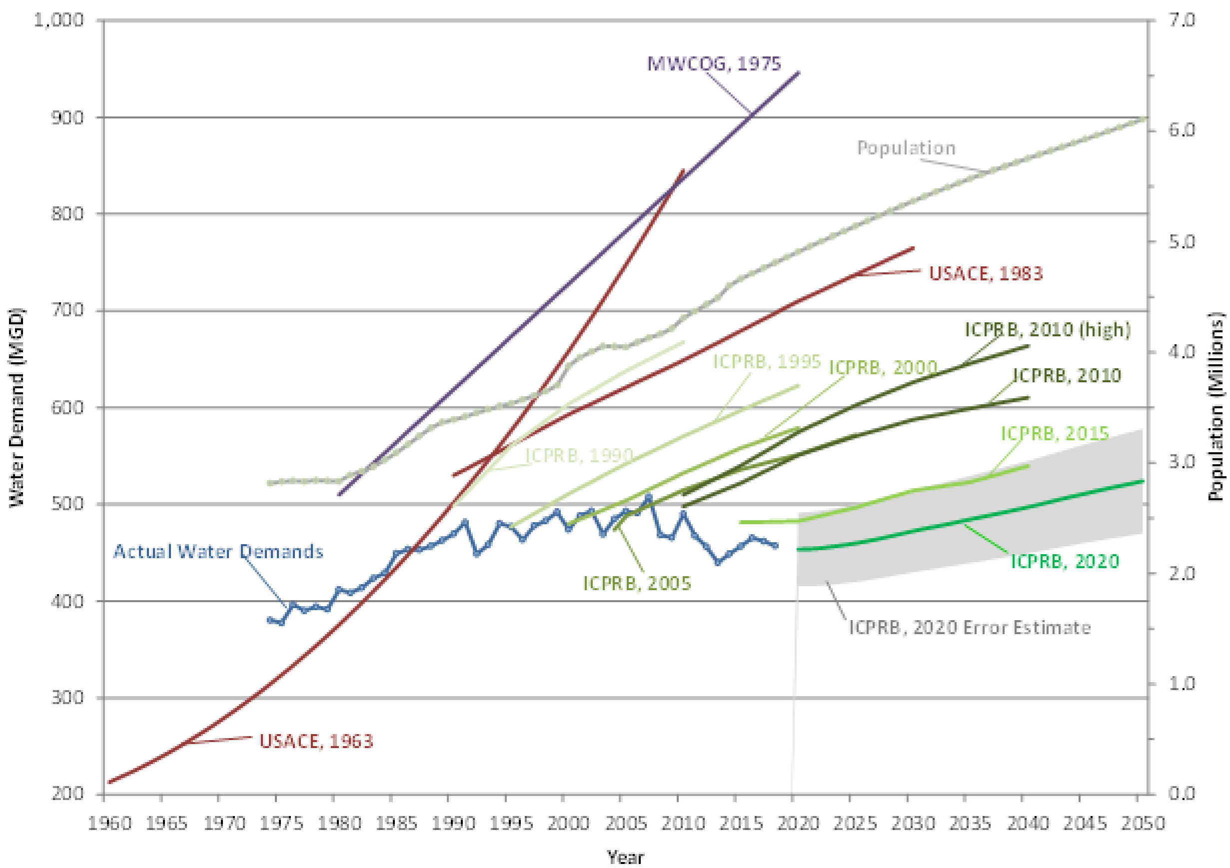

Figure ES-3: Current and past forecasts of WMA water demand (excluding Rockville).

Potential Impact of Climate Change

This study's water availability forecast includes the estimated impact that a changing climate will have on future streamflows. Projections indicate that the mid-Atlantic states, on average, are becoming and will continue to get "wetter." Climate scientists also warn that extreme conditions, that is, floods and droughts, will become more severe. The aim of the current study is to derive scenarios for regional flows that reflect the expected differences in the impact of climate change on higher flow years versus lower flow years.

There is tremendous uncertainty about how climate change will affect streamflows. The current study uses an ensemble of 224 climate projections for the Potomac River watershed upstream of Little Falls dam, derived from the Coupled Model Intercomparison Project Phase 5 (CMIP5) multi-model ensemble, statistically downscaled using monthly bias-correction and spatial disaggregation (BCSD) (Reclamation, 2013). On average, precipitation in the Potomac River watershed in 2040 and 2050 is projected to increase by 8% and 10%, respectively, and temperature is projected to increase by 2.16 °C (3.9 °F) and 2.5 °C (4.5 °F), respectively. But the range of projected changes among the ensemble members is large, contributing to uncertainty in future flows.

HOW WILL POTOMAC BASIN STREAMFLOWS RESPOND TO RISING TEMPERATURES IN 2040 AND 2050?

Lower Flows Scenario – significant response:

- 11% to 14% increase in very wet years
- Little change in average years
- 27% to 35% decrease in very dry years

Medium Flows Scenario – moderate response:

- 14% to 18% increase in very wet years
- 5% to 6% increase in average years
- 9% to 13% decrease in very dry years

Higher Flows Scenario – minimal response:

- 18% to 23% increase in very wet years
- 11% to 13% increase in average years
- 7% to 8% increase in very dry years

A second significant source of uncertainty stems from the limitations of the models used to predict streamflows from climate projections. This study relies on a simple climate response function, based on a least squares multiple regression analysis, to predict mean annual natural Potomac River flow from mean annual precipitation, mean annual temperature, and the previous year's mean flow. To represent the potential range of response of Potomac basin flow to temperature, three "flow scenarios" are constructed, (see box to the left). In the "Lower Flows" scenario, the response to rising temperatures is significant, resulting in a drying effect which outweighs the projected future increases in precipitation. In the "Higher Flows" scenario, the response of basin hydrology to rising temperatures is minimal, with rising precipitation dominating changes in flow. Each flow scenario is constructed from changes in long-term flow statistics computed over 30-year periods centered around the forecast years, 2040 and 2050, as compared to values before the onset of climate change (over the 1950-1979 time period). The changes in annual flows for lower flow years are found to be very different than those for higher flow years, indicating that droughts may become more extreme even in a future where average flows rise. Representative changes, shown in the box, are given for annual flow in very wet years (99th percentile annual flow), average years (50th percentile) and very dry years (1st percentile).

IMPACT OF STATE DROUGHT MANAGEMENT ON UPSTREAM CONSUMPTIVE USE

The impact of upstream consumptive use, that is, the net amount of water withdrawn by users above the WMA, is considered in the water availability forecasts. In the current study, estimates of upstream consumptive use include the effects of state drought management decisions. Under state drought plans, water use restrictions may be imposed, with the level of restrictions dependent on the severity of drought conditions. These governmental actions may mitigate the impact of upstream consumptive use on downstream users. For this study, Maryland and Virginia drought stage declarations are represented in CO-OP's planning model, PRRISM, allowing simulation of the impact of state management decisions on flow in the Potomac River at WMA intakes. When state drought management measures are simulated, results indicate that average Potomac River flow from June through September increases by 6 to 12 MGD and minimum flow above WMA intakes improves by 10 to 18 MGD during a severe drought.

Ability of Future System to Meet Forecasted Demands

Nine scenarios for future conditions are used to represent ranges of uncertainties in future WMA water demand and in the impact of climate change on water availability in the Potomac basin. These are formed by combinations of three demand scenarios, based on this study's forecasts for total WMA demand plus or minus the estimated standard errors, and three flow scenarios, described above.

For each of the nine future scenarios, CO-OP's planning model, PRRISM, was used to evaluate how well four potential future configurations of the WMA water supply system would perform. These configurations are based on the recommended phased options presented in the 2017 alternatives study (Schultz *et al.*, 2017). The configurations are listed in the box on the right, in order of increasing enhancement. The recommended operational alternatives include improvements in river flow forecasts and alternative strategies for use of several existing reservoirs.

What Will the Future WMA Water Supply System Look Like?

Baseline: Current resources + Milestone Reservoir + Vulcan Quarry, Phase 1.

Baseline + Ops: Baseline + four recommended operational alternatives

Baseline + Ops + Travilah: Baseline + Ops + Travilah Quarry

Baseline + Ops + Travilah + Luck: Baseline + Ops + Travilah + Luck Stone Quarry B

Qualitative results of the PRRISM analyses are given below in Table ES-1 and Table ES-2, where the colors indicate system performance during a severe drought, comparable to the 1930 drought of record but in an altered climate. GREEN denotes reliable performance, YELLOW denotes marginal performance, that is, with some emergency water use restrictions and/or a small chance of a shortage of water averaging 1 MGD or less, and RED denotes system failure, that is, the inability of the system to meet combined WMA water supply needs and the 100 MGD flow-by requirement at Little Falls. Quantitative results are given in Chapter 8 and Appendix A.5.

Results in Table ES-1 indicates that the Baseline system would perform marginally in the event of a severe drought in 2040 under the Medium Flows/Medium Demands scenario. Emergency water use restrictions would be imposed on WMA households and businesses and reservoir storage would fall to extremely low levels. However, implementation of the suite of four recommended operational alternatives elevates system performance to reliable. Under all the 2040 Lower Flows scenarios, the addition of Travilah Quarry is necessary to avoid system failure in a severe drought.

In 2050 in the event of a severe drought, the Baseline system performs well in simulations under all the Higher Flows scenarios, but experiences difficulties, ranging from moderate to extreme, under the Medium and Lower Flows scenarios. The implementation of the four operational alternatives improves system performance significantly under three scenarios. With Travilah Quarry, the system performance becomes reliable or marginally reliable under three additional scenarios. However, even with both the Travilah and Luck quarries in place, PRRISM simulations indicate that during a severe drought, the system is unable to meet WMA water demands plus the Little Fall flow-by under two of the Lower Flows scenarios.

It should be noted that PRRISM simulations were also conducted under the assumption that climate change will have no impact on future demands or streamflows, to provide continuity with results of some of the past ICPRB studies. Results for the “no climate change” PRRISM runs indicate that the Baseline system would be reliable with forecasted 2040 demands under a re-occurrence of the 1930 drought of record, but by 2050, implementation of the four operational alternatives would be required.

The nine scenarios for 2050 provide a look at potential resource needs at the end of the 30-year planning horizon. Results from this study indicate that if droughts become much more severe, as represented by the Lower Flows climate scenarios, the WMA system may be unable to meet combined water supply needs and the environmental flow-by at Little Falls even if all of the recommended options of the 2017 alternatives study are implemented, including Travilah Quarry and Luck Stone Quarry B. Resource options above and beyond those considered in the current study are available. For example, construction of a reverse osmosis membrane water treatment plant drawing from the Occoquan estuary was the subject of a preliminary engineering study by CDM on behalf of Fairfax Water (CDM, 2004) and was shown in the 2017 alternatives study to provide significant benefits to the WMA system in terms of system safe yield. Benefits from the alternatives considered in the current study, for example, use of Jennings Randolph water quality storage in drought emergencies, might be increased if better strategies are developed for their implementation, perhaps through use of optimization techniques in the PRRISM planning model. Also, new regional resource options have been proposed.

Stakeholders may want to wait for more information to help gage the likelihood of the 2050 Lower Flows climate scenario. ICPRB’s next water supply study, planned for 2025, will reassess the potential impact of climate change on regional streamflow based on additional data on climate and flow trends and projections. If it’s determined that steps need to be taken to address the risk of an extreme low flow scenario, engineering studies will be conducted for new resource options so that they can be simulated and evaluated for effectiveness in future water supply planning studies.

Table ES- 1: WMA water supply system performance for 2040 scenarios (GREEN – reliable, YELLOW – marginal, RED – system failure).

	Higher Flows			Medium Flows			Lower Flows		
	Low Demands	Medium Demands	High Demands	Low Demands	Medium Demands	High Demands	Low Demands	Medium Demands	High Demands
Baseline	GREEN	GREEN	GREEN	GREEN	YELLOW	RED	RED	RED	RED
Baseline + Ops	GREEN	GREEN	GREEN	GREEN	GREEN	YELLOW	RED	RED	RED
Baseline + Ops + Travilah	GREEN	GREEN	GREEN	GREEN	GREEN	GREEN	GREEN	GREEN	YELLOW
Baseline + Ops + Travilah + Luck	GREEN	GREEN	GREEN	GREEN	GREEN	GREEN	GREEN	GREEN	GREEN

Table ES- 2: WMA water supply system performance for 2050 scenarios (GREEN – reliable, YELLOW – marginal, RED – system failure).

	Higher Flows			Medium Flows			Lower Flows		
	Low Demands	Medium Demands	High Demands	Low Demands	Medium Demands	High Demands	Low Demands	Medium Demands	High Demands
Baseline									
Baseline + Ops									
Baseline + Ops + Travilah									
Baseline + Ops + Travilah + Luck									

1 Introduction

This study is the seventh in a series of water demand and availability forecasts that have been conducted by the Section for Cooperative Water Supply Operations on the Potomac (CO-OP) of the Interstate Commission on the Potomac River Basin (ICPRB). The objective of these studies is to aid in long-range water supply planning by

- forecasting water demands for the Washington, DC, metropolitan area (WMA) throughout the planning horizon, taking into account projected demographic and societal changes that may affect future water use,
- forecasting water availability, considering the potential impact of changes in climate and upstream water use on system resources, and
- evaluating the ability of current and planned system resources to meet the forecasted demands.

The current study has a fourth objective, and that is to assess the effectiveness of several options for enhancing the current system that were recommended in a special study conducted in 2017 (Schultz *et al*., 2017). This special study, which will be referred to as the 2017 alternatives study, evaluated and compared the ability of ten proposed changes and additions to the WMA water supply system to meet the challenges of growing regional demand for water and the potential impacts of climate change.

The current study has been conducted on behalf of the three major water suppliers ("CO-OP suppliers"): Fairfax County Water Authority (Fairfax Water), the Washington Suburban Sanitary Commission (WSSC Water), and the Washington Aqueduct Division of the U.S. Army Corps of Engineers (Washington Aqueduct). The WMA is defined in this study as the District of Columbia and the portions of the Maryland and Virginia suburbs that are supplied water, either directly or indirectly, by the CO-OP suppliers, Loudoun Water, and/or the City of Rockville.

The study satisfies a requirement of both the *Low Flow Allocation Agreement* (LFAA), as amended by Modification 1, signed in 1978 by the United States, the State of Maryland, the Commonwealth of Virginia, the District of Columbia, WSSC Water, and Fairfax Water; and the *Water Supply Coordination Agreement* (WSCA), signed in 1982 by the United States, Fairfax Water, WSSC Water, the District of Columbia, and ICPRB. As stated in the WSCA, it is agreed that "In April 1990 and in April of each fifth year thereafter… the Aqueduct, the Authority, the Commission and the District shall review and evaluate the adequacy of the then available water supplies to meet the water demands in the Washington Metropolitan Area which may then be expected to occur during the succeeding 20-year period." The current study includes 20-year forecasts, to the year 2040, as required by the WSCA and LFAA. It also includes forecasts to the year 2050 to provide the CO-OP suppliers with results for a longer-term planning horizon and to help Virginia suppliers meet requirements of the Virginia Department of Environmental Quality (VADEQ) water supply planning program.

1.1 Study Overview

Water demand and availability forecasts are important for water supply planning because the time required to develop new resources is lengthy. ICPRB has conducted water supply planning studies every five years beginning in 1990 (Holmes and Steiner, 1990; Mullusky, *et al.*, 1996; Hagen and Steiner, 2000; Kame'enui *et al.*, 2005; Ahmed *et al.*, 2010; Ahmed *et al.*, 2015). This five-year time interval allows each study to incorporate the most up-to-date regional demographic forecasts, published by the Metropolitan Washington Council of Governments (MWCOG), along with recent data on water use in the WMA. Successive studies also take advantage of continued improvements in data availability and in simulation and analysis tools. In addition to allowing for updates and refinements to forecasts and analyses, this iterative approach to water supply planning increases the visibility of regional water supply issues and fosters communication between regional stakeholders (Hagen *et al.*, 2005). The current study incorporates the following new elements:

- a range of uncertainty for the annual demand forecasts, based on a statistical analysis of data uncertainty (Chapter 3, Section 3.5);
- a representation of the range of potential impact of climate change on future stream flows in the Potomac basin, which is based on projections of changes in inter-annual variability (Chapter 6); and
- a representation of the impact of state drought stage declarations in upstream areas on river flow at WMA supplier intakes (Chapter 7).

Forecasts of average annual water demand are developed by combining end-use customer billing data provided by the suppliers, information from suppliers and local planning agencies on the current and future extent of water service areas, and the most recent demographics from the MWCOG Round 9.1 (MWCOG, 2018) forecasts, as described in Chapter 3. MWCOG forecasts are currently available at five-year intervals up through the year 2045, so extrapolation techniques are relied upon to obtain the 2050 annual demand forecasts. Estimates of seasonal and daily variations in demand, described in Chapter 4, are dependent on the time of year, day of the week, and meteorological conditions, and are simulated using statistical regression and modeling techniques similar to those used by Ahmed *et al.* (2015); Ahmed *et al.* (2010); Kame'enui *et al.* (2005); and Steiner (1984).

Forecasts of water availability consider the potential impact of climate change on Potomac basin streamflows and the impact of upstream consumptive use of water on river flow at WMA intakes. The climate change analysis is based on a large ensemble of precipitation and temperature projections from global climate models (GCMs) that have been adjusted, via a technique called bias correction and spatial disaggregation, to improve the match with the historical record in the Potomac basin. A climate response function, based on a multiple least squares regression model, is developed to predict mean annual Potomac River flow from projections of annual precipitation and temperature. A quantile scaling approach is used to obtain flow-dependent change factors for annual flows, based on the projected fractional change in future annual Potomac River flow, for each flow percentile, as measured from its value in a pre-climate change era. These change factors are then applied to the historic flow record to provide scenarios for how climate change will impact river flows and reservoir inflows. The estimates of upstream consumptive use include a new component which represents the impact of state drought management decisions on downstream Potomac River flow. The water availability forecasts also incorporate recent or anticipated changes to the physical WMA water supply system, including loss of reservoir storage capacity due to sedimentation, changes in water treatment plant production rates, and changes to finished water distribution systems.

The assessment of the WMA system performance, presented in Chapter 8, evaluates how the WMA's water supply system, with current, planned, and proposed resources, would respond to forecasted water demands under the range of hydrologic conditions that may be experienced in a future influenced by climate change. The analysis is conducted using CO-OP's planning model, the Potomac Reservoir and

River Simulation Model (PRRISM) to simulate future water demand and availability for the WMA. PRRISM simulates on a daily basis the processes that govern water supply and demand in the system, including flows in the Potomac River, inflows, storage, and releases from reservoirs, and withdrawals by WMA suppliers.

1.2 Water Suppliers

The Potomac River is the primary water supply source for the WMA. This study represents the operations of the five WMA suppliers, listed below, that withdraw and treat water from the Potomac River:

- Washington Aqueduct, serving the District of Columbia via the District of Columbia Water and Sewer Authority (DC Water) and Arlington County, Virginia, and serving Falls Church, Virginia, via sale of water to Fairfax Water;
- WSSC Water, serving Montgomery and Prince George's counties in Maryland, providing a limited amount of water to Howard and Charles counties, and providing water on an emergency basis to the City of Rockville and to DC Water;
- Fairfax Water, serving most of Fairfax County, Virginia, and certain other Virginia suburbs;
- City of Rockville, in Montgomery County, Maryland; and
- Loudoun Water, serving Loudoun County, Virginia; Loudoun Water supplies its customers with a combination of water withdrawn from the Potomac River and treated by its new Trap Rock Water Treatment Facility and treated water purchased from Fairfax Water.

Collectively, these suppliers obtain on average just over three quarters (76%) of their water from the Potomac River. The CO-OP suppliers – Washington Aqueduct, WSSC Water, and Fairfax Water – jointly provide funding for and have rights to use water stored in two upstream reservoirs: Jennings Randolph and Little Seneca. They also provide a portion of the funding for a third upstream reservoir, Savage, which is operated in conjunction with Jennings Randolph. Water in these reservoirs can be released during times of drought to augment natural river flow. The remaining (24%) of supplier water comes from water stored in reservoirs which are outside of the drainage area of the freshwater portion of the Potomac River, on the Occoquan and Patuxent rivers, which serve Fairfax Water and WSSC Water, respectively. An additional off-Potomac source is Loudoun Water's Milestone Reservoir, a retired hard rock quarry that is scheduled for completion in 2024. Milestone Reservoir will provide a portion of Loudoun Water's supply during droughts, under conditions specified in its Virginia Water Protection Permit No. 10-2020.

1.3 History of Cooperation

Concern about WMA water supply began in the 1960s. The population of the WMA was expected to grow to five million by 1985 (USACE, 1963), after having grown from 672,000 in 1930 to two million in 1960. During this same time period, drought-induced rationing was viewed as a real threat, as demand forecasts were expected to exceed the low-flow of the largely unregulated (that is, with few dams) Potomac River (*Potomac Basin Reporter*, 1982).

Potential measures to increase water supply were evaluated during this period. The USACE conducted a study that identified 16 potential dam sites on the Potomac River upstream of the District of Columbia, whose reservoirs could augment supply during low-flow periods (USACE, 1963). There was significant public opposition to many of these sites and only one, Jennings Randolph Reservoir near Bloomington, Maryland, was constructed. Other alternatives included estuary treatment plants, interconnections in the distribution systems, and inter-basin transfers (Ways, 1993).

The actual WMA population in 1985, approximately 3.1 million people (United States Census Bureau, 2004), was lower than originally forecasted by the USACE. However, the WMA's 1971 through 1982 demand levels exceeded the Potomac River's 1966 low-flow record 41 times (Ways, 1993). The WMA did not experience water supply shortages during this period only because Potomac River flows were not reduced to such extremes due to drought.

Given the opposition to constructing reservoirs, the suppliers and local governments searched for other solutions. By the late 1970s, researchers at Johns Hopkins University had developed the basis of the cooperative system used today (Palmer *et al.*, 1979; 1982; Sheer, 1977). This research indicated that the management of Jennings Randolph Reservoir, scheduled to be completed in 1981, in coordination with the existing Occoquan and Patuxent reservoirs, could meet the region's projected demand and maintain adequate flow in the Potomac River through about 2020. Increased system reliability stems from operating rules which specify that participating suppliers depend more heavily on the free-flowing Potomac River during winter and spring months of low-flow years to preserve storage in the Patuxent and Occoquan reservoirs. This strategy is possible because even during droughts, the winter and spring Potomac River flow is more than adequate to meet water supply demand. This operating policy ensures that the Patuxent and Occoquan reservoirs remain available for use during the summer low-flow season and reduces the probability of system failure. Thus, a regional consensus emerged, minimizing the need for new dams or other costly and controversial structural measures.

Following this consensus, key agreements governing this cooperative approach were forged. In 1978, the USACE (representing Washington Aqueduct), Maryland, Virginia, the District of Columbia, Fairfax Water, and WSSC Water signed the LFAA. The agreement defines how Potomac River water withdrawals will be allocated between the suppliers in the event that the total flow is not sufficient to meet the needs of each supplier plus an environmental flow-by at Little Falls dam. These allocations are set annually, based on winter water use.

On July 22, 1982, eight agreements were signed that established the WMA's cooperative system of water supply management, which includes shared funding and use of regional resources, coordinated operations during periods of drought, and regular forecasts of water demands. Fairfax Water, WSSC Water, the District of Columbia, the USACE (representing Washington Aqueduct), and ICPRB signed the WSCA. This agreement provides for the coordinated use of the major water supply facilities in the region, including those on the Patuxent and Occoquan rivers, as a means of minimizing the potential of triggering the LFAA's low-flow allocation mechanism. Under the WSCA, the suppliers cooperate by operating as one entity that shares water across the Potomac, Patuxent, and Occoquan basins during low-flow periods.

The CO-OP suppliers jointly pay the capital and operating costs for Little Seneca Reservoir, which was completed in 1985, and for a portion of the water stored in the Jennings Randolph Reservoir, which was completed in 1981. These reservoirs are used during droughts to augment the natural flow of the Potomac River. Together, these sources provide approximately 17 billion gallons (BG) of storage upstream of the WMA Potomac River intakes designated for water supply purposes. The CO-OP suppliers also contribute to the operating costs of Savage River Reservoir.

As specified in the WSCA, ICPRB's CO-OP Section assumes a direct role in managing water supply resources and WMA withdrawals during droughts. The WSCA established an Operations Committee, consisting of representatives from Washington Aqueduct, Fairfax Water, and WSSC Water, that is responsible for overseeing CO-OP activities. The agreement assigns to CO-OP the responsibility, in consultation with the suppliers, of directing water supply releases from Jennings Randolph and Little Seneca reservoirs and setting Potomac River withdrawal rates during droughts. This portion of the agreement was driven by the realization that coordinated operations would allow each supplier to meet their own demands and collectively meet the demands of the region. This decision to seek a joint solution to potential water supply shortages has made it possible to provide adequate water supply to the WMA in a manner that has been far less expensive than other proposed solutions.

Since the establishment of the CO-OP system in 1982, water supply releases to augment natural flow of the Potomac River for water supply purposes have been made in only three years. Water supply releases were made from Jennings Randolph and Little Seneca reservoirs during low-flow periods in the summers of 1999 and 2002, and in the fall of 2010. In each of these years, cooperative operations ran smoothly, and the augmented flow of the Potomac provided the required water.

2 SYSTEM OVERVIEW

This chapter provides an overview of the WMA water supply system, including the resources which provide water and the entities that withdraw, treat, and distribute the water to area residents, businesses, and institutions. The WMA suppliers' service areas and current, planned, and proposed system resources are depicted in Figure 2-1. Also shown in this figure is the U.S. Geological Survey (USGS) stream gage which measures flow in the Potomac River at Little Falls dam near Washington, DC (USGS Station No. 01646500), a location which is just downstream of WMA Potomac water supply intakes. Schematics of water supply systems in the WMA are provided in Appendix A.1. CO-OP's goal during droughts is to operate in a manner that optimizes use of system resources, meets customers' water demands, and maintains flow in the Potomac River at Little Falls dam above the environmental flow-by of 100 million gallons per day (MGD), equivalent to 155 cubic feet per second (cfs).

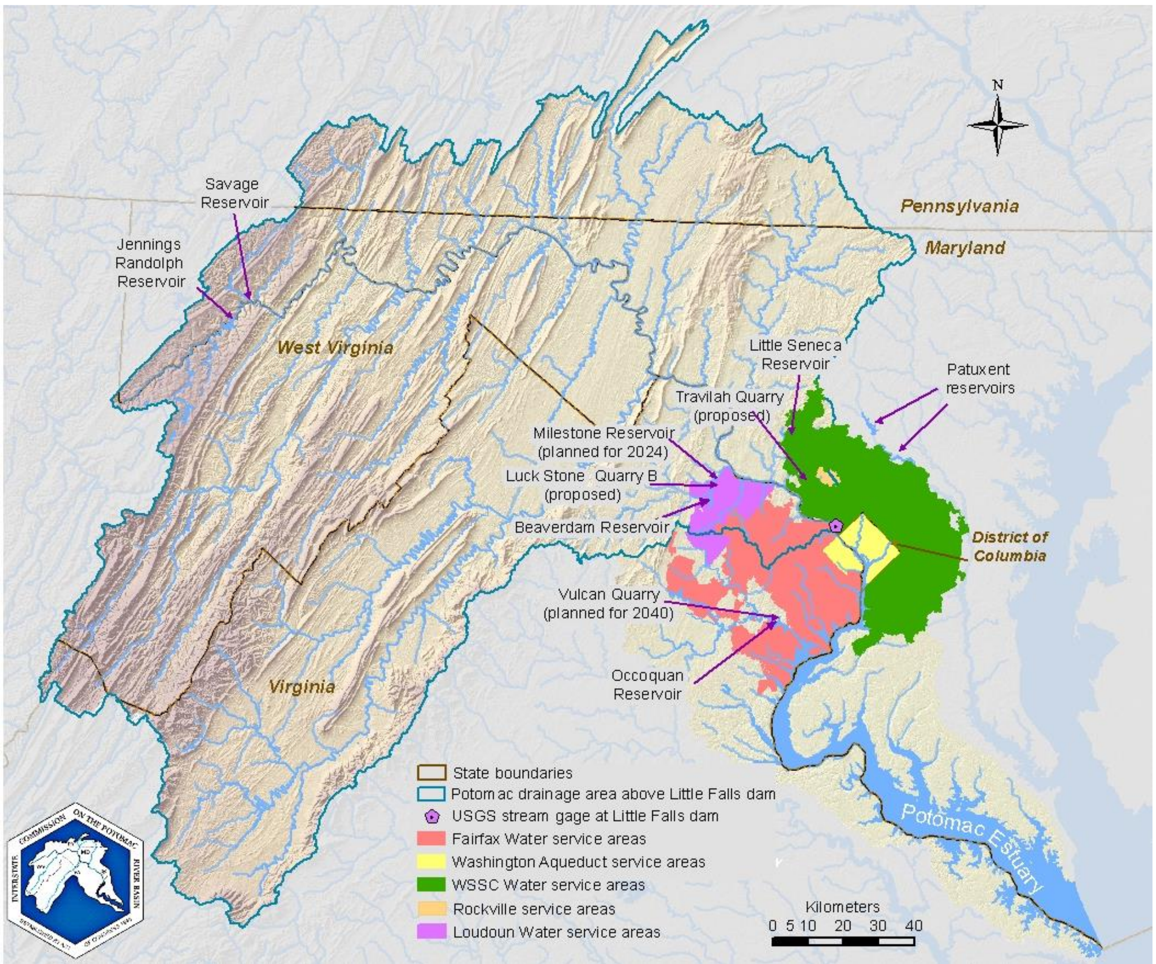

Figure 2-1: WMA current, planned, and proposed water supply resources, and supplier service areas.

2.1 System Demands

The WMA suppliers provide water to approximately 4.8 million people who reside in their combined water service areas.

2.1.1 Water Service Areas

A schematic of the WMA water supply system's current and planned resources and suppliers' service areas is shown in Figure 2-2. This figure shows the water sources of each of the five suppliers that withdraw and treat water from the Potomac River. These suppliers distribute treated water directly to homes, businesses, and institutions located in their "retail" service areas. The figure also shows transfers of treated water between from some of these suppliers to their "wholesale" customers. The wholesale customers distribute the water bought from the suppliers through their own distribution system in other areas of WMA.

Fairfax Water provides water to customers in its retail service area (comprising over 4,100 miles of pipeline) in Fairfax County, which as of January 2014, also includes the City of Fairfax and the City of Falls Church (and its former service area beyond the city limits). The City of Fairfax formerly owned and operated its own municipal water supply system. The City of Falls Church was formerly a wholesale customer of Washington Aqueduct. To supply water to the City of Falls Church and surrounding areas, Fairfax Water is now a wholesale customer of Washington Aqueduct. Fairfax Water also serves other areas via sales of treated water to its wholesale customers: Loudoun Water, Virginia American Water Company (providing water to the City of Alexandria and Dale City), Prince William County Service Authority, the Vienna Department of Public Works (DPW), Herndon, Fort Belvoir, and Dulles Airport.

Washington Aqueduct sells water to three wholesale customers: The District of Columbia Water and Sewer Authority (DC Water), serving the District of Columbia; Arlington County; and Fairfax Water.

WSSC Water serves Prince George's and Montgomery counties, provides water on an emergency basis to the City of Rockville, and also provides a limited amount of water to Charles and Howard counties, all in Maryland.

Rockville owns and operates its own water supply system which withdraws water from an intake on the Potomac River just downstream of WSSC Water's intake.

Loudoun Water supplies a portion of its demand with water purchased from Fairfax Water and a portion with water withdrawn at its new intake on the Potomac River and treated at its Trap Rock Water Treatment Facility (Trap Rock WTF), which went into service in the fall of 2018. Loudoun Water formerly supplied its customers primarily with water purchased from Fairfax Water, though from 2014 through 2018 it also produced some water at a treatment plant on Goose Creek, which it purchased from the City of Fairfax in 2014 (D. Geldert, personal communication, December 18, 2019).[2]

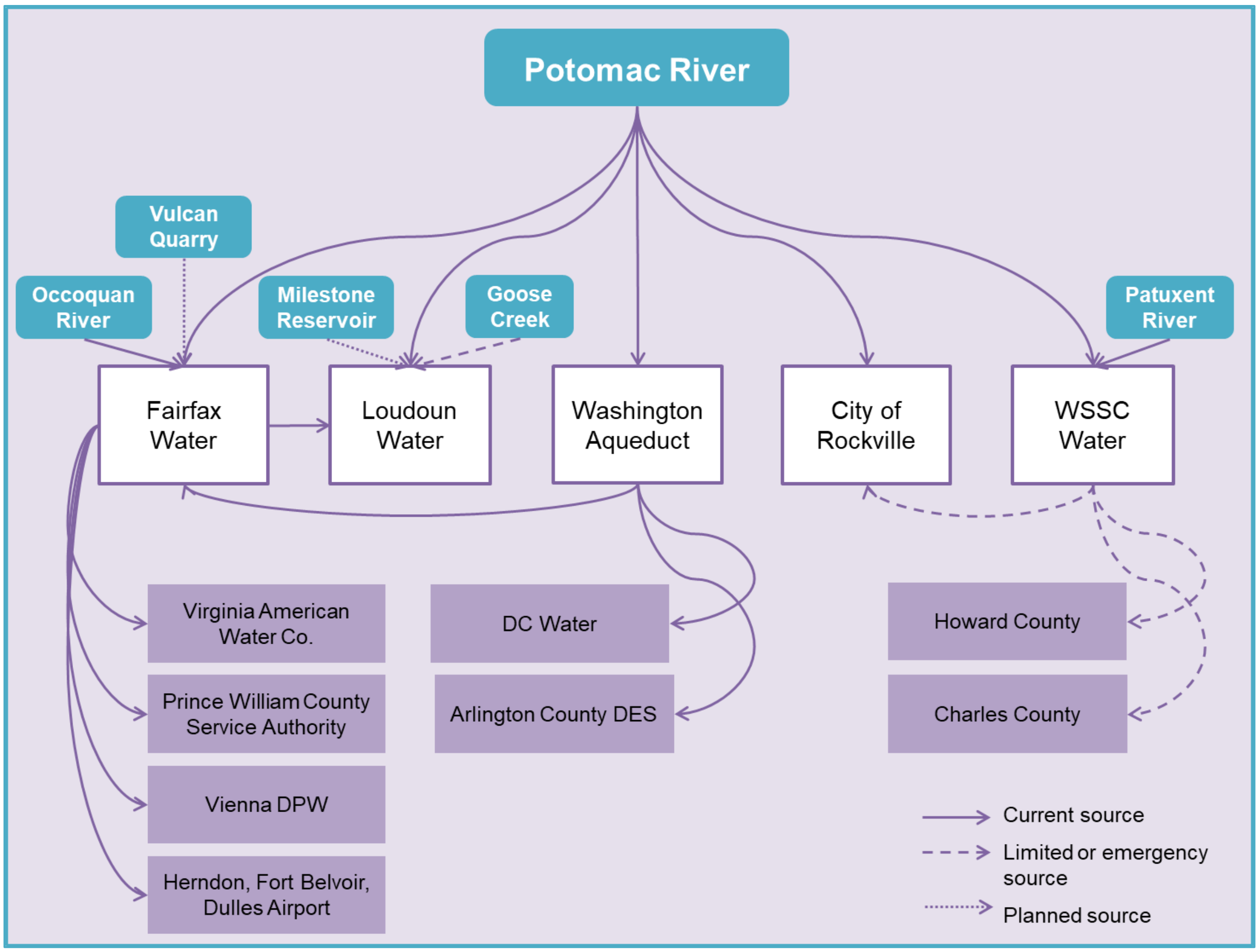

Figure 2-2: Schematic of the WMA's current and planned water sources, five major suppliers, and their wholesale customers.

[2] The Goose Creek Emergency Water Supply Connection Project will provide the infrastructure to transport water from the Goose Creek Reservoir to the Trap Rock WTF for treatment in the event of an emergency. This project will provide resiliency to Loudoun Water customers in advance of off-river quarry reservoir storage that is planned for operation in 2024 (P. Kenel, personal communication, June 18, 2020).

2.1.2 Historical Water Production Trends

Combined average annual water production by the CO-OP suppliers continues to hold remarkably steady over the past several decades. Production is the amount of water produced by the suppliers' water treatment plants and, in this study, total WMA production is defined to be equivalent to total WMA water demand, though production and demand would differ in the case of an individual supplier if a portion of their demand is met by water purchased from another supplier. Figure 2-3 shows annual average production of Washington Aqueduct, Fairfax Water, and WSSC Water as well as average total annual, summer, winter, and peak-day production by all three suppliers from 1990-2018 (Appendix A.2 archives tabular data for years 2010-2018, see older data in past demand studies). It should be noted that during this period, Fairfax Water provided the majority of the water distributed by Loudoun Water. Statistical analyses indicate that there are no trends, at the 5% significance level, in combined annual, summer, or peak-day demands of the suppliers over the 1990-2018 historical period shown in the graph. Over this same period, population in the WMA increased from approximately 3.4 million people in 1990 to an estimated 4.8 million in 2018, an increase of approximately 41%.

Figure 2-3 illustrates that both summer and peak-day production can be significantly greater than the annual average production. Production during the summer months is higher than in the winter months due to outdoor water use (primarily the watering of lawns and landscapes). For the period for which new data was made available for this study, 2014-2018, the average summer production was 11% higher than the annual average production and the annual peak-day production was, on average, 31% higher.

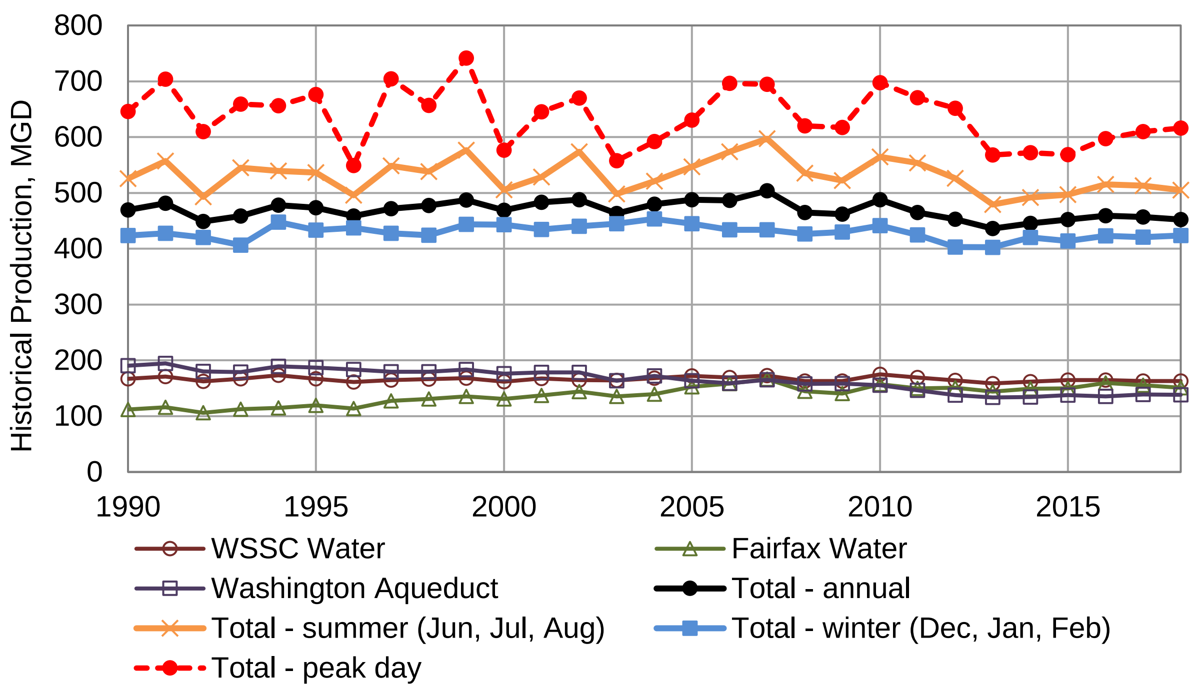

Figure 2-3: CO-OP supplier historical annual production, and combined total annual, summer, winter (by water year), and annual peak-day production.

During the last five years for which data was available for this study, 2014-2018, total production by the three CO-OP suppliers averaged 453 MGD, with 137 MGD for Washington Aqueduct (30% of system total), 153 MGD for Fairfax Water (34% of system total), and 163 MGD for WSSC Water (36% of system total). A significant portion of the water treated by WSSC Water and Fairfax Water is withdrawn from the Patuxent and Occoquan reservoirs, respectively. Over the period between 2014 and 2018, 30% of WSSC Water's production came from its Patuxent water treatment plant and 40% of Fairfax Water's production came from its Griffith treatment plant on the Occoquan Reservoir.

No new peak day production records were set in the years 2014-2018. Between 1990 and 2018, Fairfax Water's peak-day production record was 259 MGD, set on July 7, 2010. Over this same period, WSSC Water's peak-day production was 263 MGD on June 8, 1999; this can be compared to WSSC Water's historical peak-day production of 267 MGD, which occurred on July 8, 1988. Washington Aqueduct's historical peak-day production of 281 MGD occurred on July 7, 1999. The historical peak-day combined production of the three suppliers is 741 MGD, which occurred on June 8, 1999. Peak day production factors, that is, the ratios of historical peak day production to average production are 1.6, 1.7, and 1.9 for WSSC Water, Washington Aqueduct, and Fairfax Water, respectively, and 1.6 for CO-OP system combined production.

2.2 WMA System

The current WMA water supply system includes ten raw water intakes, seven significant storage reservoirs, seven water treatment plants (WTPs), or equivalently, water filtration plants (WFPs) or water treatment facilities (WTFs), and thousands of miles of pipes which convey finished water from treatment plants to retail and to wholesale customers. The primary source of water is the Potomac River, with all WMA suppliers withdrawing water via intakes located in an approximately 18 mile stretch of the river upstream of Little Falls dam near Washington, DC. The region also currently relies on off-Potomac storage in three reservoirs, Fairfax Water's Occoquan and WSSC Water's Patuxent reservoirs, and three shared reservoirs located in the Potomac watershed upstream of the WMA intakes: Jennings Randolph, Savage, and Little Seneca. Agreements and contracts are in place for two future raw water storage facilities planned to be operational by 2040: Loudoun Water's Milestone Reservoir and Fairfax Water's Vulcan Quarry (Phase 1). Finally, work has been initiated to implement a suite of operational changes and new storage facilities to enhance the reliability of the WMA system in future years, as recommended in the 2017 alternatives study (Schultz *et al.*, 2017), including the Travilah and Luck Stone quarries. The locations of current, planned, and proposed system resources appear in Figure 2-1. Key capacities and constraints of the current system and of planned or proposed additions to the system are given in Table 2-1 and Table 2-2 in Section 2.3.5.2. Schematics of water supply systems in the WMA are provided in Appendix A.1.

2.2.1 Fairfax Water

Fairfax Water owns and operates the two largest water treatment facilities in Virginia: The James J. Corbalis Jr. water treatment plant (Corbalis WTP), at the northern tip of Fairfax County, and the Frederick P. Griffith Jr. water treatment plant (Griffith WTP), on the southern border of Fairfax County. These plants rely on raw water withdrawn from two sources: the Potomac River and the Occoquan Reservoir, which is fed by the Occoquan River. The Corbalis plant treats water withdrawn from Fairfax Water's two intakes on the Potomac River: its onshore intake and its mid-river offshore intake. The Griffith plant relies on water withdrawn from the Occoquan Reservoir. Treated water from the Corbalis and Griffith plants is distributed to Fairfax Water's retail and wholesale customers, with the western portion of Fairfax Water's service area (Western SA) being primarily supplied by the Corbalis WTP and the eastern portion (Eastern SA) by the Griffith WTP.

Treated water is also sold to Fairfax Water's wholesale customers and is distributed to homes, businesses, and agencies in Loudoun County, via Loudoun Water, in Prince Williams County, via Prince Williams County Service Authority, in Alexandria and Dale City, via Virginia American Water Company, in Vienna, via Vienna Department of Public Works[3], and in Herndon, Fort Belvoir, and Dulles Airport. Fairfax Water also purchases water from Washington Aqueduct, which it distributes to its customers in Falls Church and the vicinity (Central SA). For the current study, the proportions of Fairfax Water combined retail and wholesale demand in these three areas for the forecast period are assumed to be as follows (N. Saji, personal communication, February 20, 2020):

- Western SA: 47.7%
- Eastern SA: 42.0%
- Falls Church and vicinity: 10.3%

Fairfax Water is planning to use the Vulcan Quarry, located in Fairfax County near the Griffith WTP, to augment its raw water storage. This quarry, discussed in Section 2.3.4, will serve to augment storage as a water supply source in addition to Fairfax Water's Occoquan Reservoir.

2.2.2 WSSC Water

The Washington Suburban Sanitary Commission (WSSC Water) is a water and wastewater utility that has been in operation since May 1, 1918, serving customers in Montgomery and Prince Georges counties in Maryland. Its sources of raw water are the Patuxent and Potomac rivers. WSSC Water owns and operates two water filtration plants, the Patuxent WFP, located near Laurel, Maryland, and the Potomac WFP, located adjacent to the Potomac River in Potomac, Maryland. The Patuxent plant relies on water stored in two reservoirs —Triadelphia and T. Howard Duckett (also known as Rocky Gorge). The Potomac WFP withdraws water from the Potomac River. Treated water is distributed to customers by a network of 5,768 miles of pipelines to a service area that covers about 1,000 square miles in Prince George's and Montgomery counties. Some portions of WSSC Water's water service areas typically receive blended water from both the Patuxent and Potomac WFPs. WSSC Water's distribution system is capable of conveying treated water to any service point from either of its water treatment plants, providing a measure of redundancy in the event of an emergency shutdown of one of the treatment plants. However, the Patuxent plant alone cannot meet WSSC's entire demand in the summer.

[3] Vienna, a wholesale customer of Fairfax Water, has the capability of being supplied water from either a Fairfax Water treated source or from Washington Aqueduct purchased water. Water supplied from Washington Aqueduct is reflected in the historic Fairfax Water purchase data from Washington Aqueduct. For the purpose of the demand and production forecast, Vienna is about 2 MGD and is assumed to always come from Fairfax Water.

2.2.3 Washington Aqueduct

Washington Aqueduct is a federally owned and operated public water supply agency. Its name is derived from the first aqueduct completed by the USACE in 1859 to convey water from an intake on the Potomac River at Great Falls to two small water supply reservoirs in the District of Columbia: Dalecarlia Reservoir, on the border between the District of Columbia and Montgomery County, and Georgetown Reservoir, two miles downstream. Later, in 1902, a third small reservoir was added to the District system, McMillan Reservoir, located near Howard University. A second aqueduct from Great Falls to Dalecarlia was completed in the 1920's. In 1959 a second intake and pumping station was constructed on the Potomac River at Little Falls. The three Washington Aqueduct reservoirs are used operationally but their storage capacities are very small (totaling only approximately a single day's supply), so they are not considered as storage reservoirs in this study.

Washington Aqueduct operates two water treatment plants: the Dalecarlia WTP, adjacent to Dalecarlia Reservoir, and the McMillan WTP, adjacent to McMillan Reservoir. Washington Aqueduct does not own its own distribution system. Instead, finished drinking water is distributed to consumers living, working, or visiting in the District of Columbia, Arlington County (including Fort Myer), and the Falls Church vicinity via sale of water to the wholesale customers of Washington Aqueduct: DC Water, Arlington County, and Fairfax Water.

As of January 3, 2014, the ownership of Falls Church Water Utility, which had been a wholesale customer of Washington Aqueduct, was transferred to Fairfax Water. At that time Falls Church became part of Fairfax Water's retail service area and in turn Fairfax Water became a wholesale customer of Washington Aqueduct.

2.2.4 Loudoun Water

Loudoun Water is a water and wastewater utility serving customers in Loudoun County, Virginia. Until recently, most of the water it distributed was purchased from Fairfax Water. But in 2018, Loudoun Water began meeting a portion of its demand with water withdrawn from its new Potomac River intake and treated at its Trap Rock WTF and a portion of its demand from water purchased from Fairfax Water. Loudoun Water also has an intake and treatment plant on Goose Creek, purchased in 2014 from the City of Fairfax. However, since its Trap Rock facility became operational, the Goose Creek plant has been taken out of service. Loudoun Water was recently granted a modification of its Virginia water appropriation permit to use its Goose Creek intake to supply its new raw water system during emergency events (P. Kenel, personal communication, June 18, 2020).

Loudoun Water has acquired a retired quarry from the Luck Stone Company. It plans to convert the quarry, formerly referred to as Quarry A, into a water storage facility, renamed Milestone Reservoir, by 2024. The reservoir, with a planned initial storage capacity of 1.25 billion gallons (BG), will be filled with raw water pumped from Loudoun Water's Potomac River intake and used to augment Loudoun Water's supply during periods of drought. Loudoun Water's Potomac River withdrawals and its future use of Milestone Reservoir are regulated by Virginia Water Appropriations permit No. 10-2020, which requires operations during drought to be coordinated with CO-OP water supply releases from Jennings Randolph Reservoir.

As part of its purchase from the City of Fairfax in 2014, Loudoun Water also acquired Beaverdam Reservoir, located in the Goose Creek watershed upstream of Loudoun's Goose Creek intake. Beaverdam Reservoir's primary purpose is to serve as a water supply resource, and currently Beaverdam serves as a backup supply for Loudoun Water in case of emergency. Public access and recreational use of this reservoir are also planned and are being managed by Loudoun Water in partnership with the Northern Virginia Regional Park Authority.

2.2.5 City of Rockville

The City of Rockville's Water Treatment Plant (Rockville WTP), with a four MGD production capacity, began service in 1958. The plant was upgraded in 1965 to increase production to eight MGD. In the mid-1990's additional upgrades to the plant were carried out to meet U.S. Environmental Protection Agency and Maryland Department of the Environment regulations. Since that time, an average of five MGD per day of raw (untreated) water has been withdrawn from the Potomac River, treated by the WTP, and then distributed to the City's water customers.

The city serves 70% of the city, while WSSC Water serves the remainder of the city. When Rockville's WTP is not operating because of necessary improvements or maintenance activities, or in cases of regional drought, Rockville purchases water from the WSSC Water. In 2018, Rockville purchased about 188 MG of water (approximately 11% of their annual production) from WSSC Water.

2.3 System Resources

The raw water supply sources assumed to be available over this study's planning horizon are the Potomac River, which provides just over three quarters of the WMA supply, the Occoquan and Patuxent reservoirs, which are resources owned and operated by Fairfax Water and WSSC Water, respectively, Loudoun Water's Milestone Reservoir, planned to be operational by 2024, and Fairfax Water's Vulcan Quarry (Phase I), planned to be operational in 2040. The CO-OP suppliers also rely on shared storage in two upstream reservoirs, Jennings Randolph and Little Seneca, to augment Potomac River flows during periods of drought. An additional upstream reservoir, Savage, is operated by the USACE's Baltimore District Office in conjunction with Jennings Randolph Reservoir. Also considered in this study and discussed below are two proposed reservoirs, Travilah Quarry and Luck Stone Quarry B, and a set of four proposed operational changes that have been shown to benefit system reliability.

2.3.1 Potomac River

The freshwater portion of the Potomac River extends down to the head of tide, located between Little Falls dam and Chain Bridge near Washington, DC. The area of the watershed upstream of Little Falls dam is approximately 11,560 square miles. The river's long-term average (mean) adjusted flow at the USGS stream gage at Little Falls dam is about 7.8 billion gallons per day (BGD) over the period, 1931-2018, with higher flows typically occurring in the winter months and lower flows in the late summer and early fall. Adjusted flow is flow that would have occurred in the absence of WMA withdrawals. The CO-OP suppliers' average summer (June, July, August) demand for water from the Potomac River in recent years (2014-2018) has been about 0.38 BGD (382 MGD), and the average for recent dry years (1999, 2002, 2007, and 2010) is approximately 0.46 BGD (459 MGD). At most times, water supply withdrawals from the Potomac have averaged about 5% of adjusted flow over recent years.

2.3.2 Shared Reservoirs

The three CO-OP suppliers entered into cost share agreements in 1982 to jointly fund storage in two reservoirs, Jennings Randolph and Little Seneca, located upstream of their Potomac River intakes, for augmentation of Potomac River flows during droughts. In addition, they fund a portion of the operations and maintenance costs of a third upstream reservoir, Savage, which is operated in conjunction with Jennings Randolph.

Jennings Randolph Reservoir: This reservoir is located in the far northwest corner of the Potomac River basin, bordering Garrett County, Maryland, and Mineral County, West Virginia. It is operated by the USACE's Baltimore District Office. Usable storage capacity in the reservoir is 29.3 BG. This includes 13.1 BG which is solely dedicated to the water supply needs of the CO-OP suppliers. The remaining 16.2 BG is used on a daily basis by the USACE to help maintain downstream water quality and to support recreational uses of the reservoir and the North Branch of the Potomac River. Releases from Jennings Randolph water supply storage are only made at the direction of CO-OP based on existing and projected water demand, flow forecasts, and status of other system reservoirs. Jennings Randolph Reservoir is approximately 200 miles upstream of the WMA and releases take more than a week to travel to WMA intakes during low-flow conditions. The drainage area of Jennings Randolph Reservoir is about 263 square miles.

Little Seneca Reservoir: This reservoir is located in Black Hill Regional Park in Montgomery County, Maryland. Little Seneca Reservoir dam is operated by WSSC Water. During droughts, CO-OP may request releases from this reservoir to help augment flow in the Potomac River to meet water demands and the flow-by at Little Falls dam. The storage capacity of Little Seneca Reservoir, 3.9 BG, is considerably smaller than that of Jennings Randolph Reservoir. But Little Seneca releases make more efficient use of system storage because the travel time for a release to reach Little Falls dam is only about a day. Little Seneca Reservoir's drainage area is about 21 square miles.

Savage Reservoir: This reservoir is located on the Savage River in the headwaters of the Potomac River basin near Jennings Randolph Reservoir. The reservoir is owned by the Upper Potomac River Commission (UPRC). The UPRC operates the dam with guidance from USACE's Baltimore District Office. The USACE determines release rates from Savage Reservoir in tandem with those from Jennings Randolph Reservoir. During CO-OP drought operations, the combined Jennings Randolph and Savage releases are used to meet a flow target, determined by CO-OP, at the USGS stream flow gage (Station ID 01598500) at Luke, Maryland. The storage capacity of Savage Reservoir is approximately 6.1 BG. The drainage area of Savage Reservoir is about 105 square miles. Savage Reservoir is also the water supply source for the Town of Westernport, Maryland.

2.3.3 Other Existing Reservoirs

Three off-Potomac River reservoirs are owned and operated by individual suppliers: Fairfax Water's Occoquan Reservoir, and WSSC Water's two Patuxent reservoirs, Triadelphia and Rocky Gorge.

Occoquan Reservoir: Fairfax Water operates this reservoir on the Occoquan River, which is within the Potomac basin, but outside the freshwater drainage area that supplies water to the intakes on the Potomac mainstem. The reservoir's current storage capacity is estimated by ICPRB to be 7.85 BG (based on a 2010 bathymetric survey). Water from the Occoquan Reservoir is treated at Fairfax Water's Griffith treatment plant and then distributed to customers in Fairfax Water's Eastern service area and to Prince William County. Fairfax Water currently has a limited ability to transfer water from the Griffith plant to its Western service area, at a rate of up to 35 MGD, but this maximum rate is assumed to be increased to 50 MGD by the year 2040. The drainage area of Occoquan Reservoir is 592 square miles.

Patuxent reservoirs: WSSC Water operates two reservoirs in the neighboring Patuxent River watershed, Triadelphia Reservoir and T. Howard Duckett Reservoir (sometimes referred to as Rocky Gorge Reservoir). These reservoirs are operated in series and are treated in this study as a single source. Total combined usable storage capacity of these reservoirs is about 10.4 BG. The combined drainage area of the Patuxent reservoirs is 132 square miles. Water from the Patuxent reservoirs is treated at the Patuxent WFP. WSSC Water uses water produced at its Patuxent plant on a daily basis to supplement water produced at its Potomac plant.

2.3.4 Planned Reservoirs

Vulcan Quarry: According to Fairfax Water's two-phase Vulcan Quarry Plan, Vulcan Quarry Phase 1 will be operational by 2040. Vulcan Materials will cease quarry activities in the northern portion of the quarry (the Northern Reservoir) in the year 2035 and make a 1.7 BG volume available for use by Fairfax Water. The Northern Reservoir will be used as a dual-purpose facility for raw water storage and for Griffith WTP solids disposal. The solids waste stream consists of water and residuals from the treatment process, formed when the suspended solids in the raw water react with coagulants and other treatment process chemicals. It will be discharged into the Northern Reservoir to allow for solids settling. Water will be reclaimed from the reservoir and piped back to the Griffith WTP for treatment.

Vulcan Quarry, Phase 1, was one of the ten alternatives considered in ICPRB's 2017 alternatives study (Schultz *et al.*, 2017). In that study, it was assumed that several future upgrades would be made to Fairfax Water's system to allow the regional benefits of Vulcan storage to be realized. These were: enhancements to allow treated water to be transferred at a higher rate and more easily from the Griffith WTP to the Western service area and also an increase in the production capacity of the Griffith plant from 120 MGD to 160 MGD. With these assumed system changes, the regional benefits of Vulcan Phase 1 were estimated to be 25 MGD, in terms of that study's key metric, system safe summertime yield. Because water demand has grown at a lower rate than was anticipated several years ago, the current study assumes that no upgrade is made to the Griffith WTP, but rather that plant capacity remains at 120 MGD in 2040 and 2050. Under this assumption, sensitivity tests conducted for the 2017 alternatives study indicate that the regional benefit of Vulcan Phase 1 is 5 MGD.

Milestone Reservoir: Loudoun Water plans to convert a retired quarry it acquired from the Luck Stone Company, formerly referred to as Quarry A, into a raw water storage facility, Milestone Reservoir, by 2024. The reservoir, with a planned initial storage capacity of 1.25 BG, will be filled with raw water pumped from Loudoun Water's Potomac River intake and used to augment Loudoun Water's supply during periods of drought. Loudoun Water's Potomac River withdrawals and its future use of Milestone Reservoir are regulated by Virginia Water Protection permit No. 10-2020, which requires operations during drought to be coordinated with CO-OP water supply releases from Jennings Randolph Reservoir.

2.3.5 Recommended Phased Implementation of Alternatives

In its recommended strategy to assure the reliability of the future WMA water supply system, the 2017 alternatives study (Schultz *et al.*, 2017) called for a phased approach, with implementation of four operational changes by the year 2025, implementation of Vulcan Phase 1 by 2035, and implementation of Travilah Quarry by 2040 (or of Luck Stone Quarry B if Travilah were unavailable). Over a longer timeframe, results of that study indicated that two proposed Luck Stone quarries should be added to the regional system.

The potential additions to the WMA system evaluated in the current study, described below, are based on the recommended strategy outlined in the 2017 alternatives study.

2.3.5.1 Proposed Reservoirs

Several reservoirs have been proposed for future inclusion into the WMA system: Travilah Quarry in Montgomery County, Maryland, and two additional quarries in Loudoun County owned by the Luck Stone Company. ICPRB's 2017 alternatives study (Schultz *et al.*, 2017) evaluated the benefits that these resources could provide in terms of additional system safe yield, and recommended that over the long-term planning horizon, all of these quarries be converted to raw water storage facilities and added to the WMA system.

Travilah Quarry: Travilah Quarry is a hard rock quarry located in Montgomery County, Maryland, owned and mined by LafargeHolcim. This quarry has been evaluated a number of times for its suitability for use as a raw water storage reservoir (WSSC Water, 2002). More recently, ICPRB, on behalf of the CO-OP suppliers, contracted with Black & Veatch to evaluate Travilah Quarry for regional water supply purposes (Black & Veatch, 2014; Black & Veatch, 2015). Consistent with the Black & Veatch study, it is assumed in both the 2017 alternatives study and in the current study that the quarry would be filled with raw water pumped from the Potomac River via a new intake located adjacent to WSSC Water's Potomac River intake and a new raw water pumping station located within or adjacent to WSSC Water's Potomac WFP. It is also assumed that during drought, 200 MGD of raw water would be available for treatment at WSSC Water's Potomac WFP and an additional 200 MGD would be routed to Washington Aqueduct's treatment plants. The most recent estimate of the future usable capacity of Travilah, assuming certain structural reconfigurations and enhancements, is 7.8 BG (T. Hilton, personal communication, Dec 13, 2019).

An active effort is currently underway, led by the CO-OP water suppliers and supported by the ICPRB, to initiate the planning studies and stakeholder dialogs necessary to acquire and convert Travilah Quarry for use as a regional water supply storage resource.

Luck Stone Quarry B ("Luck quarry"): Loudoun Water and the Luck Stone Company are developing a plan for future use of two quarries as raw water storage facilities, referred to as "Quarry B" and "Quarry C." Both quarries, owned by Luck Stone, are located in Loudoun County, Virginia, adjacent to Goose Creek and near Loudoun Water's new Trap Rock WTF. Quarry B is expected to have a volume of approximately 2.5 BG when mining activities cease in 2035 and Quarry C is expected to have a final volume of approximately 4.0 BG when mining is completed in 2060. The quarries could be filled using water withdrawn from the Potomac River via Loudoun Water's new Potomac River intake. Goose Creek, a Potomac River tributary, might also provide a source of refill for these reservoirs. It is assumed in both the 2017 alternatives study (Schultz *et al.*, 2017) and in the current study that Quarry B will be available by 2040 for use as a regional resource to augment Potomac River flow during droughts, with releases made via Goose Creek. However, an effort to develop regional agreements for this resource has not been initiated. Quarry C is proposed for use outside of the forecast period for this study.

2.3.5.2 Proposed Operational Alternatives

Initial steps have been taken towards implementation of all four of the "operational" alternatives in the 2017 alternatives study (Schultz *et al.*, 2017), and the current study assumes that they are all in place by 2040. Though the alternatives study found that the benefit to the WMA system of any one of the operational alternatives was modest, the benefit of implementing the combination of all four was significant in terms of that study's primary evaluation metric, system safe summer yield, estimated to be 25 to 80 MGD, depending on the climate change scenario. Detailed descriptions of the four recommended operational alternatives are provided in the alternatives study. These alternatives are summarized below, with additional details and assumed constraints given in Table 2-2. It should be noted that assumptions for use of Beaverdam and Milestone reservoirs are preliminary; it is expected that operational constraints will be better defined when Milestone Reservoir is placed into service in 2024.

<u>Cooperative use of Milestone Reservoir (formerly referred to as Quarry A):</u> The first of the four recommended operational alternatives in the 2017 alternatives study, referred to in that study as "cooperative use of Quarry A", is coordination of Loudoun Water's operations with CO-OP water supply releases from Little Seneca Reservoir, rather than with releases from Jennings Randolph Reservoir. In PRRISM's current simulation of this alternative, it is assumed that there are no restrictions on Loudoun Water's withdrawals related to Jennings Randolph water supply releases, but rather that Loudoun Water Potomac withdrawals and use of their reservoir are coordinated with CO-OP's releases from Little Seneca Reservoir. It's assumed that Loudoun Water helps conserve storage in Little Seneca Reservoir by completely relying on Milestone Reservoir on days in which a water supply release from Little Seneca Reservoir is occurring or when a Potomac River withdrawal by Loudoun Water would reduce Potomac River flow to an extent that would require a release from Little Seneca.

Implementation of this operational alternative will require support from Loudoun Water and from the VADEQ water withdrawal permitting program. In Virginia, the regulation of instream flow and withdrawal of surface water must be balanced to meet the needs of all beneficial uses of state waters. The Loudoun Water System has an operational permit from this program. When Milestone Reservoir becomes operational, CO-OP plans to conduct a drought exercise to help familiarize stakeholders with the proposed alternative and facilitate discussion on its impact on the WMA system, Loudoun Water, and flow in the Potomac River. Implementation also may require additional modeling by CO-OP to assess the impact on aquatic ecosystems and additional refinement of the operational strategy.

<u>Use of Beaverdam Reservoir for low-flow augmentation</u>: The second of the recommended operational alternatives in the 2017 alternatives study is use of Beaverdam Reservoir for augmentation of Potomac River flows during drought. Implementation of this operational alternative would likely require that a contract between the CO-OP suppliers and Loudoun Water be negotiated and put into place for use of this supply, and also support from the VADEQ water supply permitting program. In this alternative, it is assumed that Loudoun Water operates cooperatively with the CO-OP suppliers during droughts to make low-flow augmentation releases from Beaverdam Reservoir in coordination with releases from Little Seneca Reservoir. It is also assumed that percent storage in Beaverdam Reservoir will be kept in balance with percent storage in other WMA system resources.

<u>Improved river flow forecasts</u>: Under the improved forecasts alternative, the accuracies of both the nine-day and the one-day forecasts of Potomac River flow at Little Falls are assumed to improve by 10%. CO-OP is actively working to implement two changes to its drought support tools to support improved forecasts: incorporation of real-time Potomac River withdrawal forecasts into CO-OP's Low Flow Forecast System (LFFS) and use of the National Weather Service's LAG/K flow routing algorithm.

<u>Use of Jennings Randolph water quality storage</u>: The 2017 alternatives study included a very preliminary investigation of the potential benefits of using Jennings Randolph water quality storage for water supply

purposes during water supply emergencies, as called for in Section 5019 of the Water Resources and Development Act of 2007 (USACE, 2014a). This alternative is simulated as a limited transfer of water quality storage to water supply storage in certain cases when water supply storage is low. ICPRB and the USACE are in the process of completing a joint scoping study for a potential update of the Jennings Randolph Water Control Plan, and the study recommends development of a Drought Contingency Plan, which may facilitate a joint evaluation of this alternative.

Table 2-1: Current WMA system capacities and constraints.

System resource/connections	Description	Current	2040-2050
Fairfax Water			
Potomac River intakes/Corbalis WTP (primarily for Western SA)	Maximum production rate, MGD Minimum production rate, MGD	225 60	225 60
Occoquan Reservoir intake/Griffith WTP (primarily for Eastern SA)	Maximum production rate, MGD Minimum production rate, MGD Maximum change in production, MGD per day	120 45 40	120 45 40
Finished water purchased from Washington Aqueduct (for Central SA)	Maximum flow from Washington Aqueduct to Falls Church, MGD	35	35
Transfer of finished water between Eastern and Western SA	Maximum transfer from Western to Eastern SA, MGD	65	65
	Maximum transfer from Eastern to Western SA, MGD Maximum change in Eastern to Western SA transfer, MGD per day	35 10	50 40
Transfer of finished water from Central to Western SA	Transfer rate, MGD	+6 to -10	+6 to -10
Loudoun Water			
Potomac River intake/Trap Rock WTF	Maximum pump rate, MGD Maximum treatment rate, MGD	40 20	40 30
WSSC Water			
Potomac River intake/WFP	Maximum production rate, MGD Minimum production rate, MGD	288 100	288 100
Patuxent reservoir intake/WFP	Maximum production rate (emergency purposes only), MGD Minimum production rate, MGD Minimum environmental flow-by over Duckett dam, MGD Storage trigger for discontinuation of load-shifting, BG (withdrawals reduced to 20 MGD via intermittent WFP shutdowns)	72 33 10.3 1.0	110 33 10.3 1.0
Washington Aqueduct			
Dalecarlia WTP	Maximum production rate, MGD Minimum production rate, MGD	225 60	225 60
McMillan WTP	Maximum production rate, MGD Minimum production rate, MGD	120 60	120 60
Pipe from Dalecarlia to Fairfax Water's Falls Church SA	Maximum transfer rate of finished water, MGD	35	35
Shared resources			
Jennings Randolph Reservoir	Minimum downstream flow target for North Branch Potomac River at Luke, Maryland, MGD (cfs)	77.6 (120)	77.6 (120)
Savage Reservoir	Minimum downstream flow target, MGD (cfs)	12.9 (20)	12.9 (20)
Little Seneca Reservoir	Minimum environmental flow-by over dam, MGD (cfs)	1.12 (1.73)	1.12 (1.73)

Table 2-2: Planned and proposed resource assumed capacities and constraints.

	System resource/alternative	Assumptions
Planned resources		
	Vulcan Quarry (Phase 1)	Available in 2040 1.7 BG initial usable storage capacity Refill is from backwash of Fairfax Water's Griffith WTP (5% of plant production) Sedimentation rate based on Griffith production, from M. Pirnie (2012)
	Milestone Reservoir (formerly Quarry A)	Available in 2024 1.25 BG storage capacity and 1.12 BG usable capacity beginning in 2024 Refill is via the 40 MGD pipe from Loudoun Water's Potomac River intake 1.12 MG/year sedimentation rate[1]
Proposed structural alternatives		
	Travilah Quarry	Proposed as a direct supply of raw water for Washington Aqueduct and WSSC Water by 2040 7.8 BG initial usable storage capacity[2] 0 MG/year sedimentation rate[3] Use of Travilah storage is triggered when Patuxent storage falls below 4.0 BG 200 MGD maximum supplied to WSSC Water's Potomac WFP 200 MGD maximum supplied to Washington Aqueduct's Dalecarlia & McMillan WTPs Refill rate of 60 MGD (refill allowed when flow in Potomac River, in excess of water supply needs plus the Little Falls flow-by, is greater than 135 MGD)
	Luck Stone Quarry B (Luck 1)	Available for low-flow augmentation in 2040 2.5 BG initial usable storage capacity 2.5 MG/year sedimentation rate[1] Refill via the 40 MGD pipe from Potomac intake 80 MGD max release to Potomac River via Goose Creek
Proposed operational alternatives		
	Cooperative operations of Milestone Reservoir	Assumes that Loudoun Water's Potomac River withdrawals and use of Milestone Reservoir are coordinated with Little Seneca Reservoir releases rather than with Jennings Randolph water supply releases

	Beaverdam Reservoir used for low-flow augmentation	Assumes Beaverdam is available for Potomac River low-flow augmentation, via Goose Creek
		• Usable capacity based on initial value of 1.29 BG in the base year, 2005
		• Sedimentation rate of 1.3 MG/year
		• Refill from
		  ○ natural inflow
		  ○ 15 MGD pumping from Goose Creek when flow in Goose > 139 MGD (215 cfs)
		Maximum water supply release is 40 MGD

	Improved river flow forecasts	The following improvements are made in forecasts of Potomac River flow at Little Falls • 10% improvement in accuracy of 9-day forecasts for North Branch water supply releases • 10% improvement in accuracy of 1-day forecasts used to support Little Seneca Reservoir releases and certain other operational decisions
	Use of Jennings Randolph water quality storage	• A lump volume of 2.0 BG is transferred from the Jennings Randolph water quality account to its water supply account when storage in the water supply account falls below 2.6 BG (approximately 20% conservation pool storage) • The transfer does not take place if water quality storage is below 5.0 BG.

[1] Assuming 0.1% annual capacity loss.
[2] Provided by WSSC Water (T. Hilton, personal communication, Dec 13, 2019).
[3] Provided by WSSC Water (T. Hilton, personal communication, July 10, 2020).

3 Annual Demand Forecast

3.1 Introduction

This chapter presents the WMA average annual water demand forecasts along with estimates of the range of uncertainty of those forecasts. Forecasts are provided for the WMA suppliers, including their retail and wholesale customers, for the years 2020 through 2050. This chapter describes the data and methods used in the computations of future demands and in the estimates of uncertainty. Final forecasted demands appear in Section 3.6, Table 3-24. Details on the data and results for retail and wholesale customer are available in Appendix A.3. The annual demand forecasts are incorporated into CO-OP's planning model, PRRISM, which combines the annual demand forecasts with estimates of daily demand variations described in Chapter 4. The resulting daily demand forecasts are then used in PRRISM to simulate future daily WMA withdrawals from the Potomac River and system reservoirs.

The demand forecast process is outlined in Figure 3-1. Geographic, demographic, and water use billing and production data are collected from the WMA suppliers, their wholesale customers, and from local planning agencies. Unit use rates are developed for each supplier based on historical water billing data and demographic data for water service areas. Unit use describes average daily water use in the WMA for three customer categories: single family households (SFH), multi-family households (apartment and condominiums, MFH), and employees (commercial, industrial, and institutional users, EMP). Each of these categories has its own characteristics and trends.

Future unit use rates are estimated from the historical unit use values, with adjustments made based on estimated changes in future water use conditions (Section 3.3). Per household water use in the WMA has been falling for decades, consistent with trends observed throughout the United States (DeOreo and Mayer, 2012). ICPRB's forecasts of WMA demand include estimates of future reductions in per household and per employee water use because of policies and programs which promote adoption of more efficient plumbing fixtures and appliances, like the *Energy Policy Act of 1992* and the U.S. Environmental Protection Agency (USEPA) WaterSense program (see Section 3.3.2).

The forecasted annual demands are estimated by multiplying the forecasted unit use rates by the forecasted number of household or employee units within each retail or wholesale customer service area, at five-year increments for the period 2020 through 2045 (which is the forecast limitation of the MWCOG Round 9.1 data). The forecasted water demands are extended to the year 2050 using linear extrapolation to provide the WMA suppliers with a longer-term planning horizon and to help support the VADEQ water supply planning process.

This study also provides ranges of uncertainty for the forecasted annual water demands, computed using estimates of the potential range of errors of each of the primary data categories used in the calculation process. Statistical error propagation techniques are used to combine individual uncertainties into estimates of the error range for each set of forecasted water demands for the each of the sets of demand forecasts for the CO-OP supplier retail area served, Loudoun Water, Rockville, and for the wholesale customers, as described in Section 3.5.

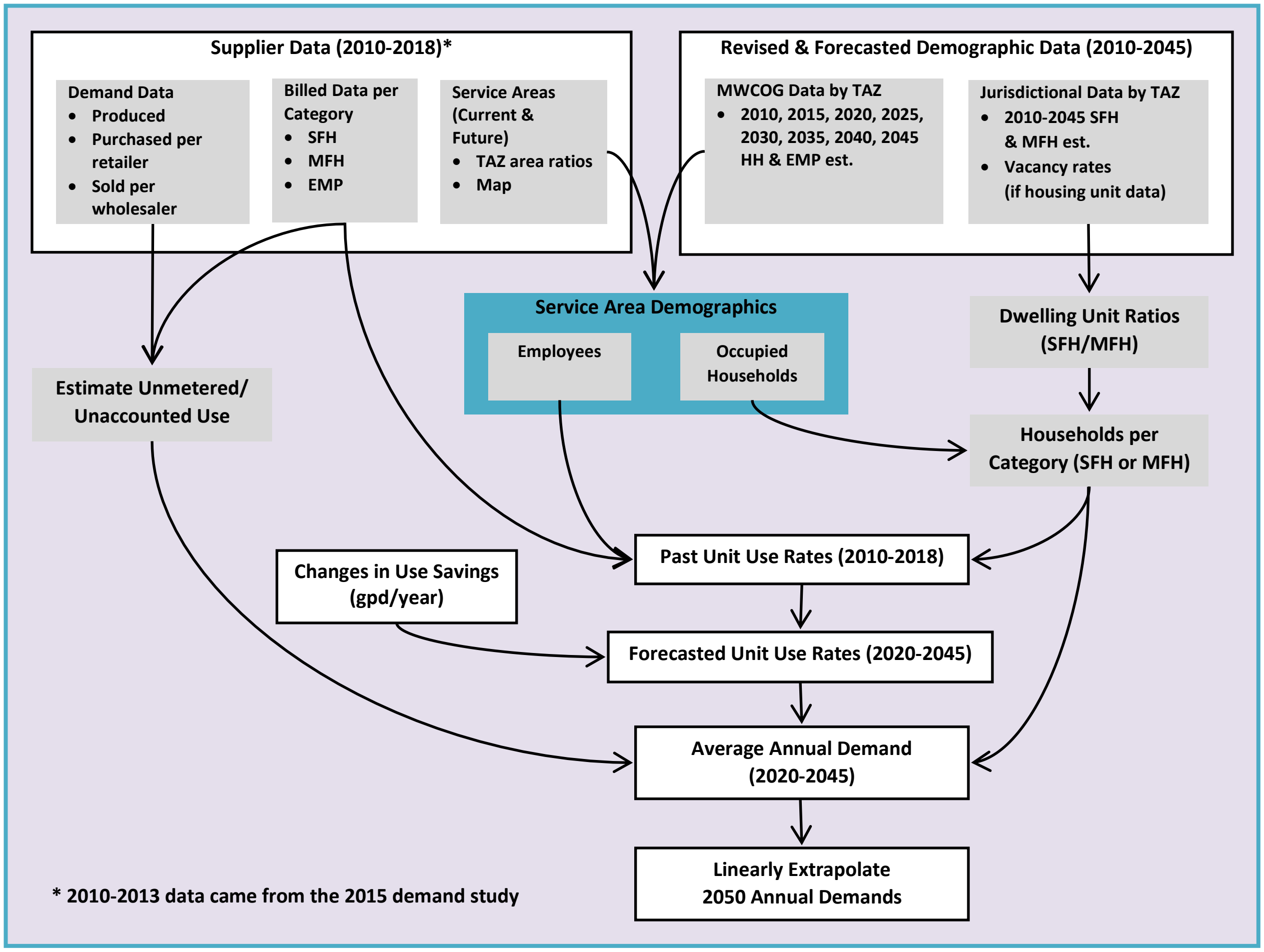

Figure 3-1: Components and process for determining the annual demand forecast.

3.2 Method for Determining Historic Unit Use Rates

The annual demand forecast process includes understanding both the historical demands and current conditions. Past demands are converted into unit use rates – average of per household or per employee use of water each day – for each supplier's retail service area and for their wholesale customers. This is done using supplier billing data (Section 3.2) and MWCOG demographic data (Section 3.2.2), which is modified using supplier service area boundaries (Section 3.2.2.2) and jurisdictional dwelling unit ratios (Section 3.2.2.1). Anticipated changes in unit use rates are applied to a unit use rate baseline. The unit use rate baseline is selected based on a linear trendline analysis of the historical unit use rates and estimated for the year 2018 (Section 3.3.1).

3.2.1 Historic Water Use Billing Data

Unit use rates for the year 2018 are used as starting values to estimate future unit use. Unit use rates in 2018, for each supplier's retail and wholesale customer service areas, are estimated water used based on historic billing data and demographic data for each supplier service area. The WMA suppliers and their wholesale customers provided billing data, as available, for the period 2014 through 2018. Data for years 2010 through 2013 are taken from the 2015 demand study (Ahmed *et al.*, 2015).[4] Each supplier tracks and bills end users differently. To calculate unit use rates for this study's SFH, MFH, and EMP categories, billing data is sorted into common categories following similar assumptions described in the 2015 demand study. Data received comes either as an annual number or aggregated into one from quarterly or fiscal year billing cycle data. The number and type of end user categories vary among suppliers. Some only have a residential and commercial category, whereas others have multiple categories for different types of residences and commercial activities. It is important to note that Loudoun Water billing data for the 2020 study excluded their water sold through their Broad Run Water Reclamation Facility (P. Kenel, personal communication, July 31, 2020). This water is reused for non-potable purposes such as data center cooling within the Loudoun Water service area. Loudoun Water expects to see an increase in water use for their non-potable reuse systems within the employee customer category of the MWCOG data. This demand on Broad Run wastewater effluent is already modeled in PRRISM within the forecast of Broad Run discharge to the system (see Section 5.5 for modeled PRRISM assumptions). In future ICPRB studies a more detailed representation of the effects of non-potable demand on the Broad Run discharge may be warranted.

In addition to the billing data, each supplier provided the amount of water produced and/or purchased and an estimate of unmetered water. Unmetered water is the portion of total production not attributed to SFH, MFH, or EMP use. Rather, unmetered water can include water used to flush system pipes and clean tanks, fire hydrant use, or water lost to leaks, among other possibilities. It is also referred to as unaccounted for and non-revenue water. An estimate of unmetered water was made by calculating the difference between the amount of water produced and/or purchased and that billed to customers (see Section 3.4.2 for forecast assumptions). Unmetered water does not include water treatment plant production loss, which is defined in this study as the difference between withdrawals and production (see Section 5.6).

3.2.2 Historic Demographic Data

The number of units used to calculate unit use rates are estimated from demographic data specific to retail and wholesale customer service areas, sorted into the customer categories for single family households, multi-family households, and employees (defined earlier as SFH, MFH, and EMP, respectively). This demographic data is collected from three sources: (1) the Metropolitan Washington

[4] In the case of the Town of Vienna (a Fairfax Water wholesale customer), 2010 Demand Study data from 2005-2008 is used to inform their 2010-2018 estimated values. Billing data as metered consumption by calendar year for the SFH, MFH, and EMP categories is unavailable, but the Water & Sewer Superintendent of the Town of Vienna said they could begin collecting this data for the next request (L. Blandon, personal communication, July 29, 2019).

Council of Governments (MWCOG); (2) local planning agencies; (3) the five-year American Community Survey (ACS) by the U.S. Census Bureau.[5] MWCOG gathers total household (occupied housing units, which combines both SFH and MFH into one estimate and accounts for household vacancy rates), employee, and population data for WMA jurisdictions for the purpose of providing forecasts, as described in more detail in Section 3.4.1. The demographic data for past years are collected from the most recent forecasts for those years. This study uses Round 8.4 (Goodwin and Mohammed, 2015) data for 2010 values and Round 9.1 (MWCOG, 2018) data for 2015 through 2020 values. This data is available in five-year increments, so values for 2011, 2012, 2013, 2014, 2016, 2017, and 2018 are interpolated. The MWCOG total household data is disaggregated into SFH and MFH estimates using more detailed demographic data from the local jurisdictions or the U.S. Census Bureau. This is done using dwelling unit ratios (DURs) described in Section 3.2.2.1 and summarized in Table 3-1. The SFH, MFH, and EMP data is then scaled to reflect retail and wholesale customer service areas using ratios described in Section 3.2.2.2 and summarized in Table 3-2 through Table 3-4.

3.2.2.1 Historic Dwelling Unit Ratios

Historic dwelling unit ratios (DURs) disaggregate 2010 through 2018 MWCOG total occupied household forecasts into SFH and MFH units. These disaggregated numbers are required to calculate the historic unit use rates for these two water use categories. To estimate the number of SFH and MFH units, DURs are developed for each jurisdiction within the suppliers' service areas. DURs are defined as the number of SFH divided by the number of MFH. Households by SFH and MFH category numbers are obtained for each jurisdiction from local planning agencies or estimated from available data.

Dwelling unit ratios for the major jurisdictions in the WMA are shown in Table 3-1 below. The ratios are compiled using information from the City of Alexandria Department of Planning and Zoning, Prince William County Planning Office, the City of Rockville Community Planning and Development Services, District of Columbia Office of Planning, the U.S. Census Bureau, Arlington County Department of Community Planning, Housing and Development, Fairfax County Department of Systems Management for Human Service, the Town of Herndon Department of Community Development, the Loudoun County Department of Management and Budget, the Montgomery and Prince George's offices of the Maryland National Capital Park and Planning Commission, and the City of Falls Church Planning Division.

For some jurisdictions, the supplier service area boundaries do not correspond exactly to the political jurisdiction boundaries associated with county planning data. For example, WSSC Water does not serve all of Montgomery County. Therefore, as much as possible, the dwelling unit ratios are calculated specific to the service areas within each jurisdiction as described in Appendix A.3.

[5] American Community Survey (ACS) data is from "Tables DP04 Selected Housing Characteristics": https://factfinder.census.gov/faces/nav/jsf/pages/searchresults.xhtml?refresh=t

Table 3-1: Historic dwelling unit ratios (single family households divided by multi-family households, dimensionless).

Supplier/Wholesaler	Jurisdiction	2010	2011	2012	2013	2014	2015	2016	2017	2018[5]
Fairfax Water – Retail customer	Fairfax County	2.67	2.66	2.63	2.61	2.57	2.47	2.46	2.44	2.40
Fairfax Water – Dulles International Airport	Loudoun/Fairfax Counties	(2.67)	(2.66)	(2.63)	(2.61)	(2.57)	(2.47)	(2.46)	(2.44)	(2.40)
Fairfax Water – Fort Belvoir	Fairfax County	(2.67)	(2.66)	(2.63)	(2.61)	(2.57)	(2.47)	(2.46)	(2.44)	(2.40)
Fairfax Water – Town of Herndon	Town of Herndon[1]	2.11	2.12	2.14	2.14	2.15	2.15	2.16	2.16	2.17
Fairfax Water – PWCSA	Prince William County	4.41	4.19	3.97	3.75	3.52	3.30	3.24	3.17	3.10
Fairfax Water – Vienna PWD	Town of Vienna[1,3]					11.03	11.03	11.02	11.01	11.01
Fairfax Water – Virginia American Alexandria	City of Alexandria	0.41	0.41	0.40	0.41	0.47	0.46	0.45	0.45	0.45
Fairfax Water – Virginia American Dale City	Dale City[2]	8.76	8.61	8.45	8.30	8.14	7.99	7.68	7.37	7.06
Washington Aqueduct – DC Water	District of Columbia	0.62	0.62	0.62	0.62	0.61	0.61	0.60	0.59	0.58
Washington Aqueduct – Arlington County DES	Arlington County	0.59	0.59	0.58	0.58	0.57	0.56	0.55	0.54	0.53
Washington Aqueduct – Arlington Fort Myer	Arlington County	(0.59)	(0.59)	(0.58)	(0.58)	(0.57)	(0.56)	(0.55)	(0.54)	(0.53)
Washington Aqueduct – Falls Church	City of Falls Church[3]	1.50	1.47	1.44	1.41					
Washington Aqueduct – Vienna PWD	Town of Vienna[1]	10.60	10.67	10.77	10.87					
WSSC Water	Montgomery County	2.07	2.03	2.00	1.99	1.99	2.01	1.98	1.94	1.91
WSSC Water	Prince George's County	2.51	2.50	2.49	2.48	2.47	2.45	2.45	2.44	2.43
City of Rockville DPW	City of Rockville[4]	1.87	1.71	1.58	1.46	1.36	1.28	1.23	1.19	1.15
Loudoun Water	Loudoun County	4.17	4.14	4.11	4.09	4.07	4.04	3.97	3.90	3.84

Note: Values in parenthesis are assumed from other jurisdictions and 2018 values are linearly interpolated.

[1] The towns of Herndon and Vienna are considered separately from Fairfax County.

[2] Dale City is considered separately from the Prince William County.

[3] Falls Church and the Town of Vienna joined Fairfax Water retail and wholesale, respectively, in 2014.

[4] Rockville is considered separately from Montgomery County.

3.2.2.2 Historic Supplier Service Area Demographics

Unit use rates are calculated for specific supplier service areas. Each supplier was contacted to help delineate the current areas.[6] The service areas of the suppliers and their wholesale customers as of the year 2018 are shown in Figure 3-2. Suppliers either provided updated Geographical Information System (GIS) data files of their service area boundary (Fairfax Water Retail, WSSC Water, Prince William County Service Authority (PWCSA), Herndon, and Vienna) or confirmed that there were no changes since the 2015 demand study (Ahmed *et al.*, 2015).

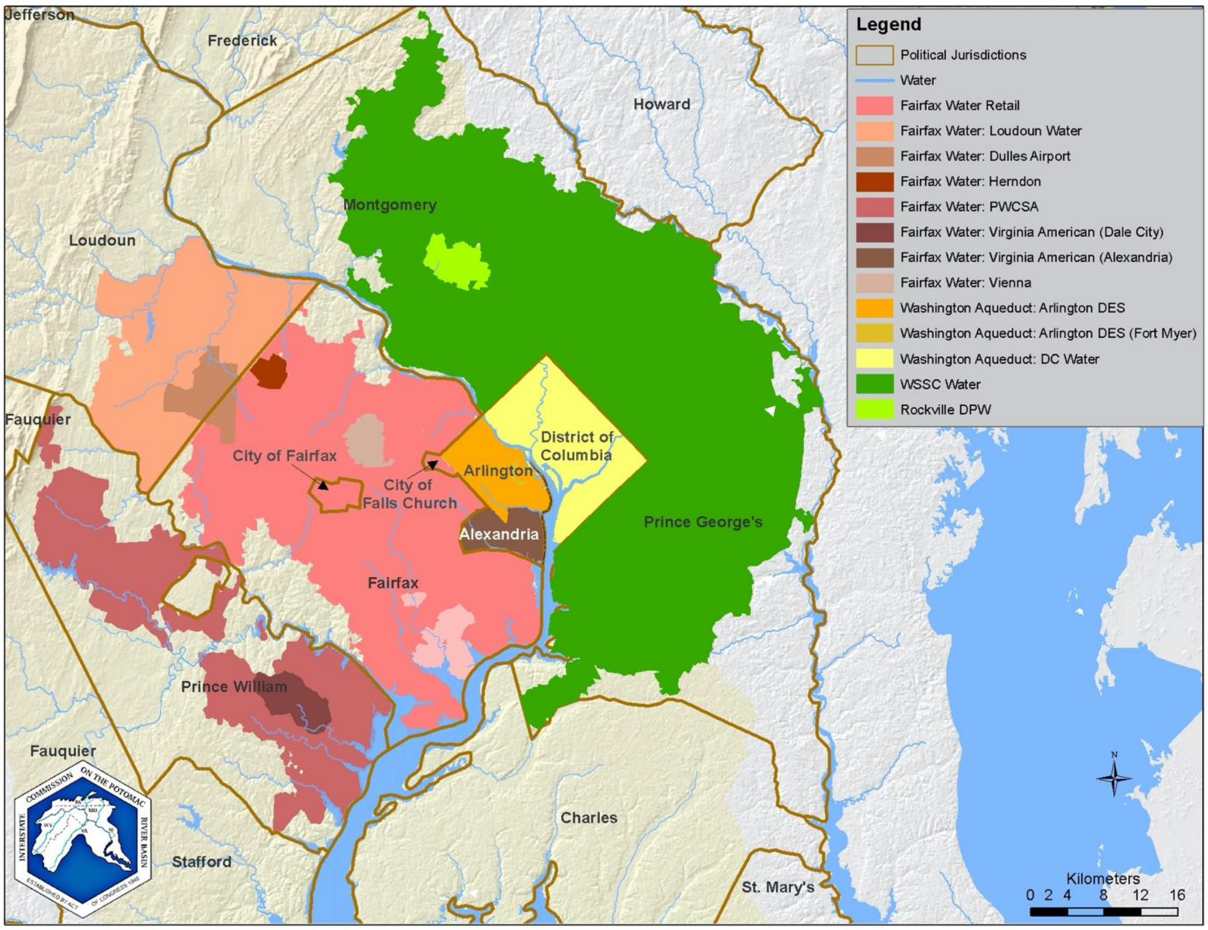

Figure 3-2: Water supplier service areas as of 2018.

[6] In the 2015 demand study (Ahmed *et al.*, 2015), Fairfax Water reports expanding their retail customers to include the City of Falls Church (previously a Washington Aqueduct wholesale customer) and the City of Fairfax (previously independent) and adds the Town of Vienna as a wholesale customer (previously a City of Falls Church wholesale customer, supplied by Washington Aqueduct-treated water). These changes were complete around the beginning of the year 2014 and, therefore, Fairfax Water values for years 2010-2013 reflect the old Fairfax Water service area for the purpose of calculating unit use rates.

The intersection between these service area boundaries and MWCOG's spatial planning units, known as transportation analysis zones (TAZ), are calculated in ESRI's ArcMap™ software to create a set of area ratios by TAZ. The area ratios are used to adjust MWCOG data, which are by county and municipal jurisdiction, to only include the number of units (households, employees, or population) within each service area. Table 3-2 through Table 3-4 summarize demographic data by supplier service areas.

An example of a demographic data adjustment by TAZ area ratio follows: If a TAZ has 50% of its area within a service boundary then 50% of its households, employees, and population are assumed to be customers of that supplier. To test this assumption, that supplier's service area footprint and the overlapping TAZs are exported to Google Maps and overlaid on satellite imagery in order to survey visible households. If a TAZ is only partially within the service area, the satellite image is used to refine the percentage estimate of the households within the TAZ and the service area.

In the 2015 demand study (Ahmed *et al.*, 2015), only a small difference in the total number of households was found by adjusting the TAZ ratios based on satellite imagery. Therefore, this verification step mainly applied to TAZ ratios of overlapping service areas (see Appendix A.3 for specific cases). As an additional verification step, TAZ ratios that belong to jurisdictions outside of the expected service area are replaced with a value of zero.[7]

[7] For example, Fairfax Water retail service area selects slivers of TAZs from Alexandria, Loudoun, Montgomery, Prince George's and Prince William County and those ratios are set to zero. Additional information on expected service area coverage per jurisdiction for the suppliers could improve this data validation step in the future and be quicker than using satellite imagery.

Table 3-2: Historic MWCOG Round 8.4 (2010) and Round 9.1 (2015-2020) population figures by supplier.

Supplier – customer (retail or wholesale)	2010	2011	2012	2013	2014	2015	2016	2017	2018
Fairfax Water – Retail customers[1]	853,360	859,134	864,908	870,681	1,063,611	1,071,499	1,079,233	1,086,966	1,094,700
Fairfax Water – Dulles International Airport	101	103	105	107	109	111	141	172	202
Fairfax Water – Fort Belvoir	7,060	7,520	7,980	8,440	8,900	9,360	9,427	9,494	9,561
Fairfax Water – Town of Herndon	20,067	20,601	21,170	21,739	22,308	22,911	22,593	22,311	22,028
Fairfax Water – PWCSA	292,953	300,546	308,138	315,730	323,322	330,914	334,353	337,791	341,229
Fairfax Water – Vienna PWD[2]					27,394	27,533	27,596	27,659	27,721
Fairfax Water – Virginia American Alexandria	139,989	141,516	143,042	144,569	146,096	147,622	149,924	152,226	154,528
Fairfax Water – Virginia American Dale City	66,658	67,144	67,629	68,115	68,600	69,086	69,852	70,617	71,383
Fairfax Water Subtotal (no Loudoun Water)	1,380,188	1,396,564	1,412,972	1,429,381	1,660,340	1,679,036	1,693,119	1,707,236	1,721,352
Washington Aqueduct – Arlington County DES	206,475	209,132	211,789	214,445	217,102	219,759	223,235	226,710	230,186
Washington Aqueduct – DC Water	601,764	615,857	629,950	644,044	658,137	672,230	683,684	695,138	706,593
Washington Aqueduct – Arlington Fort Myer	1,003	1,003	1,003	1,003	1,003	1,003	1,003	1,003	1,003
Washington Aqueduct – Falls Church[1]	131,080	132,715	134,349	135,983					
Washington Aqueduct – Vienna PWD[2]	26,839	26,978	27,116	27,255					
Washington Aqueduct Subtotal	967,161	985,685	1,004,207	1,022,730	876,242	892,992	907,922	922,851	937,782
WSSC Water	1,709,535	1,724,704	1,739,874	1,755,043	1,770,213	1,785,382	1,795,480	1,805,578	1,815,675
COOP Supplier Subtotal	4,056,884	4,106,953	4,157,053	4,207,154	4,306,795	4,357,410	4,396,521	4,435,665	4,474,809
City of Rockville DPW	46,749	47,355	47,961	48,567	49,173	49,779	50,465	51,151	51,837
Loudoun Water	211,418	221,257	231,097	240,937	250,777	260,617	269,670	278,723	287,776
WMA Subtotal	4,315,051	4,375,565	4,436,111	4,496,658	4,606,745	4,667,806	4,716,656	4,765,539	4,814,422

[1] Falls Church and the City of Fairfax joined Fairfax Water retail in 2014.

[2] Vienna PWD joined Fairfax Water wholesale customers in 2013. For modeling purposes, the change is assumed to start in 2014. Fairfax Water purchase records, however, show that some water was purchased in 2012 and 2013 in addition to what was purchased from Washington Aqueduct via Falls Church (see Appendix A.2 for details).

Table 3-3: Historic MWCOG Round 8.4 (2010) and Round 9.1 (2015-2020) occupied household figures by supplier.

Supplier – customer (retail or wholesale)	2010	2011	2012	2013	2014	2015	2016	2017	2018
Fairfax Water – Retail customers[1]	307,049	309,402	311,756	314,109	385,513	388,677	390,986	393,295	395,605
Fairfax Water – Dulles International Airport	42	43	44	44	45	46	57	67	78
Fairfax Water – Fort Belvoir	2,098	2,221	2,344	2,467	2,590	2,713	2,737	2,761	2,785
Fairfax Water – Town of Herndon	7,129	7,195	7,271	7,347	7,423	7,508	7,512	7,526	7,540
Fairfax Water – PWCSA	97,140	99,429	101,718	104,006	106,295	108,584	110,228	111,872	113,515
Fairfax Water – Vienna PWD[2]					9,199	9,239	9,238	9,238	9,237
Fairfax Water – Virginia American Alexandria	68,085	68,702	69,320	69,938	70,556	71,174	72,068	72,961	73,855
Fairfax Water – Virginia American Dale City	21,219	21,313	21,408	21,502	21,597	21,691	22,044	22,397	22,751
Fairfax Water Subtotal (no Loudoun Water)	502,762	508,305	513,861	519,413	603,218	609,632	614,870	620,117	625,366
Washington Aqueduct – Arlington County DES	97,821	98,963	100,105	101,247	102,389	103,531	105,188	106,845	108,502
Washington Aqueduct – DC Water	266,707	272,788	278,869	284,950	291,031	297,112	301,548	305,983	310,419
Washington Aqueduct – Arlington Fort Myer	175	175	175	175	175	175	175	175	175
Washington Aqueduct – Falls Church[1]	50,703	51,394	52,085	52,776					
Washington Aqueduct – Vienna PWD[2]	9,039	9,079	9,119	9,159					
Washington Aqueduct Subtotal	424,445	432,399	440,353	448,307	393,595	400,818	406,911	413,003	419,096
WSSC Water	618,459	624,164	629,868	635,572	641,277	646,981	652,384	657,787	663,189
COOP Supplier Subtotal	1,545,666	1,564,868	1,584,082	1,603,292	1,638,090	1,657,431	1,674,165	1,690,907	1,707,651
City of Rockville DPW	19,154	19,236	19,317	19,398	19,479	19,560	19,857	20,153	20,449
Loudoun Water	70,684	73,518	76,352	79,186	82,019	84,853	87,603	90,353	93,104
WMA Subtotal	1,635,504	1,657,622	1,679,751	1,701,876	1,739,588	1,761,844	1,781,625	1,801,413	1,821,204

[1] Falls Church and the City of Fairfax joined Fairfax Water retail in 2014.

[2] Vienna PWD joined Fairfax Water wholesale customers in 2013. For modeling purposes, the change is assumed to start in 2014. Fairfax Water purchase records, however, show that some water was purchased in 2012 and 2013 in addition to what was purchased from Washington Aqueduct via Falls Church (see Appendix A.2 for details).

Table 3-4: Historic MWCOG Round 8.4 (2010) and Round 9.1 (2015-2020) employees figures by supplier.

Supplier – customer (retail or wholesale)	2010	2011	2012	2013	2014	2015	2016	2017	2018
Fairfax Water – Retail customers[1]	424,167	427,305	430,443	433,581	600,391	604,241	612,603	620,966	629,329
Fairfax Water – Dulles International Airport	17,747	17,363	16,979	16,595	16,211	15,826	15,989	16,152	16,314
Fairfax Water – Fort Belvoir	28,462	30,348	32,233	34,118	36,003	37,888	38,629	39,370	40,110
Fairfax Water – Town of Herndon	21,138	21,376	21,648	21,920	22,191	22,520	22,943	23,423	23,903
Fairfax Water – PWCSA	89,961	93,477	96,993	100,510	104,026	107,542	111,024	114,506	117,988
Fairfax Water – Vienna PWD[2]					13,049	12,976	13,127	13,279	13,430
Fairfax Water – Virginia American Alexandria	102,882	103,550	104,219	104,888	105,557	106,225	107,002	107,778	108,554
Fairfax Water – Virginia American Dale City	10,099	10,342	10,584	10,827	11,069	11,312	11,518	11,724	11,930
Fairfax Water Subtotal (no Loudoun Water)	694,456	703,761	713,099	722,439	908,497	918,530	932,835	947,198	961,558
Washington Aqueduct – Arlington County DES	216,467	214,250	212,040	209,830	207,620	205,417	206,851	208,292	209,734
Washington Aqueduct – DC Water	783,282	786,280	789,278	792,275	795,273	798,271	807,827	817,383	826,940
Washington Aqueduct – Arlington Fort Myer	25,219	21,024	16,830	12,635	8,441	4,246	4,246	4,246	4,246
Washington Aqueduct – Falls Church[1]	128,344	128,756	129,168	129,580					
Washington Aqueduct – Vienna PWD[2]	13,345	13,271	13,197	13,123					
Washington Aqueduct Subtotal	1,166,657	1,163,581	1,160,513	1,157,443	1,011,334	1,007,934	1,018,924	1,029,921	1,040,920
WSSC Water	769,321	769,364	769,408	769,452	769,496	769,539	775,992	782,445	788,897
COOP Supplier Subtotal	2,630,434	2,636,706	2,643,020	2,649,334	2,689,327	2,696,003	2,727,751	2,759,564	2,791,375
City of Rockville DPW	60,262	61,019	61,776	62,534	63,291	64,048	64,301	64,554	64,807
Loudoun Water	94,697	98,235	101,772	105,310	108,848	112,386	117,024	121,662	126,300
WMA Subtotal	2,785,393	2,795,960	2,806,568	2,817,178	2,861,466	2,872,437	2,909,076	2,945,780	2,982,482

[1] Falls Church and the City of Fairfax joined Fairfax Water retail in 2014.

[2] Vienna PWD joined Fairfax Water wholesale customers in 2013. For modeling purposes, the change is assumed to start in 2014. Fairfax Water purchase records, however, show that some water was purchased in 2012 and 2013 in addition to what was purchased from Washington Aqueduct via Falls Church (see Appendix A.2 for details).

3.2.3 Historic Unit Use Rates

The water use billing and demographic data described above are used to calculate unit use rates for the years of available data (2010-2018). These rates represent average daily water use by end customer category in gallons per day (gpd) per unit category (e.g., either single family, multi-family households, or employees). Unit use rates are calculated by dividing the total amount of water used per customer category by the number of units in that category. Table 3-5 reports unit use values revised from the 2015 demand study using MWCOG Round 8.4 data (Goodwin and Mohammed, 2015). Table 3-6 reports unit use rates updated for the current study using MWCOG Round 9.1 data (MWCOG, 2018).

Table 3-5: Revised historic unit use values by supplier (gpd/unit).

	2010			2011			2012			2013		
	SFH	MFH	EMP	SFH	MFH	EMP	SFH	MFH	EMP	SFH	MFH	EMP
Fairfax Water – Retail customers[1]	206.6	158.0	40.7	198.6	163.2	39.9	190.7	152.1	37.3	184.1	157.8	34.1
Fairfax Water – Dulles International Airport	(206.6)	(158.0)	39.6	(198.6)	(163.2)	42.0	(190.7)	(152.1)	41.5	(184.1)	(157.8)	43.4
Fairfax Water – Fort Belvoir	(206.6)	(158.0)	43.2	(198.6)	(163.2)	40.3	(190.7)	(152.1)	41.3	(184.1)	(157.8)	31.0
Fairfax Water – Town of Herndon	159.9		49.2	151.5		48.2	144.4		44.8	126.6		44.7
Fairfax Water – Loudoun Water	219.8	146.3	58.9	202.0	141.3	55.3	202.9	138.7	60.9	192.1	140.8	54.3
Fairfax Water – PWCSA	(206.6)	(158.0)	61.1	(198.6)	(163.2)	63.4	(190.7)	(152.1)	68.0	(184.1)	(157.8)	58.9
Fairfax Water – Virginia American Alexandria	(206.6)	(158.0)	24.2	(198.6)	(163.2)	19.3	(190.7)	(152.1)	26.0	(184.1)	(157.8)	17.5
Fairfax Water – Virginia American Dale City	(206.6)	(158.0)	17.9	(198.6)	(163.2)	13.8	(190.7)	(152.1)	36.6	(184.1)	(157.8)	22.3
Washington Aqueduct – Arlington County DES	155.7	91.8	40.9	149.8	89.5	38.8	146.9	86.7	38.6	141.8	85.8	39.6
Washington Aqueduct – City of Falls Church DES[1]	(206.6)	(158.0)	42.8	(198.6)	(163.2)	36.5	(190.7)	(152.1)	38.7	(184.1)	(157.8)	29.1
Washington Aqueduct – Vienna PWD[2,3]	212.8	133.6	27.5	205.0	129.6	26.8	216.4	138.0	28.6	205.1	132.0	27.4
Washington Aqueduct – DC Water	166.6	111.1	54.3	161.5	106.2	55.2	150.7	99.1	53.7	144.2	95.6	49.5
Washington Aqueduct – Arlington Fort Myer	(155.7)	(91.8)	9.9	(149.8)	(89.5)	10.2	(146.9)	(86.7)	13.8	(141.8)	(85.8)	37.7
WSSC Water	165.2	160.2	39.8	161.3	154.6	40.9	157.7	134.8	46.2	155.1	140.5	42.1
City of Rockville DPW	153.2	137.8	24.7	155.7	140.2	25.2	152.3	137.1	22.9	156.2	140.6	18.3

Note: Values in parenthesis are assumed, based on values from another supplier.
[1] City of Falls Church DES and the City of Fairfax joined Fairfax Water retail in 2014.
[2] Vienna PWD joined Fairfax Water wholesale customers in 2013. For modeling purposes, the change is assumed to start in 2014. Fairfax Water purchase records, however, show some water purchased in 2012 and 2013 in addition to water purchased from Washington Aqueduct via Falls Church.
[3] Vienna PWD unit use is calculated from assumed 2010-2013 SFH, MFH, and EMP water use data. The 2005-2008 billing and purchase data set is the most complete for Vienna PWD. To update the time series for years 2010-2013: total billed amount was calculated by assuming the reported purchase amount was 5% less than the billed amount; water use category amounts (SFH, MFH, and EMP) were estimated from 2005-2008 billing ratios.

Table 3-6: New historic unit use values by supplier (gpd/unit).

	2014			2015			2016			2017			2018		
	SFH	**MFH**	**EMP**	**SFH**	**MFH**	**EMP**	**SFH**	**MFH**	**EMP**	**SFH**	**MFH**	**EMP**	**SFH**	**MFH**	**EMP**
Fairfax Water – Retail customers[1]	170.8	156.6	32.0	170.6	151.7	32.4	172.4	152.9	33.5	167.8	152.9	31.9	159.5	150.6	30.5
Fairfax Water – Dulles International Airport	(170.8)	(156.6)	44.5	(170.6)	(151.7)	45.6	(172.4)	(152.9)	43.9	(167.8)	(152.9)	42.2	(159.5)	(150.6)	42.8
Fairfax Water – Fort Belvoir	(170.8)	(156.6)	26.6	(170.6)	(151.7)	33.7	(172.4)	(152.9)	29.7	(167.8)	(152.9)	32.6	(159.5)	(150.6)	28.5
Fairfax Water – Town of Herndon	147		36.9	145.3		36.4	153.6		37.8	154		37.2	155.8		36.9
Fairfax Water – Loudoun Water	199.9	129.1	43.8	203.1	136.7	45.8	210.6	141.9	44.7	197.0	134.1	39.6	184.6	130.0	46.4
Fairfax Water – PWCSA	183.2	152.0	46.4	183.3	145.1	47.3	190.5	147.6	47.4	187.3	144.6	44.8	179.7	139.2	41.4
Fairfax Water – Vienna PWD[2]	(178.5)	(116.6)	(24.1)	(184.9)	(120.8)	(25.2)	(183.3)	(119.6)	(24.7)	(181.9)	(118.6)	(24.2)	(173.3)	(112.9)	(22.8)
Fairfax Water – Virginia American Alexandria	(170.8)	(156.6)	23.7	(170.6)	(151.7)	27.6	(172.4)	(152.9)	26.4	(167.8)	(152.9)	19.8	(159.5)	(150.6)	22.9
Fairfax Water – Virginia American Dale City	(170.8)	(156.6)	54.0	(170.6)	(151.7)	53.1	(172.4)	(152.9)	46.3	(167.8)	(152.9)	41.7	(159.5)	(150.6)	50.0
Washington Aqueduct – Arlington County DES	140.4	82.6	39.7	140.7	82.4	41.6	140.1	83.0	42.5	136.7	78.6	40.3	130.6	75.2	40.5
Washington Aqueduct – DC Water	140.1	93.4	46.1	134.9	91.6	50.5	131.4	105.0	45.1	128.3	104.1	43.3	121.0	99.8	43.2
Washington Aqueduct – Arlington Fort Myer	(140.4)	(82.6)	26.6	(140.7)	(82.4)	59.3	(140.1)	(83.0)	50.9	(136.7)	(78.6)	40.4	(130.6)	(75.2)	68.2
WSSC Water	162.7	138.1	41.8	159.3	144.5	46.4	171.9	139.4	44.3	144.5	137.4	42.3	142.5	138.1	41.6
City of Rockville DPW	151.3	136.2	16.3	157.7	142.0	16.4	152.4	137.2	14.9	148.9	134.0	13.9	147.2	132.5	14.2

Note: Values in parenthesis are assumed, based on values from another supplier.

[1] Falls Church and the City of Fairfax joined Fairfax Water retail in 2014.

[2] Vienna PWD joined Fairfax Water wholesale customers in 2013. For modeling purposes, the change is assumed to start in 2014.

3.3 Method for Forecasting Unit Use Rates

The average annual demand forecasts require estimates of unit use rates throughout the forecast period. Historic unit use values, calculated from reported data, fluctuate from year to year due to factors such as weather, demographic and economic conditions, and minor variations in estimation methods. Unit use rates also exhibit long-term trends because of changes in customer use behavior. Unit use rates calculated in the current and past studies are shown on the following pages in Table 3-7 and graphed in Figure 3-3 for Fairfax Water (retail customers only), Washington Aqueduct (DC Water customers only), and WSSC Water.

The unit use rates calculated from water use billing and demographic data for 2010 through 2018, as shown in Table 3-5 and Table 3-6 of the previous section, inform the unit use forecast in the current study. From these historic rates, a starting value for unit use at the beginning of the forecast period – 2018 in this study – is determined. Then, using the estimates of future changes in water use patterns described in Section 3.3.2, the unit use forecast through 2050 is developed. This section details the data and methods used for this forecast.

Table 3-7: Unit use factors calculated in past and current studies (gpd/unit).

Year	Fairfax Water (retail customers only)			Washington Aqueduct (DC Water customers only)			WSSC Water		
	SFH	MFH	EMP	SFH	MFH	EMP	SFH	MFH	EMP
1990[1]	240	177	44	325	315	50	241	224	58
1995[2]	229	156	47	237	237	50	249	233	53
1998[3]	218.6	191.8	45.8	304.4	304.4	44.8	181.8	183.8	44.2
1999[3]							161	171.1	42.9
2000[4]	227	165	44	279	279	60.7	179	184	45
2002[5]	241.5	171.1	49.9	168.2	172.9	58.1	185	173.4	45.9
2003[5]	207.1	167.5	47.8	184.7	156.8	55.8	183.7	174.3	44.1
2004[5]	206.4	158.9	45.1	169.6	159.8	56.9	178.9	175.3	46.6
2005[6]	206.4	170	41.8	177.5	140.4	58.6	179.6	162.6	49
2006[6]	211.2	167.5	42.3	174.7	137.9	61.5	185.7	154.2	44
2007[6]	227.6	167.8	44.4	169.9	132.9	60.2	186.9	152.2	42.5
2008[7]	201.4	163.3	41.2	175.1	121	58.5	182.5	154.5	40
2009[7]	195.5	162.7	39.2	169.4	113.3	55.3	165.6	154.9	36
2010[8]	206.6	158.0	40.7	166.6	111.1	54.3	165.2	160.2	39.8
2011[8]	198.6	163.2	39.9	161.5	106.2	55.2	161.3	154.6	40.9
2012[8]	190.7	152.1	37.3	150.7	99.1	53.7	157.7	134.8	46.2
2013[8]	184.1	157.8	34.1	144.2	95.6	49.5	155.1	140.5	42.1
2014[9]	170.8	156.6	32.0	140.1	93.4	46.1	162.7	138.1	41.8
2015[9]	170.6	151.7	32.4	134.9	91.6	50.5	159.3	144.5	46.4
2016[9]	172.4	152.9	33.5	131.4	105.0	45.1	171.9	139.4	44.3
2017[9]	167.8	152.9	31.9	128.3	104.1	43.3	144.5	137.4	42.3
2018[9]	159.5	150.6	30.5	121.0	99.8	43.2	142.5	138.1	41.6

[1] 1990 study results (Holmes and Steiner, 1990), based primarily on 1988 data.
[2] 1995 study results (Mullusky *et al.*, 1996), based primarily on 1993 or 1994 data (WSSC Water results are for existing housing units).
[3] From 2000 study spreadsheet.
[4] Revised 2000 value reported in 2005 study (Kame'enui *et al.*, 2005)
[5] 2004 results from 2005 study (Kame'enui *et al.*, 2005); 2002 and 2003 restults from 2005 study spreadsheet.
[6] Part 1 of the 2010 study results (Ahmed *et al.*, 2010).
[7] 2015 study results (Ahmed *et al.*, 2015).
[8] Current study revision from 2015 study (Ahmed *et al.*, 2015) using updated demographic information.
[9] Current study results.

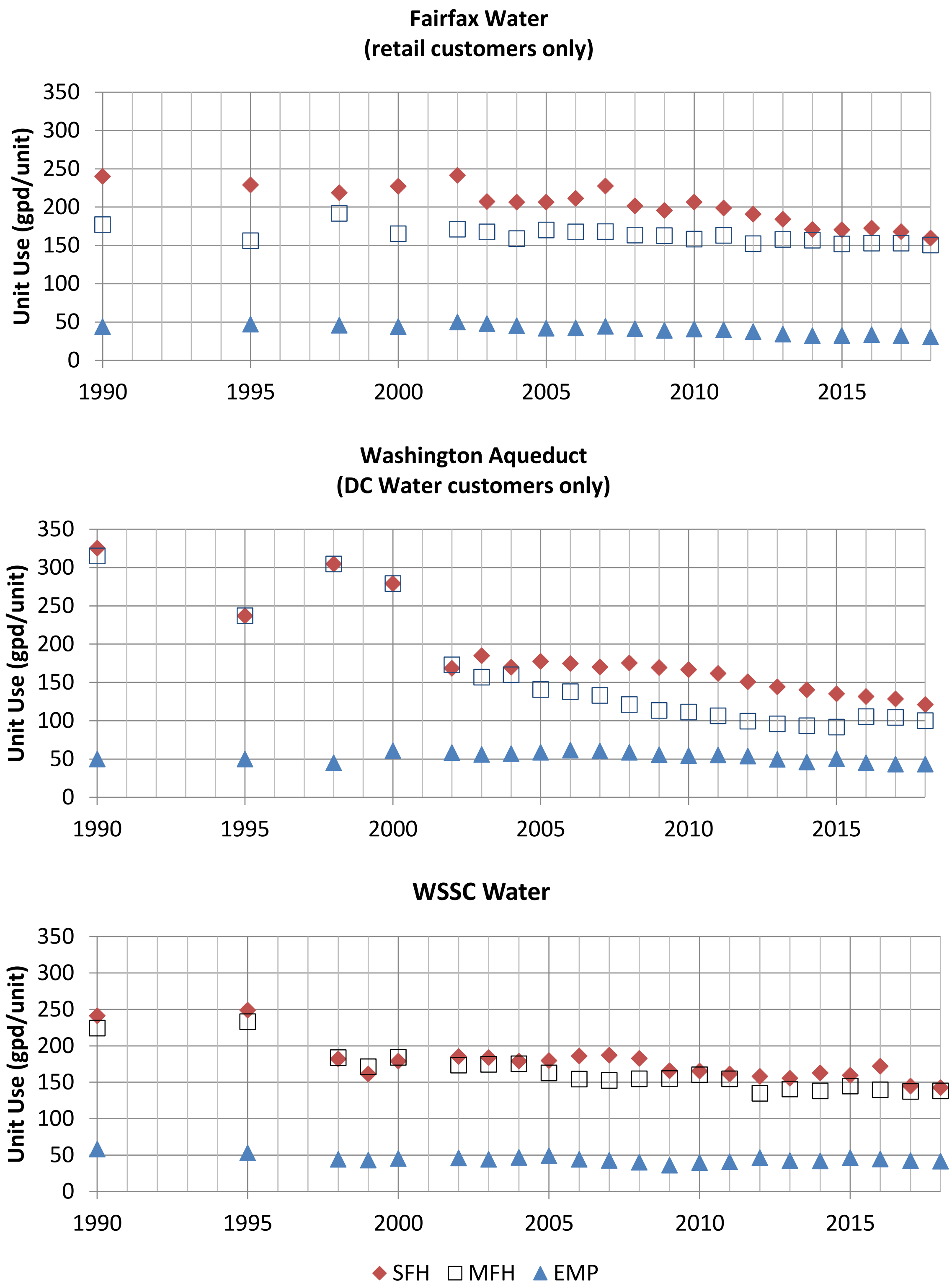

Figure 3-3: Unit use rates for the three CO-OP suppliers for 1990-2018.

3.3.1 Selecting Unit Use Rate for Beginning of Demand Forecast Period

Different methods have been used to set the starting value of unit use rates for the first year of the forecast period. In early ICPRB studies, unit use rates for the beginning of the forecast period were generally approximated by the values calculated for the most recent year in which data were available, with minor adjustments sometimes made to account for weather effects. In the 2010 study (Ahmed *et al.*, 2010), statistical methods were used to determine if trends were present in the unit use time series, and if so, to estimate the forecast starting values. For the 2015 demand study (Ahmed *et al.*, 2015), the averages of the unit use rates for 2008 through 2013 (as available) were used as the forecast starting values. This approach was thought to be appropriate because it was believed that there might be temporary declines in unit use rates due to the economic downturn of the “Great Recession” that lasted 18 months from peak to trough (December 2007 to June 2009).

The graphs of total water production for the period 2006 through 2018, shown in Figure 3-4 and Figure 3-5, indicate that declines in water use during the Great Recession were not notable, except in the case of Fairfax Water. The figures show that water use from 2007 to 2009 fell by 15.6%, 5.5%, 4.1%, and 8.5% for Fairfax Water, WSSC Water, Washington Aqueduct, and Loudoun Water, respectively. The post-recession period of 2010 through 2018 shows some recovery in 2010, except in the case of Washington Aqueduct. A downward trend in Washington Aqueduct production is evident both during the Great Recession and in the post-recession period. For example, from 2007 through 2018, their production fell by 16.2%. These findings are consistent with the Water Resource Foundation #4458 findings (Kiefer, 2014).

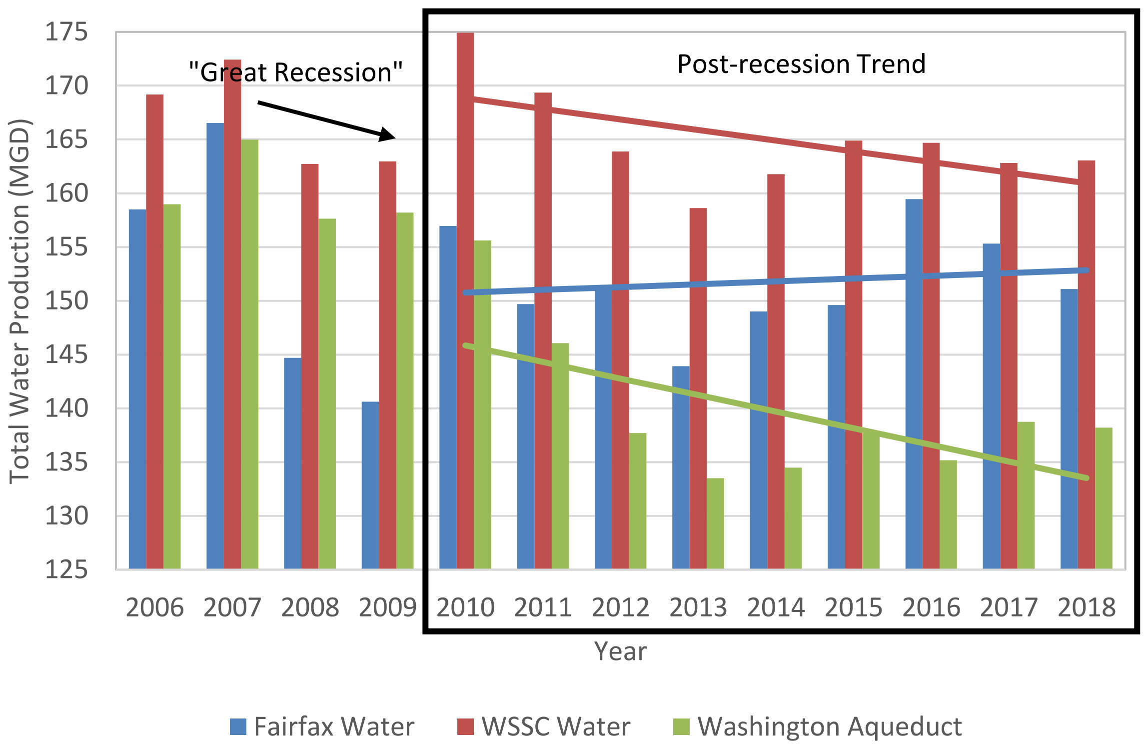

Figure 3-4: CO-OP supplier total water productions in context of the Great Recession (2007-2009) and post-recession (2010-2018).

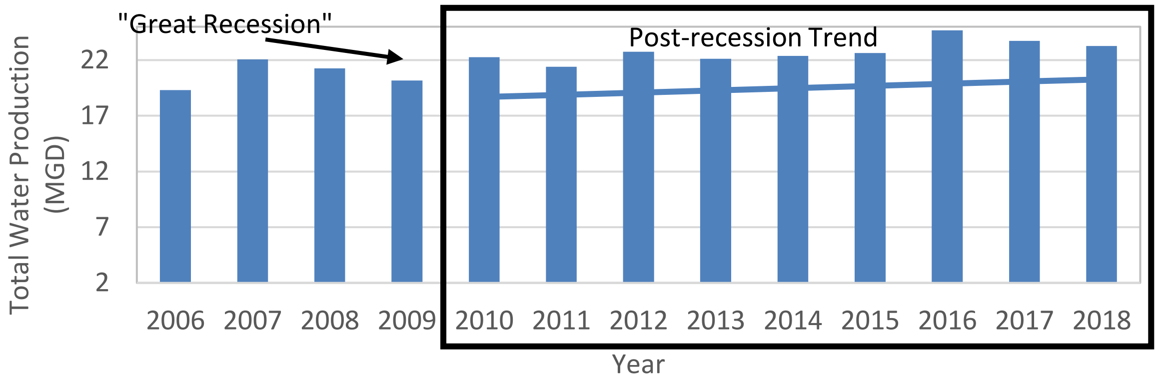

Figure 3-5: Loudoun Water total water productions in context of the Great Recession (2007-2009) and post-recession (2010-2018).

For the current iteration of the study, a least squares linear regression model for the post-recession period 2010 through 2018 is developed for each retail supplier and wholesale customer set of unit use values. These linear models are used to estimate the starting value for unit use for the beginning of the forecast period, 2018. This method captures recent trends in unit use values and removes fluctuations which may occur because of variations in weather conditions and other factors. Because of the post-recession period, the regression estimates are not affected by any decline in water use from 2007 to 2009. Table 3-8 compares the unit use values derived from 2018 reported data (historical) to estimates calculated from the regression models, which is defined as our "baseline" year.

Table 3-8: 2018 historical unit use rate values compared to the 2018 estimates.

Water Supplier	2018 - Value			2018 - Estimate		
	SFH	MFH	EMP	SFH	MFH	EMP
Fairfax Water - Retail customers	159.5	150.6	30.5	158.1	150.8	29.8
Fairfax Water - Dulles International Airport	(159.5)	(150.6)	42.8	158.1	150.8	44.2
Fairfax Water - Fort Belvoir	(159.5)	(150.6)	28.5	158.1	150.8	27.3
Fairfax Water - Town of Herndon	155.8		36.9	150.5		34.4
Fairfax Water - PWCSA	179.7	139.2	41.4	179.8	140.9	40.7
Fairfax Water - Vienna PWD	(173.3)	(112.9)	(22.8)	172.5	113.7	23.3
Fairfax Water - Virginia American Alexandria	(159.5)	(150.6)	22.9	158.1	150.8	23.5
Fairfax Water - Virginia American Dale City	(159.5)	(150.6)	50.0	158.1	150.8	54.8
Washington Aqueduct - Arlington County DES	130.6	75.2	40.5	132.3	76.6	41.1
Washington Aqueduct - DC Water	121.0	99.8	43.2	120.1	97.8	42.6
Washington Aqueduct - Arlington Fort Myer	(130.6)	(75.2)	68.2	132.3	76.6	63.2
WSSC Water	142.5	138.1	41.6	150.6	134.6	43.6
City of Rockville DPW	147.2	132.5	14.2	150.0	135.0	12.3
Loudoun Water	184.6	130.0	46.4	192.7	132.0	40.8

Note: Values in parenthesis are assumed, based on values from another supplier.

3.3.2 Potential Changes in Customer Demand

Since the first WMA water demand and resource study in 1990, values of per household water use have consistently fallen, as is evident from Table 3-7 and Figure 3-3. Thus, one important component of predicting future demands is estimating possible future changes in household water use. Water use in homes is influenced by many factors like weather and pricing structures as well as policies like the *Energy Policy Act of 1992* and programs like the USEPA's WaterSense program, both of which promote adoption of more efficient fixtures and appliances. The purpose of this section is to provide estimates of future household savings from these programs and policies in the WMA.

This study makes assumptions based on the *Energy Policy Act of 1992*, WaterSense program, and consumer behavior literature to estimate reductions in household and employee unit use factors in the WMA after the baseline year 2018 (see Section 3.3.1). Changes over time in the number of households in the combined service areas of the WMA suppliers were also incorporated using the MWCOG Round 9.1 forecast (MWCOG, 2018). While climate change is expected to impact WMA water demand and resources, those impacts are the subject of Chapter 6.

The methodology used to estimate reductions follows that used in the 2015 demand study (Ahmed *et al.*, 2015). Specifically, reduction estimates are based on assumptions about residential water use rates; the number of existing households that have been remodeled; bathroom, fixture, and appliance replacement rates; the number of new houses with associated low-flow appliances and fixtures (this helps account for the various ages of the housing stock in the WMA); and market share estimates for these products. The method from the 2015 demand study is based on two studies: *WaterSense Program: Methodology for National Water Savings Analysis Model Indoor Residential Water Use* (McNeil *et al*., 2008) and *Tampa Bay Water: Water Demand Management Plan Final Report* (Hazen and Sawyer, 2013). Average savings are estimated for the entire WMA system, not for any single supplier. More accurate estimates for individual suppliers were not computed based on supplier-specific data.

Maryland Department of the Environment reports that outdoor watering can double household water use in the summer (MDE, 2020). Historic production data from the CO-OP suppliers demonstrates this additional summer water usage due to outdoor water use (Ahmed *et al.*, 2015). As reported in Section 2.1.2, the average summer production was 11% higher than the annual average production and the annual peak-day production was, on average, 31% higher for the period 2014 through 2018. While outdoor water use may be reduced in the future due to more efficient fixtures, changes in outdoor water use are not included in this assessment due to limited literature data on the topic and the extensive WMA-specific data needed to develop estimates (Schein *et al*., 2017; DeOreo *et al*., 2016) like monthly or seasonal household water use.

For the current study, the methodology is updated based on available literature to include revised fixture replacement rates (Schein *et al*., 2017*)* and use event frequencies (DeOreo *et al*., 2016*)*. In addition, ranges in literature values for market shares (McNeil *et al*., 2008) and fixture replacement rates are used to develop three different water savings projections. The range in potential reductions is useful for evaluating a range of possible futures as well as sensitivities in this approach. Three savings projections, denoted as SP1, SP2, and SP3, use different assumptions for market shares and replacement rates, as described in more detail in Appendix A.3.1.5. SP1 assumes the highest values for replacement rates and market shares of high efficiency fixtures and appliances, SP3 assumes the lowest values, and SP2 falls in the middle.

Table 3-9 summarizes the household water use in 2018 and 2045 by appliance and in total. Using this information and similar information for intermediate years, expected household savings are calculated for the 2018 through 2045 period. These savings are applied to the baseline (2018) single family and multi-family household unit use rates for each supplier starting in 2020. See Appendix A.3.1.5 for estimated savings for intermediate forecast years.

There are no differences in the values for the SP1, SP2, and SP3 savings projections for clothes washers and dishwashers because market share and lifetime ranges are not available in the literature for these fixtures. The projections are different for showers only because of available minimum, average, and maximum lifetime values. Toilet and faucet market share and lifetime values are available for all projections.

Table 3-9: Estimated WMA household water use in 2018 and 2045 by savings category (gpd/unit).

Water Use	**2018**			**2045**		
	SP1	**SP2**	**SP3**	**SP1**	**SP2**	**SP3**
Toilets	19.6	25.9	29.9	16.8	17.9	20.7
Clothes Washers	10.1	10.1	10.1	9.9	9.9	9.9
Dishwashers	1.3	1.3	1.3	1.2	1.2	1.2
Faucets	31.5	36	39.6	30	30.1	30.6
Showerheads	17.6	20.5	22.5	16.2	16.4	17.3
Total	**80.1**	**93.9**	**103.4**	**74.1**	**75.5**	**79.8**

Using the same approach, a savings estimate for employee use of low-flow toilets is also calculated. The resulting savings per employee range from 0.2 to 1.8 gpd depending on projection and year, with savings increasing over time. A more detailed analysis was not conducted due to the extensive data requirements, such as the number of female and male employees and the number of toilets and urinals in each building.

Tabular results are presented in Appendix A.3.1.5. The incremental change in water use savings used to make the unit use forecasts over the years 2020 through 2045 is summarized in Table 3-10. These numbers are what modify the 2018 baseline unit use estimates reported in Table 3-8.

Table 3-10: Water use savings by forecast increment (gpd/unit).

	SFH and MFH (Total Water Use)			**EMP (Toilets)**		
Year	**SP1**	**SP2**	**SP3**	**SP1**	**SP2**	**SP3**
2018-2020	2.1	3.9	4.1	0.2	0.2	0.2
2021-2025	2.5	6.8	7.6	0.6	0.6	0.4
2026-2030	0.9	3.7	5.2	0.3	0.3	0.4
2031-2035	0.3	2.1	3.4	0.3	0.3	0.3
2036-2040	0.2	1.2	2.2	0.2	0.2	0.2
2041-2045	0.1	0.7	1.1	0.2	0.2	0.2
2046-2050 estimate[1]		1.0			0.2	

[1] 2050 values are linearly extrapolated from 2035, 3040, and 2045 values.

Figure 3-6 displays the estimated savings since 1994 for the SP1, SP2, and SP3 water savings projections from this study compared to estimates from the 2015 demand study (shown in blue). It can be seen from Figure 3-6 that in the highest replacement rate and high efficiency market share projection, SP1, water savings are realized earlier, resulting in little water savings between 2018 and 2045 as compared to the lowest replacement rate projection, SP3. The middle savings projection, SP2, used in this study is comparable to that estimated in the 2015 demand study. For that savings projection, the ICPRB efficiency model is relatively insensitive to changes that have occurred since 2015.

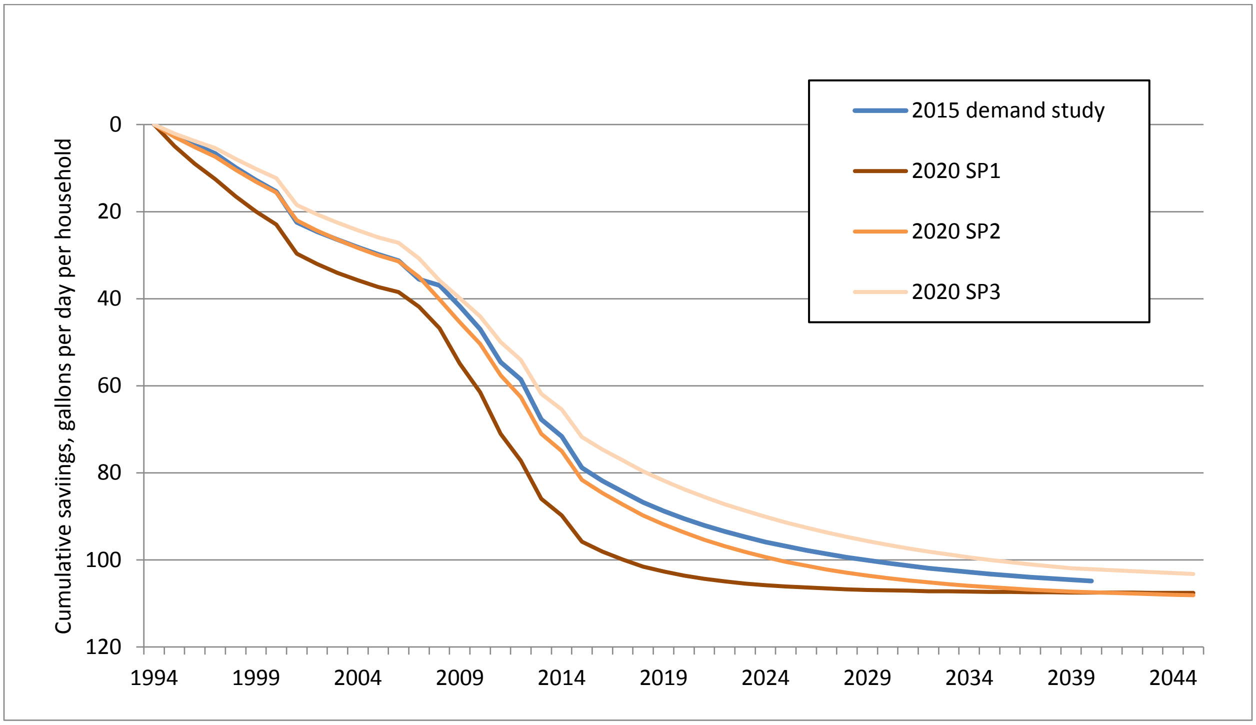

Figure 3-6: Estimated per household savings since 1994.

3.3.3 Unit Use Forecast

In Table 3-11, the estimated unit use rates for each supplier and wholesale customer are given for the 2020 through 2050 forecast years. As described in the previous sections, the forecast relies on historical information supplied by the suppliers, past demographic information, and assumptions about changing customer behavior. The baseline 2018 estimates, shown in Table 3-8 (Section 3.3.1), are modified using the incremental water use savings reported in Table 3-10 (Section 3.3.2). The unit use rates reported at five-year increments for the period 2020 through 2045 are based on the best available data as described in previous sections of this report. The forecasted unit use rates are linearly extrapolated to the year 2050 using of the 2035, 3040, and 2045 values to provide the WMA suppliers with a longer-term planning horizon and to help support the VADEQ water supply planning process.

It is important to note that the forecasted unit use rates are based on a system-wide analysis of water use savings that assumes that all WMA suppliers will experience the same savings. However, assumptions used in this analysis, such as the age of the housing stock and fixture and appliance replacement rates, will differ by supplier service area. In future ICPRB water supply studies, a more individual analysis of water use savings may be warranted.

Table 3-11: Unit use forecast by supplier (gpd/unit).

	2020			2025			2030			2035			2040			2045			2050[1]		
	SFH	**MFH**	**EMP**	**SFH**	**MFH**	**EMP**	**SFH**	**MFH**	**EMP**	**SFH**	**MFH**	**EMP**	**SFH**	**MFH**	**EMP**	**SFH**	**MFH**	**EMP**	**SFH**	**MFH**	**EMP**
Fairfax Water - Retail customers	154.2	146.9	29.6	147.4	140.1	29.0	143.7	136.4	28.7	141.6	134.3	28.4	140.4	133.1	28.2	139.7	132.4	28.0	138.6	131.3	27.8
Fairfax Water - Dulles International Airport	(154.2)	(146.9)	44.0	(147.4)	(140.1)	43.4	(143.7)	(136.4)	43.1	(141.6)	(134.3)	42.8	(140.4)	(133.1)	42.6	(139.7)	(132.4)	42.4	(138.6)	(131.3)	42.2
Fairfax Water - Town of Herndon	150.5		34.4	146.6		34.2	139.8		33.6	136.1		33.3	134		33	132.8		32.8	131.1		32.4
Fairfax Water - Fort Belvoir	(154.2)	(146.9)	27.1	(147.4)	(140.1)	26.5	(143.7)	(136.4)	26.2	(141.6)	(134.3)	25.9	(140.4)	(133.1)	25.7	(139.7)	(132.4)	25.5	138.6	(131.3)	25.3
Fairfax Water - Loudoun Water	188.8	128.1	40.6	182.0	121.3	40.0	178.3	117.6	39.7	176.2	115.5	39.4	175.0	114.3	39.2	174.3	113.6	39.0	173.3	112.6	38.8
Fairfax Water - PWCSA	175.9	137.0	40.5	169.1	130.2	39.9	165.4	126.5	39.6	163.3	124.4	39.3	162.1	123.2	39.1	161.4	122.5	38.9	160.4	121.4	38.7
Fairfax Water - Vienna PWD	168.6	109.8	23.1	161.8	103.0	22.5	158.1	99.3	22.2	156.0	97.2	21.9	154.8	96.0	21.7	154.1	95.3	21.5	153.1	94.3	21.3
Fairfax Water - Virginia American Alexandria	(154.2)	(146.9)	23.3	(147.4)	(140.1)	22.7	(143.7)	(136.4)	22.4	(141.6)	(134.3)	22.1	(140.4)	(133.1)	21.9	(139.7)	(132.4)	21.7	(138.6)	(131.3)	21.5
Fairfax Water - Virginia American Dale City	(154.2)	(146.9)	54.6	(147.4)	(140.1)	54.0	(143.7)	(136.4)	53.7	(141.6)	(134.3)	53.4	(140.4)	(133.1)	53.2	(139.7)	(132.4)	53.0	(138.6)	(131.3)	52.8
Washington Aqueduct - Arlington County DES	128.4	72.7	40.9	121.6	65.9	40.3	117.9	62.2	40.0	115.8	60.1	39.7	114.6	58.9	39.5	113.9	58.2	39.3	112.8	57.2	39.1
Washington Aqueduct - DC Water	116.2	93.9	42.4	109.4	87.1	41.8	105.7	83.4	41.5	103.6	81.3	41.2	102.4	80.1	41.0	101.7	79.4	40.8	100.6	78.3	40.6
Washington Aqueduct - Arlington Fort Myer	(128.4)	(72.7)	63.0	(121.6)	(65.9)	62.4	(117.9)	(62.2)	62.1	(115.8)	(60.1)	61.8	(114.6)	(58.9)	61.6	(113.9)	(58.2)	61.4	(112.8)	(57.2)	61.2
WSSC Water	146.7	130.7	43.4	139.9	123.9	42.8	136.2	120.2	42.5	134.1	118.1	42.2	132.9	116.9	42.0	132.2	116.2	41.8	131.1	115.2	41.6
City of Rockville DPW	146.1	131.1	12.1	139.3	124.3	11.5	135.6	120.6	11.2	133.5	118.5	10.9	132.3	117.3	10.7	131.6	116.6	10.5	130.5	115.5	10.3

Note: Values in parenthesis are assumed, based on values from another supplier.

[1] 2050 values are linearly extrapolated from 2035, 2040, and 2045 values.

3.4 METHODS FOR ANNUAL DEMAND FORECAST

The annual water demand forecast calculation for each supplier combines the following four datasets: (1) unit use rate forecasts from Table 3-11 (Section 3.3.3, above); (2) demographic forecasts of single family households, multi-family households, and employees in each supplier's service area (Section 3.4.1, below); (3) wholesale water use assumptions (See Appendix A.3 for details); (4) and unmetered water use estimates (Section 3.4.2, below). This section explains the development of the demographic forecast and unmetered water use assumptions. The demographic forecast is based on MWCOG Round 9.1 (MWCOG, 2018) data for the years 2020 through 2045 and is linearly extrapolated out to the year 2050. The unmetered water use is estimated from historic water billing data and is introduced in Section 3.2.1. Although no tabular historic unmetered water use data is provided here, detailed information can be found in Appendix A.3 for each retail and wholesale customer.

The methodology for forecasting annual water demands, described in the following sections, is developed to be general enough to apply to all the region's suppliers. Most suppliers conduct their own demand forecasts that often account for specific, local conditions that may lead to different results than those of this study (See Appendix A.3.5 for two examples).

3.4.1 Demographic Forecasts

Household, employment, and population projections for each supplier's service area are based on the MWCOG Round 9.1 Cooperative Forecast (MWCOG, 2018) and on a delineation of the current and future water service areas using ESRI's ArcMap^{TM} GIS tools. The number of single family and mutli-family households in each local jurisdiction are used to calculate the dwelling unit ratio (where the DUR is equal to the number of SFH divided by the number of MFH) for each area served. In turn, the DUR is used to separate the MWCOG total household forecasts into the number of SFH and MFH.

The MWCOG forecast is developed through a cooperative process involving MWCOG and local government agencies. The Cooperative Forecasting Program, established in 1975 and administered by MWCOG, allows for coordinated local and regional planning using common assumptions about future growth and development. The forecast available at the beginning of this study, Round 9.1, for the period 2015 through 2045, was approved by the MWCOG Board of Directors in October 10, 2018 (MWCOG, 2018).

The MWCOG forecast uses both a regional econometric model and bottom-up approach undertaken by local planning agencies. The econometric model is based on national and local economic and demographic trends, while the local planning agencies rely more on development and transportation plans in addition to local economic and demographic trends. After these two forecasts are independently completed, they are reconciled through MWCOG's Cooperative Forecasting and Data Subcommittee and approved by MWCOG's Board of Directors. The final product is an estimate of population, employees, and households as distributed by transportation analysis zones (TAZs). Each county within the WMA has several hundred MWCOG TAZs, which are selected and modified by TAZ area ratios to reflect the proportion of the individual water supplier service areas included within each TAZ. In the WMA (as defined by this report), there are currently 2,568 TAZs of varying size when using the 3722 TAZ system. TAZs tend to be smaller closer to the urban core (*i.e.,* DC has the most TAZs of all jurisdictions in the area). More information on the development of this forecast can be found at MWCOG's website: www.mwcog.org.

No additional growth areas were incorporated into the MWCOG forecast, although there are two areas of interest: (1) Amazon HQ2, and (2) Loudoun County's Comprehensive Plan revision. Amazon HQ2 is a planned corporate headquarters in Crystal City, Arlington, Virginia for the technology company Amazon. HQ2 was announced in September 2017 and is an expansion of the existing headquarters in Seattle, Washington. The Round 9.1 forecast was developed a year before the Amazon decision (G. Goodwin, personal communication, October 24, 2019). Although, HQ2 was not specifically incorporated into the forecast, some assumptions about potential jobs in Arlington County were made; now it is more specifically known that HQ2 will be providing those jobs. Therefore, it was not recommended to adjust the Round 9.1 forecast. In Loudoun County's case, an update to the Comprehensive Plan was completed in June 2019 that resulted in approval for an increase in the Loudoun Water service area, and development densities. However, the County has yet to complete detailed planning for these areas and there are no official projections that could be used to modify the Round 9.1 projections (D. Geldert, personal communication, July 14, 2020).

3.4.1.1 Dwelling Unit Ratios Forecasts

Dwelling unit ratio forecasts are used to disaggregate 2020 through 2045 MWCOG total occupied household values into single family and multi-family household estimates. The single family and multi-family household data for each service area is collected from the major jurisdictional planning offices in the WMA as shown in Table 3-12. These household numbers are combined with unit use rate forecasts described in Section 3.3.3 and shown in Table 3-11 in order to compute the annual water demand forecasts given in Section 3.6. Details on data used and assumptions made are provided in Appendix A.3.

Table 3-12: Dwelling unit ratio forecasts (single family households divided by multi-family households, dimensionless).

Supplier/Wholesaler	Jurisdiction	2020	2025	2030	2035	2040	2045	2050[4]
Fairfax Water – Retail customer	Fairfax County	2.32	2.06	1.82	1.63	1.49	1.41	1.29
Fairfax Water – Dulles International Airport	Loudoun/Fairfax Counties	(2.32)	(2.06)	(1.82)	(1.63)	(1.49)	(1.41)	(1.29)
Fairfax Water – Fort Belvoir	Fairfax County	(2.32)	(2.06)	(1.82)	(1.63)	(1.49)	(1.41)	(1.29)
Fairfax Water – Town of Herndon	Town of Herndon[1]	1.95	1.49	1.17	0.93	0.77	0.77	0.66
Fairfax Water – PWCSA	Prince William County	2.97	2.42	2.17	2.04	1.96	1.93	1.87
Fairfax Water – Vienna PWD	Town of Vienna[1]	11.05	10.98	10.64	10.27	9.96	9.78	9.52
Fairfax Water – Virginia American Alexandria	City of Alexandria	0.44	0.41	0.40	0.37	0.34	0.31	0.28
Fairfax Water – Virginia American Dale City	Dale City[2]	6.43	5.59	5.16	4.69	4.42	4.26	4.03
Washington Aqueduct – DC Water	District of Columbia	0.56	0.51	0.47	0.44	0.42	0.40	0.38
Washington Aqueduct – Arlington County DES	Arlington County	0.50	0.47	0.44	0.42	0.40	0.38	0.36
Washington Aqueduct – Arlington Fort Myer	Arlington County	(0.50)	(0.47)	(0.44)	(0.42)	(0.40)	(0.38)	(0.36)
WSSC Water	Montgomery County	1.85	1.75	1.67	1.62	1.56	1.52	1.46
WSSC Water	Prince George's County	2.42	2.41	2.26	2.15	2.05	2.01	1.94
City of Rockville DPW	City of Rockville[3]	1.08	0.99	0.85	0.78	0.74	0.69	0.64
Loudoun Water	Loudoun County	3.72	3.23	2.75	2.44	2.34	2.30	2.22

Note: Values in parenthesis are assumed from other jurisdictions.
[1] The towns of Herndon and Vienna are considered separately from Fairfax County.
[2] Dale City is considered separately from Prince William County.
[3] Rockville is considered separately from Montgomery County.
[4] 2050 values are linearly extrapolated from 2035, 2040, and 2045 values.

3.4.1.2 Service Area Demographic Forecasts

Future service area demographics assume the same spatial extents estimated for the year 2018 and illustrated in Figure 3-2 (Section 3.2.2.2). This means that the same TAZ ratio analysis described in Section 3.2.2.2 is used to modify the MWCOG Round 9.1 household and employee estimates for years 2020 through 2045. The future extent of each supplier's service area is difficult to predict. These estimates can be based on known physical constraints of the water supply system or on county zoning maps and comprehensive plans. Unlike previous studies, no major change in water service provider was expected to occur at the time of the current study (e.g., in previous studies it was known that Fairfax Water and Washington Aqueduct were undergoing major changes in their respective customer bases, where larger areas were either added or removed from their service areas).

Table 3-13 through Table 3-15 show anticipated population, household, and employee totals for each retail and wholesale service area. Overall, MWCOG Round 9.1 forecasts indicate continued growth throughout the area served by the WMA suppliers and their wholesale customers (Table 3-16). Loudoun Water is predicted to experience the most growth of all the suppliers over the next 30 years. The largest expected gain for Loudoun Water is in the number of employees, which is predicted to grow by 64% between 2020 and 2050. Overall, the forecast indicates an increase in the number of households by 28%, employees by 32%, and population by 24% in the WMA area.

Table 3-13: Projected MWCOG Round 9.1 population figures by supplier.

Supplier – customer (retail or wholesale)	2020	2025	2030	2035	2040	2045	2050[1]
Fairfax Water – Retail customers	1,110,167	1,163,136	1,225,400	1,279,830	1,328,578	1,372,031	1,419,014
Fairfax Water – Dulles International Airport	264	401	540	610	661	701	748
Fairfax Water – Fort Belvoir	9,694	9,720	9,841	9,982	10,098	10,215	10,332
Fairfax Water – Town of Herndon	21,494	21,945	22,475	23,002	23,473	23,926	24,392
Fairfax Water – PWCSA	348,106	377,546	398,834	416,445	430,930	442,735	456,327
Fairfax Water – Vienna PWD	27,847	27,971	28,342	28,811	29,169	29,570	29,943
Fairfax Water – Virginia American Alexandria	159,132	167,479	172,745	180,427	190,787	208,413	221,196
Fairfax Water – Virginia American Dale City	72,914	75,041	76,569	78,126	79,395	80,378	81,552
Fairfax Water Subtotal	1,749,618	1,843,239	1,934,746	2,017,233	2,093,091	2,167,969	2,243,504
Washington Aqueduct – Arlington County DES	237,138	248,304	260,633	273,403	285,811	299,313	312,086
Washington Aqueduct – DC Water	729,501	787,116	842,154	893,898	940,687	987,213	1,033,914
Washington Aqueduct – Arlington Fort Myer	1,003	1,003	1,003	1,003	1,594	1,695	2,123
Washington Aqueduct Subtotal	967,642	1,036,423	1,103,790	1,168,304	1,228,092	1,288,221	1,348,123
WSSC Water	1,835,870	1,879,743	1,930,457	1,976,873	2,016,316	2,051,587	2,089,640
COOP Supplier Subtotal	4,553,130	4,759,405	4,968,993	5,162,410	5,337,499	5,507,777	5,681,267
City of Rockville DPW	53,208	57,110	60,901	63,929	67,611	70,707	74,194
Fairfax Water – Loudoun Water	305,883	328,501	340,408	348,341	351,339	352,543	354,943
Other WMA Suppliers Subtotal	359,091	385,611	401,309	412,270	418,950	423,250	429,137
WMA Subtotal	4,912,221	5,145,016	5,370,302	5,574,680	5,756,449	5,931,027	6,110,404

[1] 2050 values are linearly extrapolated from 2035, 2040, and 2045 values.

Table 3-14: Projected MWCOG Round 9.1 occupied household figures by supplier.

Supplier/Wholesaler	2020	2025	2030	2035	2040	2045	2050[1]
Fairfax Water - Retail customers	400,223	424,236	451,785	475,935	497,605	517,060	537,991
Fairfax Water - Dulles International Airport	100	158	218	248	269	285	305
Fairfax Water - Fort Belvoir	2,832	2,844	2,897	2,956	3,006	3,056	3,106
Fairfax Water - Town of Herndon	7,578	7,823	8,092	8,356	8,592	8,819	9,053
Fairfax Water - PWCSA	116,803	127,942	136,196	142,968	148,465	152,777	157,879
Fairfax Water - Vienna PWD	9,236	9,278	9,399	9,552	9,672	9,804	9,928
Fairfax Water - Virginia American Alexandria	75,642	80,756	84,095	87,825	92,875	107,057	115,151
Fairfax Water - Virginia American Dale City	23,457	24,248	24,832	25,451	25,947	26,319	26,774
Fairfax Water Subtotal	635,871	677,285	717,514	753,291	786,431	825,177	860,187
Washington Aqueduct - Arlington County DES	111,815	117,635	123,625	129,536	135,146	141,352	147,160
Washington Aqueduct - DC Water	319,290	341,019	362,524	380,594	396,233	411,872	427,511
Washington Aqueduct - Arlington Fort Myer	175	175	175	175	396	434	594
Washington Aqueduct Subtotal	431,280	458,829	486,324	510,305	531,775	553,658	575,265
WSSC Water	673,995	695,606	721,386	741,971	759,386	775,327	792,251
COOP Supplier Subtotal	1,741,146	1,831,720	1,925,224	2,005,567	2,077,592	2,154,162	2,227,703
City of Rockville DPW	21,041	22,488	24,299	25,742	27,398	28,837	30,420
Fairfax Water - Loudoun Water	98,604	106,777	112,101	115,963	117,426	117,985	119,147
Other WMA Suppliers Subtotal	119,645	129,265	136,400	141,705	144,824	146,822	149,567
WMA Total	1,860,791	1,960,985	2,061,624	2,147,272	2,222,416	2,300,984	2,377,270

[1] 2050 values are linearly extrapolated from 2035, 2040, and 2045 values.

Table 3-15: Projected MWCOG Round 9.1 employee figures by supplier.

Supplier/Wholesaler	2020	2025	2030	2035	2040	2045	2050[1]
Fairfax Water - Retail customers	646,054	679,577	713,301	744,639	781,780	812,003	846,838
Fairfax Water - Dulles International Airport	16,640	18,057	19,635	20,926	21,530	22,095	22,685
Fairfax Water - Fort Belvoir	41,592	47,291	53,235	53,241	53,314	53,358	53,421
Fairfax Water - Town of Herndon	24,921	30,873	34,063	36,070	36,411	38,289	39,142
Fairfax Water - PWCSA	124,953	141,367	157,554	173,152	188,353	202,141	216,871
Fairfax Water - Vienna PWD	13,734	13,827	13,902	13,938	13,985	14,028	14,074
Fairfax Water - Virginia American Alexandria	110,106	121,759	127,253	135,241	142,721	155,081	164,189
Fairfax Water - Virginia American Dale City	12,342	12,948	13,545	14,118	14,641	15,094	15,594
Fairfax Water Subtotal	990,342	1,065,699	1,132,488	1,191,325	1,252,735	1,312,089	1,372,814
Washington Aqueduct - Arlington County DES	212,623	219,288	234,127	244,649	256,722	264,003	274,479
Washington Aqueduct - DC Water	846,052	894,385	937,119	977,488	1,011,071	1,044,655	1,078,238
Washington Aqueduct - Arlington Fort Myer	4,246	4,246	4,247	4,248	4,248	5,053	5,322
Washington Aqueduct Subtotal	1,062,921	1,117,919	1,175,493	1,226,385	1,272,041	1,313,711	1,358,039
WSSC Water	801,802	846,196	884,997	913,028	942,700	970,923	1,000,113
COOP Supplier Subtotal	2,855,065	3,029,814	3,192,978	3,330,738	3,467,476	3,596,723	3,730,966
City of Rockville DPW	65,314	66,719	68,684	72,735	77,019	81,339	85,635
Fairfax Water - Loudoun Water	135,577	155,189	173,954	188,830	201,208	211,278	222,887
Other WMA Suppliers Subtotal	200,891	221,908	242,638	261,565	278,227	292,617	308,522
WMA Total	3,055,956	3,251,722	3,435,616	3,592,303	3,745,703	3,889,340	4,039,488

[1] 2050 values are linearly extrapolated from 2035, 2040, and 2045 values.

Table 3-16: Round 9.1 predicted demographic change between 2020 and 2050 by supplier.

Water Supplier	Additional Population (Percent)	Additional Employees (Percent)	Additional Households (Percent)
Fairfax Water (excluding Loudoun Water)	493,886 (28%)	382,472 (39%)	224,316 (35%)
Washington Aqueduct	380,481 (39%)	295,118 (28%)	143,985 (33%)
WSSC Water	253,770 (14%)	198,311 (25%)	118,256 (18%)
COOP Supplier Subtotal	1,128,137 (25%)	875,901 (31%)	486,557 (28%)
City of Rockville DPW	20,986 (39%)	20,321 (31%)	9,379 (45%)
Loudoun Water	49,060 (16%)	87,310 (64%)	20,543 (21%)
Other WMA Suppliers Subtotal	70,046 (20%)	107,631 (54%)	29,922 (25%)
WMA Total	1,198,183 (24%)	983,532 (32%)	516,479 (28%)

3.4.2 Unmetered Water Use Forecasts

Each supplier's average annual water demand forecast looks at total system water losses and calculates the total unmetered (or non-revenue) water as a percentage of the total water supplied. The purpose of the total unmetered water analysis is to resolve differences in reported total water supplied (the sum of produced and purchased water) and the water billed to customers. Forecasts of single family, multi-family, and employee billed amounts are increased by the unmetered water percentage to estimate the total water supplied for the demand forecast for each retail and wholesale customer. Analysis of the different components of system loss (e.g., apparent losses from unauthorized consumption, customer metering inaccuracies, and data handling errors, and real losses due to system leakage) is not part of this study. The estimates, therefore, vary from those reported in more detailed annual water audits submitted to the State environmental agencies.

The assumptions for the unmetered water percentage follow. First an average unmetered water use of the last ten years of historical data (with some shorter averaging periods) is assumed for forecast years 2020-2050 (Appendix A.2). A minimum water loss of 10% is assumed to be a conservative estimate that accounts for increased losses as infrastructure ages. This assumption is consistent with previous WMA demand studies and supports the MDE guidelines that indicate that well operated systems should not lose more than 10% of the total water. The minimum water loss of 10% is applied to the Fairfax Water retail area, Town of Herndon, Loudoun Water, and Vienna PWD because the average rate of historical unmetered use for these systems are estimated between 8% and 9%. Additionally, suppliers that had no unmetered water use data (Dulles International Airport, Fort Belvoir, Virginia American Alexandria, Virginia American Dale City, and Arlington Fort Myer) assume an unmetered use of 10%. Table 3-17 shows the rate used for each supplier.

No adjustments are made to accommodate expected reductions in water losses in the water distribution system. While some systems are taking a pro-active approach to reducing their water system losses (e.g., meter accuracy and replacement, customer billing systems, unauthorized consumption, leak detection and repair), these efforts take many years to compile the data to better quantify the sources of water loss and several more years to implement the programs designed to target the identified losses. Any measurable reductions in unaccounted-for water losses in the system will be received in subsequent data requests for total system water and billed water data and will, therefore, influence the average unmetered water uses assumed for the next iteration of the demand study.

Table 3-17: Unmetered water use assumption for each supplier.

Supplier/Wholesaler	Assumption	Data Collection Period Notes
Fairfax Water – Retail customers	10%	Increased from 2010-2018 average of 8%
Fairfax Water – Dulles International Airport	10%	No available data
Fairfax Water – Fort Belvoir	10%	No available data
Fairfax Water – Town of Herndon	10%	Increased from 2014-2018 average of 9% (2010-2013 were significantly different)
Fairfax Water – Loudoun Water	10%	Increased from 2010-2018 average of 9%
Fairfax Water – Prince William County Service Authority	10%	2014-2018 average (2010-2013 were estimates)
Fairfax Water – Vienna PWD	10%	Increased from 2015-2018 average of 9% (2010-2014 were estimates)
Fairfax Water – Virginia American Alexandria	10%	No available data
Fairfax Water – Virginia American Dale City	10%	No available data
Washington Aqueduct – Arlington County DES	12%	2010-2018 average
Washington Aqueduct – DC Water[1]	26%	2010-2018 average
Washington Aqueduct – Arlington Fort Myer	10%	No available data
WSSC Water[2]	18%	2010-2018 average
City of Rockville DPW[3]	14%	2010-2018 average

[1] FY15 Water Audits and Loss Reduction Plan presented in WSSC Commission Meeting (September 21, 2016) reported 25.3%.
[2] FY13- FY18 Water Audits and Loss Reduction Report ranged from 15.7% to 20.9%.
[3] FY13- FY18 Water Audits and Loss Reduction Report ranged from 9.5% to 18.15%.

3.5 Forecasting Uncertainties

Forecasts are inherently uncertain because of the difficulties in anticipating the societal, economic, and technological changes that will occur over the planning horizon. Some past ICPRB water supply studies provided an indication of uncertainty in annual demand forecasts by computing two sets of forecasts: for example, for a "likely" and a "high" demand future. At times, this was done by taking advantage of the range of values that were included in past MWCOG demographic forecasts. For example, in the MWCOG Round 6 series, "low", "likely", and "high" demographic forecasts were provided, and these were used in both ICPRB's 2000 study (Hagen and Steiner, 2000) and 2005 study (Kame'enui, *et al.*, 2005) to obtain "likely" and "high growth" water demand forecasts. Though no range of demographic forecasts were available in MWCOG Round 7.2, used for ICPRB's 2010 study (Ahmed *et al*., 2010), a high water demand scenario was devised, which included assumptions about potential growth in areas not considered in Round 7.2 and the possibility that no future reductions would occur in single family household unit use due to increases in outdoor watering.

In the current study, an effort is made to quantify uncertainty by estimating the potential range of errors for each of the five main categories of data used to compute the demand forecasts: demographic forecasts, unit use, dwelling unit ratios, changes in end-use efficiencies, and unmetered water use. Uncertainty estimates for each of these five categories are discussed below. Statistical error propagation techniques are then used to combine these individual uncertainties into estimates of the standard error for each of the sets of demand forecasts for the CO-OP supplier retail area served, Loudoun Water, Rockville, and for the wholesale customers.

3.5.1 Uncertainties in Demographic Forecasts

The MWCOG Cooperative Forecasting Program began in 1975, and the resulting sets of forecast data, spanning over 35 years, are available via the MWCOG website.[8] The earliest, Round 1, was published in 1976, and provides demographic data and forecasts for the years 1970 through 1995 for ten jurisdictions: the District of Columbia, Montgomery County, Prince George's County, Arlington County, Alexandria, Fairfax County, Fairfax City, Falls Church, Loudoun County, and Prince William County. The most recent, Round 9.1, was published in 2018, and includes forecasts for the years 2015 through 2045 for 29 jurisdictions, including counties in the outer suburbs, certain counties in the Baltimore area and the Fredericksburg area.

This study obtains estimates of the uncertainty in MWCOG demographic forecasts by comparing historical forecasts with later Census-based results. MWCOG summary tables provide forecasts by jurisdictions for number of households (HH) and number of employees (EMP) in the years 1980, 1990, 2000, and 2010. Forecast numbers are compared with actual numbers, which are derived from US Census data and are also available in MWCOG datasets. Eighteen jurisdictions had overlap between data for forecast and actual number of households and employees for the years considered. Selection of the years 1980, 1990, 2000, and 2010 is based on availability of both actual and forecast data, and on the fact that they are the subject of US Census surveys and thus provide more accurate counts than the intermediate years, 1985, 1995, 2005, and 2015.

The MWCOG forecast rounds used in the analysis are given in Table 3-18. For example, this table indicates that Round 1 provides a five-year forecast for 1980, and this forecast is compared with actual values for 1980 available in the Round 3 dataset. Comparisons of forecast versus actual results for the jurisdictions, by number of households and number of employees are shown in Figure 3-7 and Figure 3-8. These graphs show that forecast errors, as expected, increase with the length of the forecast period. The graphs also indicate that forecasts of number of households are more accurate than forecasts of number of employees.

The percent difference between the forecast and actual values are computed and compiled for each jurisdiction for which data were available. Results, given in Table 3-19 and Table 3-20, include sample size, mean percent error, and standard deviations of percent error. Out of the 18 jurisdictions considered in this study, only a subset have forecast data in a given forecast round that matched actual (Census) data in a subsequent round. The sample sizes appearing in Table 3-19 and Table 3-20 give the total number of data points available for the forecast period. For example, the sample size for the 20-year forecast period is given as 31, since it was based on 20-year forecasts for the year 2000 for eight jurisdictions from Round 2, 20-year forecasts for the year 2000 for eight jurisdictions from Round 3, and

[8] https://www.mwcog.org/documents/2018/10/17/cooperative-forecasts-employment-population-and-household-forecasts-by-transportation-analysis-zone-cooperative-forecast-demographics-housing-population/

20-year forecasts for the year 2010 for 15 jurisdictions from Round 5.1. Sample sizes necessarily diminish with forecast length, and the results for the 25-year and 30-year forecast periods are based on single MWCOG datasets, Round 4 and Round 3, respectively.

This study represents the uncertainty in the demographic forecasts of HH and EMP by the last columns of Table 3-19 and Table 3-20, regression estimate of standard deviation of percent error. These estimates are derived from linear least squares regression models of the second from the last column, computed standard deviation of percent error.

Table 3-18: MWCOG datasets used in error analysis.

MWCOG Round	**Publication Year**	**Forecast Range**	**Forecast Years Considered**			
			1980	**1990**	**2000**	**2010**
			Forecast Length, years			
Round 1[1]	1976	1970 - 1995	5	15		
Round 2[2]	1979	1970 - 2000		10	20	
Round 3[3]	1983	1980 - 2010	actual	10	20	30
Round 4[4]	1987	1985 - 2010		5	15	25
Round 5.1[5]	1994	1990 - 2020		actual	10	20
Round 5.3[6]	1996	1990 - 2020			5	15
Round 6a[7]	1998	1990 - 2020			5	15
Round 6.3[8]	2003	2000 - 2030				10
Round 7.0a[9]	2006	2000 - 2030			actual	5
Round 8.3[10]	2014	2010 - 2040				actual

[1]MWCOG, 1976.
[2]MWCOG, 1979.
[3]MWCOG, 1983.
[4]MWCOG, 1987.
[5]MWCOG, 1994.
[6]MWCOG, 1996.
[7]MWCOG, 1998.
[8]Farina and Goodwin, 2003a; 2003b.
[9]Farina and Goodwin, 2006a; 2006b.
[10]MWCOG, 2014.

Table 3-19: HH forecast percent error statistics from ICPRB analysis.

Forecast Period, years	Sample Size	Mean Percent Error	Computed Standard Deviation of Percent Error	Regression Estimate of Standard Deviation of Percent Error
5	58	0.9%	6.4%	8.0%
10	46	0.2%	9.5%	9.3%
15	52	-1.5%	13.4%	10.6%
20	31	-5.1%	12.9%	11.9%
25	14	-4.8%	10.1%	13.2%
30	12	-14.5%	15.3%	14.5%
35	NA	NA	NA	15.8%

Table 3-20: EMP forecast percent error statistics from ICPRB analysis.

Forecast Period, years	Sample Size	Mean Percent Error	Computed Standard Deviation of Percent Error	Regression Estimate of Standard Deviation of Percent Error
5	56	-1.5%	16.4%	18.8%
10	46	-6.0%	20.3%	21.3%
15	49	-3.2%	26.7%	23.7%
20	31	-6.8%	27.2%	26.2%
25	14	5.1%	33.0%	28.6%
30	12	-12.0%	25.7%	31.1%
35	NA	NA	NA	33.5%

3.5.2 Uncertainties in Unit Uses

The historical record of ICPRB's unit use values for most jurisdictions begins in the year 2010 or earlier and extends to 2018. Time series of unit use records are used to obtain estimated unit use values for the base year of 2018 and estimates of the uncertainties in future unit use projections. For each retail or wholesale service area listed in the first column of Table 3-21, a least squares regression line is calculated for unit use values for the years 2010 through 2018. Table 3-21 provides unit use values computed from 2018 billing data (2018 value), the regression line estimates of 2018 unit uses (2018 estimate) and the standard error of the estimate (SE). The regression line estimates of 2018 unit use are selected for use in the calculations of annual demands forecasts because they likely capture recent trends but should be less sensitive to yearly fluctuations which may occur due to variations in weather or other transient conditions. The SE estimates are the standard deviation of the 2018 unit use estimates, and are used in the uncertainty analysis for annual demand forecasts.

Table 3-21: 2018 unit use (gpd/unit) calculated from billing data and estimated from regression analysis.

	SFH			MFH			EMP		
Supplier	**2018 value**	**2018 estimate**	**SE**	**2018 value**	**2018 estimate**	**SE**	**2018 value**	**2018 estimate**	**SE**
Fairfax Water – Dulles International Airport	159.5	158.1	4.8	150.6	150.8	3.0	42.8	44.2	1.6
Fairfax Water – Fort Belvoir	159.5	158.1	4.8	150.6	150.8	3.0	28.5	27.3	4.1
Fairfax Water – Prince William County	179.7	179.8	5.9	139.2	140.9	3.5	41.4	40.7	4.7
Fairfax Water – retail customers	159.5	158.1	4.8	150.6	150.8	3.0	30.5	29.8	1.6
Fairfax Water – Town of Herndon	155.8	150.5	10.3	155.8	150.5	10.3	36.9	34.4	2.5
Fairfax Water – Vienna PWD	175.3	172.5	8.2	112.9	113.7	4.9	22.8	23.3	1.1
Fairfax Water – Virginia American Alexandria	159.5	158.1	4.8	150.6	150.8	3.0	22.9	23.5	3.7
Fairfax Water – Virginia American Dale City	159.5	158.1	4.8	150.6	150.8	3.0	50.0	54.8	10.7
Loudoun Water	184.6	192.7	8.8	130.0	132.0	4.5	46.4	40.8	4.3
Washington Aqueduct – Arlington Co. DES	130.6	132.3	2.3	75.2	76.6	1.3	40.5	41.1	1.2
Washington Aqueduct – Arlington – Fort Myer	130.6	132.3	2.3	75.2	76.6	1.3	68.2	63.2	10.8
Washington Aqueduct – DC Water	121.0	120.1	2.6	99.8	97.8	6.6	43.2	42.6	1.9
WSSC Water	142.5	150.6	8.6	138.1	134.6	6.9	41.6	43.6	2.4
City of Rockville	147.2	150.0	3.0	132.5	135.0	2.7	14.2	12.3	1.6

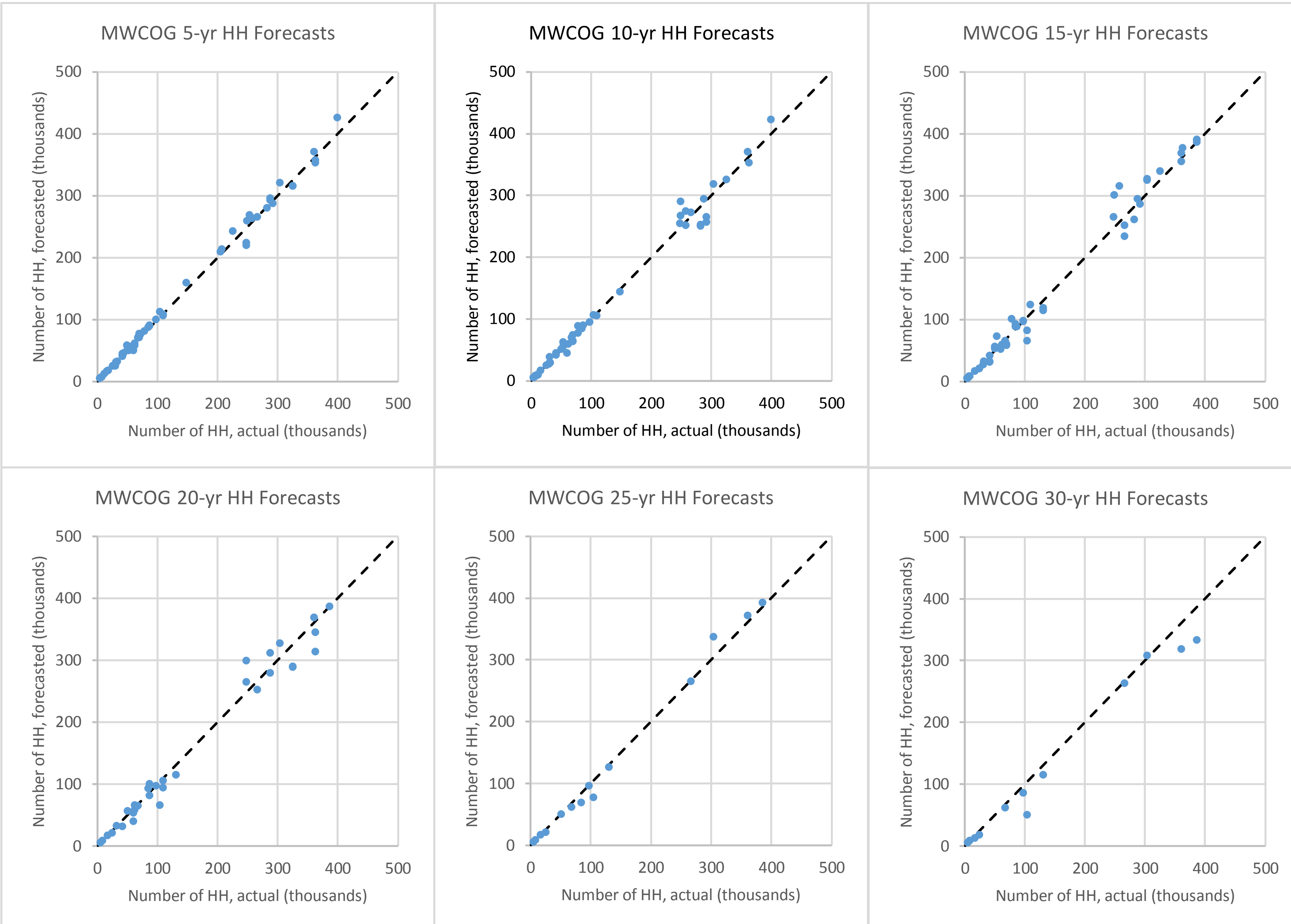

Figure 3-7: Comparison of number of households (HH) by jurisdiction - forecast and actual.

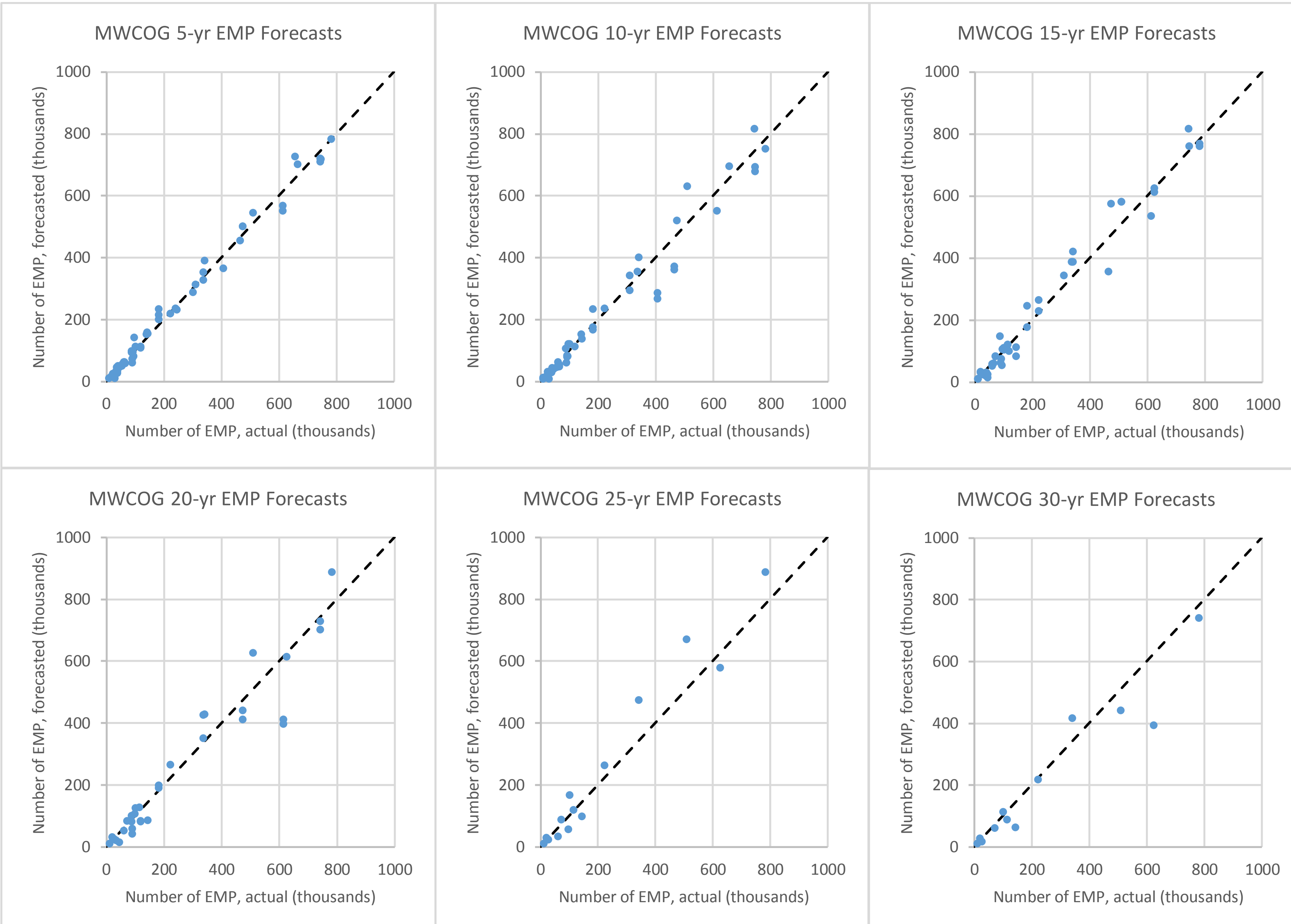

Figure 3-8: Comparison of number of employees (EMP) by jurisdiction - forecast and actual.

3.5.3 Uncertainties in Dwelling Unit Ratios

Dwelling unit ratios (DURs) represent the ratio of the number of single family households to the number of multi-family households in an area, as explained in Section 3.2.2.1. Errors in dwelling unit ratio forecasts are unavailable, but uncertainty estimates for dwelling unit ratios for recent years are available from the American Community Survey (ACS). In this study, the uncertainty in dwelling unit ratios were estimated to be the maximum of the ACS uncertainty estimates for the years 2010 through 2018. These are given in the third column of Table 3-22.

Table 3-22: Assumed uncertainties in dwelling unit ratio forecasts.

Supplier	Range of 2020 to 2050 DUR Forecasts	Assumed standard deviations of DUR Forecasts
Fairfax Water – Dulles International Airport	(2.32 to 1.29)	(0.05)
Fairfax Water – Fort Belvoir	(2.32 to 1.29)	(0.23)
Fairfax Water – Prince William County	2.97 to 1.87	0.23
Fairfax Water – Retail customers	2.32 to 1.29	0.05
Fairfax Water – Town of Herndon	1.95 to 0.66	0.34
Fairfax Water – Vienna PWD	11.05 to 9.52	3.48
Fairfax Water – Virginia American Alexandria	0.44 to 0.28	0.02
Fairfax Water – Virginia American Dale City	6.43 to 4.03	1.60
Fairfax Water – Falls Church portion of retail service area	1.12 to 0.46	0.23
Loudoun Water	3.72 to 2.22	0.26
Washington Aqueduct – Arlington County DES	0.50 to 0.36	0.02
Washington Aqueduct – Arlington – Fort Myer	(0.50 to 0.36)	(0.02)
Washington Aqueduct – DC Water	0.56 to 0.38	0.01
WSSC Water – Montgomery County	1.85 to 1.46	0.04
WSSC Water – Prince Georges County	2.42 to 1.94	0.04
City of Rockville	1.08 to 0.64	0.11

Note: Values in parenthesis are assumed, based on values from another supplier.

3.5.4 Uncertainties in End Use Efficiencies

The uncertainties in assumed end use efficiencies, used in the forecast of future unit use rates, are based on household (HH) and employee (EMP) results appearing in Table 3-23. The range of the uncertainty is assumed to be one half of the difference between the low and the high values in Table 3-10. Table 3-23 below contains the cumulative water use savings, measured from 2018, and the assumed range of uncertainty.

Table 3-23: Efficiency savings, cumulative from 2018 base year, and range of uncertainty (gpd/unit).

Year	HH	HH uncertainty	EMP	EMP uncertainty
2020	3.9	1.0	0.2	0.0
2025	10.7	3.6	0.8	0.1
2030	14.4	5.7	1.1	0.05
2035	16.5	7.3	1.4	0.05
2040	17.7	8.3	1.6	0.05
2045	18.4	8.8	1.8	0.05
2050	19.4	9.6	2.0	0.1

3.5.5 Uncertainties in Unmetered Water Use

Percent unmetered water is estimated as the mean of 2010 through 2018 values, if data are available, with the uncertainty taken to be the standard deviation of the available data. As discussed in Section 3.4.2, in cases where the mean of 2010 through 2018 values is less than 10%, the percent unmetered is assumed to be 10%. If no data are available, percent unmetered is assumed to be 10% and the uncertainty is assumed to be 5%.

3.5.6 Propagation of Errors

Standard methods are used to estimate the uncertainty, that is, the standard error of the estimate (SE), of the demand forecasts from the data used in the calculations. In this analysis, range of uncertainty differs depending on the data, as discussed above, and it is assumed that all individual data values are random variables from uncorrelated normal distributions. Then if a is the sum or difference of two variables, that is, $a = b + c$ or $a = b - c$, the uncertainly in a, Δa, is the square root of the sum of the squares of the variables, or equivalently,

$$(\Delta a)^2 = (\Delta b)^2 + (\Delta c)^2 \quad \textit{Equation 3-1}$$

To calculate the uncertainty of a product or ratio of two quantities, that is, if $a = b*c$ or $a = b/c$, the quantities are first converted to fractions. Then the uncertainty in $\Delta a/a$ can be computed using the relationship

$$(\Delta a/a)^2 = (\Delta b/b)^2 + (\Delta c/c)^2 \quad \textit{Equation 3-2}$$

The equation used to calculate the uncertainty of the demand forecast for an individual jurisdiction was derived based on Equation 3-1 and Equation 3-2. Estimated uncertainties for total forecasted WMA demands are given in Table 3-24. Uncertainties for the demand forecasts of the CO-OP supplier retail area served, Loudoun Water, Rockville, and for the wholesale customers are provided in Appendix A.3.

3.6 Annual Demand Forecast Results

The forecasts of the WMA's average annual water demand appear in Table 3-24. The forecasts are derived from current and forecast numbers of single family households, multi-family households, and employees; historical produced and billed water use; current and forecast service areas; possible changes in water use behavior; and estimates of unmetered water use. The forecasts in this table are given by retail and wholesale customer, with subtotals provided for each CO-OP supplier retail area served, Loudoun Water, Rockville, and for the wholesale customers. A detailed breakdown of each forecast is available in Appendix A.3.

Table 3-25 provides forecasts of WMA water production. Water “demand” and “production” are closely related, and in this study, they are treated as equivalent in cases in which only one supplier provides water to a given service area. However, demand and production are distinct in cases in which two or more suppliers provide water to a service area, as is evident from a comparison of Table 3-24 and Table 3-25. For example, demand and production differ for Fairfax Water’s retail service area, because this area includes the City of Falls Church, which uses water that Fairfax Water purchases from Washington Aqueduct. Similarly, Loudoun Water’s demand differs from its production because a portion of the water it distributes to its customers is purchased from Fairfax Water.

An estimate of the uncertainty in the forecast of total WMA demand is given at the end of Table 3-24, as both a percent and an absolute value. These uncertainties range from 8.2% in 2020 to 10.4% in 2050. The uncertainties are used to compute a range of uncertainty centered around the calculated total WMA demand forecast, denoted in Table 3-24 as the “medium” forecast. The “low” forecast is the difference between the medium forecast and the uncertainty, and the “high” forecast is the sum of the medium forecast and the uncertainty. The low, medium, and high forecasts are used later in this study as three planning scenarios represented a plausible range of future water demands.

Results reported in Table 3-24 show that the total WMA suppliers’ average annual water use is predicted to be approximately 457 MGD in 2020 and to reach 528 MGD by 2050. Over this period, Fairfax Water’s demand is forecast to increase by 35 MGD, Washington Aqueduct’s by 18 MGD, and WSSC Water’s by 13 MGD.

This study’s forecast for total WMA demand, along with its range of uncertainty, is compared with forecasts from past studies in Figure 3-9. Also included in this graph is the change over time of actual WMA demand and of actual and forecasted population. Past over-prediction of water demand is illustrated by this figure, indicating that systematic errors, as well as statistical errors, are influencing results. The systematic errors, not addressed in this study, are clearly at least in part associated with the inability of water planners to predict the technological changes which have reduced per household and per employee water use.

Table 3-24: Forecast of average annual water demand[1] by supplier service area, 2020-2050 (MGD).

Supplier/Wholesale Customer	2018[2]	2018 Est.[3]	2020	2025	2030	2035	2040	2045	2050
Fairfax Water									
Retail customers	97.4	97.0	95.8	97.5	101.1	104.6	108.4	112.0	115.7
Dulles International Airport	0.8	0.8	0.8	0.9	1.0	1.0	1.1	1.1	1.1
Fort Belvoir	1.8	1.7	1.7	1.9	2.0	2.0	2.0	2.0	2.0
Town of Herndon	2.3	2.2	2.2	2.4	2.5	2.6	2.6	2.7	2.7
Prince William County Service Authority	23.1	22.1	22.5	24.0	25.4	26.8	28.1	29.2	30.4
Vienna PWD	2.1	2.1	2.0	2.0	1.9	1.9	1.9	2.0	2.0
Virginia American Alexandria	15.4	15.4	15.4	15.8	16.1	16.6	17.4	19.7	20.9
Virginia American Dale City	4.7	4.7	4.7	4.7	4.7	4.8	4.9	4.9	5.0
Subtotal (excluding Loudoun Water)	147.3	146.0	145.2	149.1	154.7	160.3	166.3	173.5	179.8
Washington Aqueduct									
Arlington County DES	21.5	21.6	21.5	21.3	21.8	22.3	23.0	23.6	24.3
DC Water	95.1	93.1	93.3	95.0	97.8	100.6	103.3	106.2	108.8
Arlington Fort Myer	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.4	0.4
Subtotal (excluding sales to Fairfax Water)	117.0	115.0	115.1	116.6	119.9	123.3	126.6	130.2	133.5
WSSC Water									
Retail customers	158.7	160.2	159.8	159.4	161.9	164.3	167.1	170	172.7
Charles County[4]	4.4	4.4	1.8	1.8	1.8	1.8	1.8	1.8	1.8
Howard County[5]			5.0	5.0	5.0	5.0	5.0	5.0	5.0
Subtotal	163.1	164.6	166.6	166.2	168.7	171.1	173.9	176.8	179.5
CO-OP suppliers total (excluding Loudoun Water)	427.4	425.6	426.9	431.9	443.3	454.7	466.8	480.5	492.8
Other WMA suppliers									
City of Rockville DPW	4.5	4.4	4.3	4.4	4.5	4.7	4.9	5.1	5.4
Loudoun Water	23.3	24.4	25.4	26.8	27.9	28.7	29.2	29.6	30.1
Subtotal	27.8	28.7	29.7	31.2	32.4	33.4	34.2	34.7	35.4
WMA suppliers total									
Medium demand forecast (sum of subtotals)	455.2	454.3	456.6	463.1	475.7	488.1	501.0	515.2	528.2
Uncertainty, MGD			±38.7	±40.7	±43.2	±45.8	±48.5	±51.6	±54.7
Uncertainty, percent			±8.5	±8.8	±9.1	±9.4	±9.7	±10.0	±10.4
Low demand forecast (Med. – uncertainty)			417.9	422.4	432.5	442.3	452.5	463.6	473.5
High demand forecast (Med. + uncertainty)			495.3	503.8	518.9	533.9	549.5	566.8	582.9

[1]Demand is water distributed, including unmetered water.
[2]Actual value from supplier data.
[3]2018 value estimated by the same methods used in the forecasts.
[4]Charles County has requested an addition allocation of 5 MGD, but no agreement exists at the time of this study.
[5]Howard County wholesales may increase to 10 MGD by 2030, but no agreement exists at the time of this study.

Table 3-25: Forecast of average annual water production, by supplier customers, 2020-2050 (MGD).

Supplier/wholesale customer	2018[1]	2018 Est.[2]	2020	2025	2030	2035	2040	2045	2050
Fairfax Water									
Retail customers	82.2	83.5	82.2	83.0	86.0	88.7	91.7	94.6	97.5
Dulles International Airport	0.8	0.8	0.8	0.9	1.0	1.0	1.1	1.1	1.1
Fort Belvoir	1.8	1.7	1.7	1.9	2.0	2.0	2.0	2.0	2.0
Town of Herndon	2.3	2.2	2.2	2.4	2.5	2.6	2.6	2.7	2.7
Prince William County Service Authority	23.1	22.1	22.5	24.0	25.4	26.8	28.1	29.2	30.4
Vienna PWD	2.1	2.1	2.0	2.0	1.9	1.9	1.9	2.0	2.0
Virginia American Alexandria	15.4	15.4	15.4	15.8	16.1	16.6	17.4	19.7	20.9
Virginia American Dale City	4.7	4.7	4.7	4.7	4.7	4.8	4.9	4.9	5.0
Loudoun Water Purchased	18.9	19.9	13.4	13.8	13.9	13.7	13.2	12.6	13.1
Subtotal	151.1	152.4	144.9	148.5	153.5	158.1	162.8	168.7	174.7
Washington Aqueduct									
Arlington County DES	21.5	21.6	21.5	21.3	21.8	22.33	23.0	23.6	24.3
DC Water	95.1	93.1	93.3	95.0	97.8	100.6	103.3	106.2	108.8
Arlington Fort Myer	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.4	0.4
Fairfax Water (Falls Church retail sale)	15.1	13.5	13.6	14.5	15.1	15.9	16.7	17.4	18.1
Subtotal	132.0	128.5	128.7	131.0	135.0	139.1	143.3	147.6	151.6
WSSC Water									
Retail customers	158.7	160.2	159.8	159.4	161.9	164.3	167.1	170.0	172.7
Charles County[3]	4.4	4.4	1.8	1.8	1.8	1.8	1.8	1.8	1.8
Howard County[4]			5.0	5.0	5.0	5.0	5.0	5.0	5.0
Subtotal	163.1	164.6	166.6	166.2	168.7	171.1	173.9	176.8	179.5
CO-OP suppliers total	446.2	445.5	440.2	445.7	457.2	468.3	480	493.1	505.8
Other WMA suppliers									
City of Rockville DPW	4.5	4.4	4.3	4.4	4.5	4.7	4.9	5.1	5.4
Loudoun Water[5]	4.4	4.4	12.0	13.0	14.0	15.0	16.0	17.0	17.0
Subtotal	8.9	8.8	16.3	17.4	18.5	19.7	20.9	22.1	22.4
WMA suppliers total	455.1	454.3	456.5	463.1	475.7	488	500.9	515.2	528.2

[1]Actual value from supplier data.
[2]2018 value estimated by the same methods used in the forecasts.
[3]Charles County has requested an addition allocation of 5 MGD, but no agreement exists at the time of this study.
[4]Howard County wholesales may increase to 10 MGD by 2030, but no agreement exists at the time of this study.
[5]Using Loudoun Water Trap Rock production forecasts for 2020-2050 (P. Kenel, private communication, April 3, 2020).

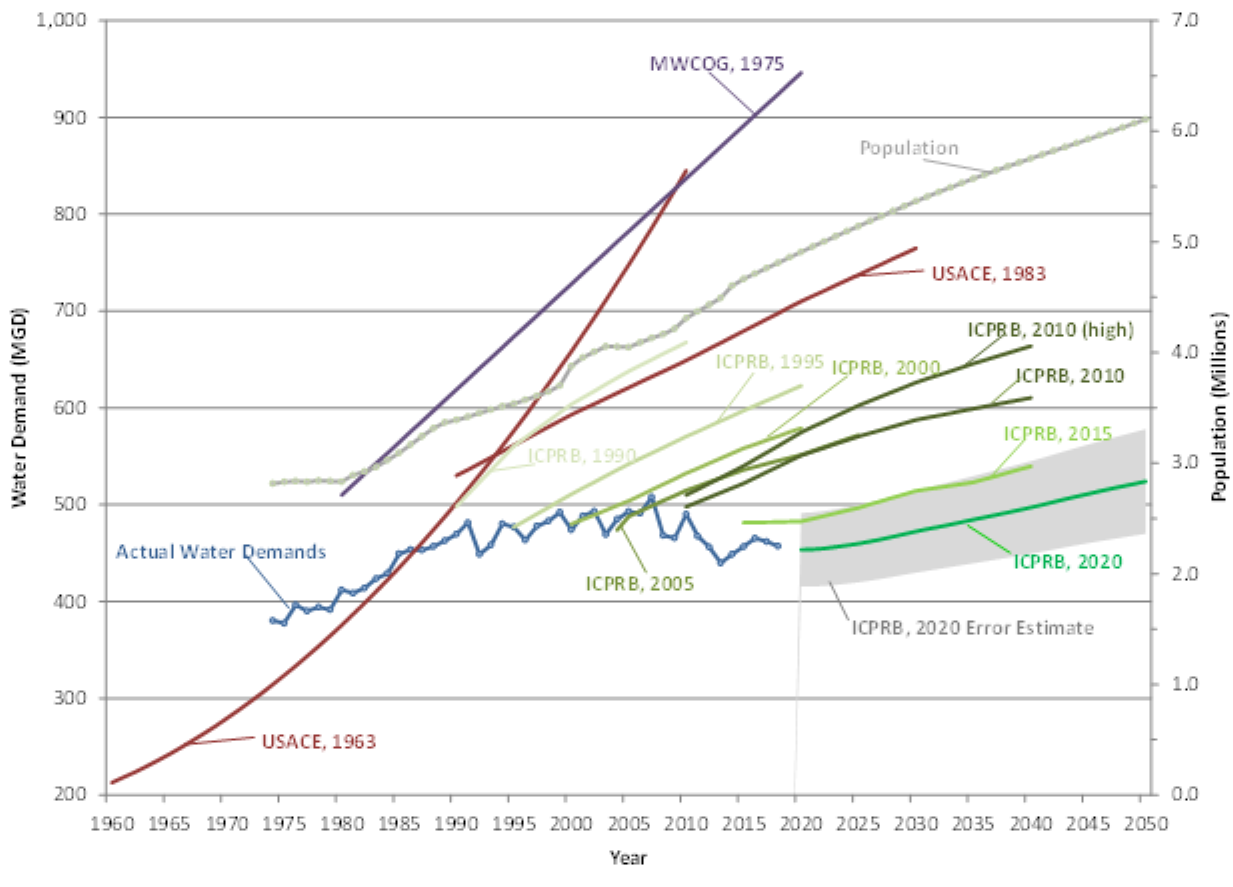

Figure 3-9: Comparison of this study's forecast of WMA total demand with forecasts from past studies (Rockville not included).

3.7 Independent Forecast Comparison

The annual demand forecasts presented in Chapter 3 follow a system-wide methodology for projecting future water demands for the aggregated WMA region. While some suppliers included in this study create independent demand forecasts for multiple purposes (e.g., infrastructure planning, finance budgeting, or supply planning), they use varying data sources and methodologies that are not necessarily comparable with those of other WMA suppliers. Appendix A.3.5 explores some key differences between the annual demand forecasts presented in Section 3.6. and the annual demand forecasts created by: (1) the WSSC Planning Group (Carpio, 2015) for the Montgomery County 2018-2027 Comprehensive Water Supply and Sewerage System Plan (MCDEP, 2018) and the Prince George's County 2018 Water & Sewer Plan (PGDPIE, 2019); and (2) Loudoun Water for their Water Distribution System Master Plan (Hazen and Sawyer, 2018a; 2018b). This comparison of individual water supplier and ICPRB forecasts illuminates the differences in methodologies, the most significant being ICPRB's use of a model to predict future reductions in per household and employee use due to increasing use of water saving fixtures and appliances (Section 3.3.2) and ICPRB's use of MWCOG Round 9.1 demographic forecasts. Other differences include the use by suppliers of TAZ level billing data for all retail and wholesale customers in the WMA, which is not available system-wide and thus not used in ICPRB forecasts. Finally, the unit use estimates for this study assume a linear trend in the data. In contrast, many of the individual suppliers base their unit use rates on specific years often selected to provide conservative assumptions for planning purposes.

4 MODELING DAILY VARIATIONS IN WATER DEMAND

4.1 INTRODUCTION

Water use in the WMA varies with season, day of the week, and hour of the day. In the summer and early fall, demand on any given day also depends on weather conditions, since people are more likely to water lawns and landscapes on hot, dry days. High summer demands often coincide with periods of low flow in the Potomac River, which typically occurs in September. To assess whether the current WMA water supply system will be able to meet future demands, seasonal and daily variations in demands are considered and combined with average annual demand forecasts presented in Chapter 3.

CO-OP's planning model, PRRISM, incorporates water demand models which are used to simulate the daily withdrawals of each of the three CO-OP suppliers and of Loudoun Water. The models add daily variation to the annual demand forecasts described in Chapter 3. These daily demand models are developed using daily water production data for the years 2005-2018, provided by the four suppliers. In PRRISM, daily water demands are a function of:

- simulation year,
- month,
- season,
- weather conditions,
- day of the week, and
- a daily error term based on an autoregressive integrated moving average (ARIMA) process.

PRRISM simulates monthly variations by applying empirically-derived monthly "production factors" to the annual demand forecasts to obtain monthly demand forecasts. Multiple least squares regression models are used to add variation due to weather conditions and day of the week. The sum of demand forecasts for the four suppliers is then further enhanced using an autoregressive integrated moving average (ARIMA) model, which adds information to the forecast not captured by the regression model.

This chapter describes the structure of the daily demand simulation models and the derivation from historical data of the model parameters used in PRRISM. The preparation of the raw data for the multiple regression and the ARIMA models is also discussed. Important features of the data preparation include the choice of predictor variables (independent variables), collation of data, preliminary analysis, detrending, and finally fitting the regression models for each supplier and season.

4.2 DATA

The models used to simulate daily variations of WMA water demand are developed from the following data:

Daily production (MGD) records of water pumped from the treatment facilities of the three CO-OP suppliers and daily records of Loudoun Water's total water use.[9] These data sets are used instead of billing data, which are relied upon for the average annual demand forecasts discussed in Chapter 3, because billing data is only available on a monthly, quarterly, or, in some cases, annual basis. Appendix A.2 summarizes the production data as it was provided by each of the suppliers.

National Weather Service data including daily maximum temperature (degrees Fahrenheit, ^{o}F), daily precipitation (inches), and number of consecutive days with precipitation less than 0.15 inches. These data sets came from records obtained from the National Climatic Data Center for Washington Reagan Airport (USW00013743), College Park (USC00181995), Frederick Police Barracks (USC00183348), Laurel 3 W (USC00185111), and Vienna (USC00448737).[10] To represent the nonlinear response of demands to climate: (1) temperature is split so that different regression coefficients can be applied to temperatures greater than and less than 85 ^{o}F. For temperatures lagged by more than one day, no partitioning was used; (2) Precipitation is capped at 0.2 inches for WSSC Water, and 0.3 inches for Washington Aqueduct, Fairfax Water, and Loudoun Water.

In addition, weekly and seasonal variations in user behavior are considered. Weekly variation in use is represented by day of the week, a variable in the multiple regression models. Instead of having variables represent seasonal influences, the multiple regression equations are separated into three independent analyses for spring, summer, and fall. Other social influences on water use are removed by detrending the raw data as described in Section 4.3.

The daily demand simulation models developed for the four suppliers are based on data for the period of January 1, 2005, through December 31, 2018. The 2005 beginning year is significant because it marks a distinct change in seasonal variation in the Loudoun Water data. This start year also allows the longest period of record to estimate Fairfax Water demands without the Loudoun Water portion. The year 2018 was the most recent full year of data available at the time of the analysis.

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[9] Loudoun Water total water is reported as consumption data separated out by entry points into their system (D. Geldert, personal communication, December 18, 2019). They purchase water from Fairfax Water (prior to January 2014, they also purchased water from the City of Fairfax, which was operated as a city facility before becoming a Fairfax Water retail customer). They produce water from Goose Greek WTF (between May 2014 and 2018, now for emergency use only), and from their main Trap Rock WTF (began operating in 2018). They have an emergency connection with Leesburg, but it was not used during the 2005-2018 period of record.

[10] Fairfax Water and Loudoun Water precipitation is a composite of Vienna, Reagan, College Park, Laurel, and Frederick Police Barracks. WSSC Water precipitation is a composite of College Park, Laurel, Frederick Police Barracks, and Reagan. Washington Aqueduct precipitation is a composite of Reagan, College Park, Laurel, and Frederick Police Barracks. The same temperature is used for all three locations and is based on a composite of Reagan, College Park, and Frederick Police Barracks. A composite time series is required to account for missing data. The priority of the data is based on the order in which it is listed above.

4.3 Removing the Long-Term Time Trends

Long-term time trends are evident in the historical production data of all four suppliers. These trends are likely due to a combination of factors, including growth of the user populations, decreases in flow rates of plumbing fixtures and household appliances, and changes in economic conditions. These factors (except for economic conditions) are included in the forecast of average annual water use, as described in Chapter 3. Therefore, these time trends are removed from the production data prior to the development of multiple regression equations to predict daily variations of demand from weather conditions and weekly and seasonal use patterns. This detrending procedure helps ensure stationarity in the mean of the data. Detrending is done by subtracting a time trend from the production data to obtain a set of residuals that are then added back to the long-term stationary mean (explained later in this section). In this way, the influences on demand that are not explicitly accounted for in the multiple regression analyses (see Section 4.5) are removed.

The detrending procedure follows the method used by Steiner (1984), Kame'enui *et al.* (2005), and Ahmed *et al.* (2010, 2015). A linear model is used for the time trends as represented by Equation 4-1,

$$Y(x) = mx + b$$ *Equation 4-1*

where Y is production in MGD, x is the time index of the corresponding production in days, m is the slope coefficient, and b is the intercept. The graphs of production data in Figure 4-1 and Figure 4-2 show relatively constant trends in each water supplier's production data. In Figure 4-2, Loudoun Water total use includes water purchased from Fairfax Water and water produced by the Trap Rock WTF. In Ahmed *et al.* (2015) a linear-quadratic time trend was used to account for the potential decrease in water consumption rates due to the onset of the Great Recession in 2008. Over the time scale of the current study, a review of the data indicates that the linear model is sufficient.

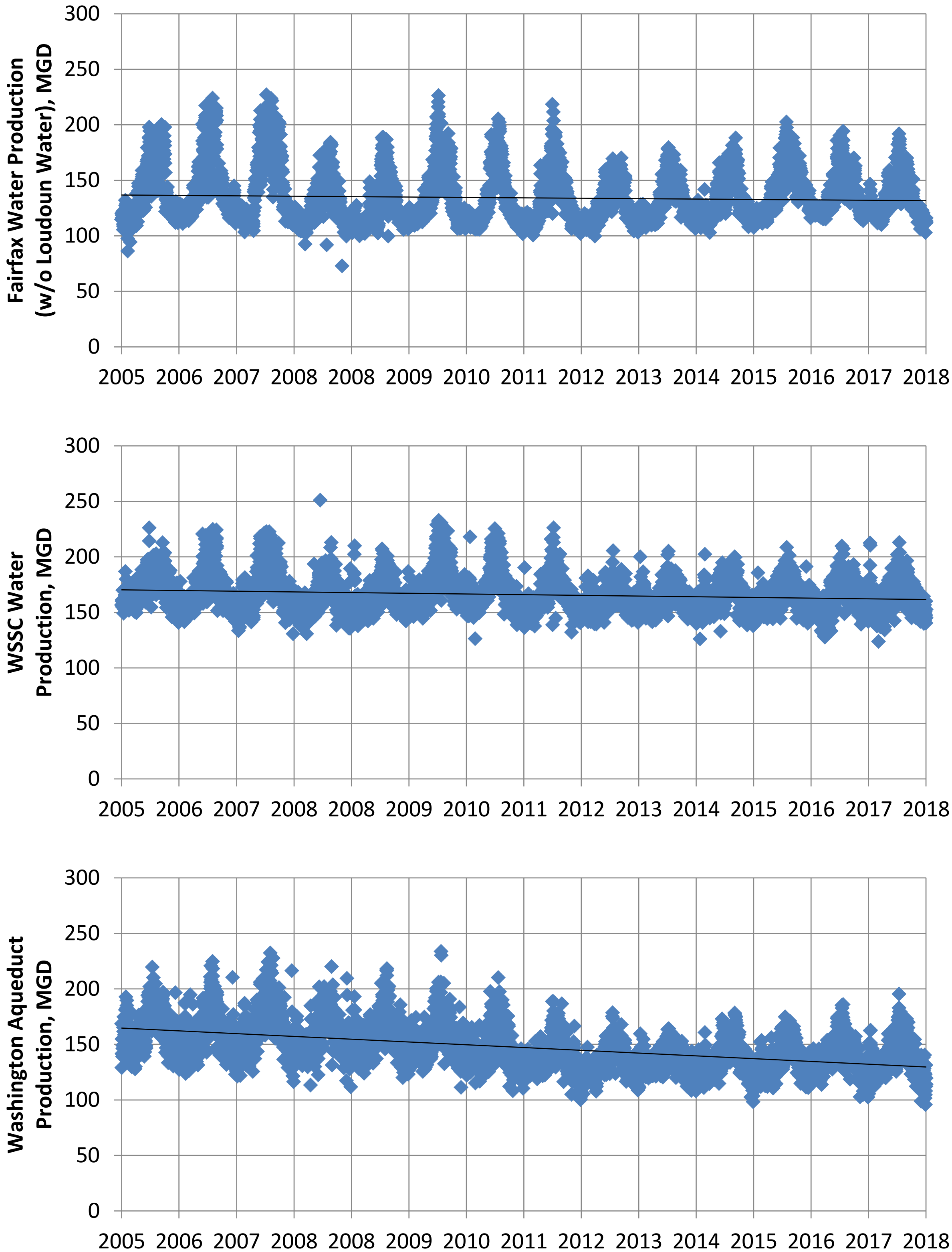

Figure 4-1: CO-OP supplier production data fitted to a linear model (black line).

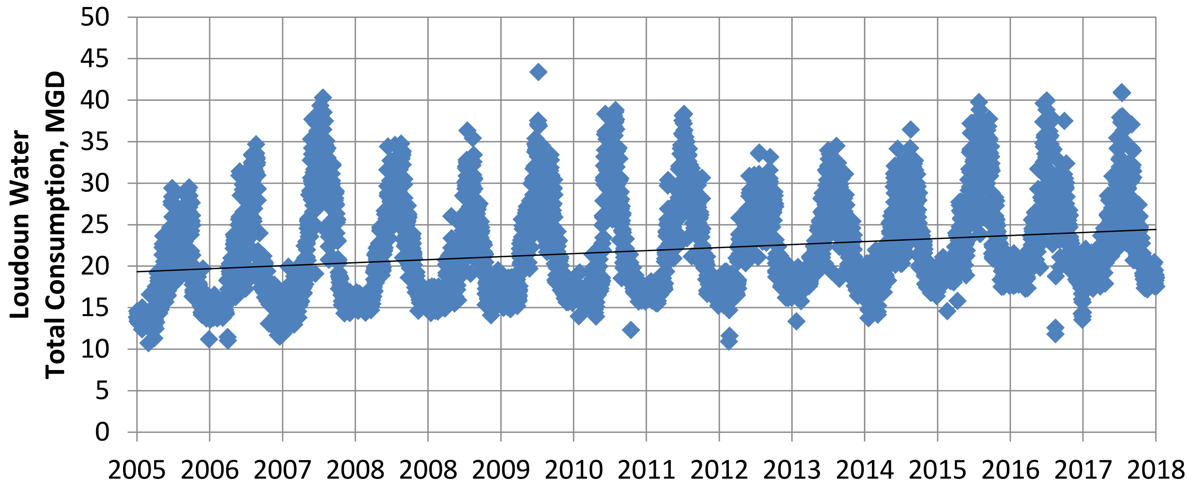

Figure 4-2: Loudoun Water total consumption data (blue points) fitted to a linear model (black line).

Table 4-1 reports statistics for the linear models for the long-term time trends. The near zero coefficients of determination (R^2) and similarly valued standard error of estimate (SE) and standard deviation (SD) statistics show that the linear models are not significantly different from their respective mean production values ($\bar{Y}$) for the years 2005 through 2018. However, all slope coefficients, *m*, and intercepts, *b*, were significant (P-values <= 0.01). Based on a positive slope coefficient, *m*, Loudoun Water shows some increase in total consumption. Based on negative slope coefficients, *m*, Fairfax Water (w/o Loudoun Water), WSSC Water and Washington Aqueduct show slight decreases in production, although Fairfax Water (w/o Loudoun Water) and WSSC Water production remains relatively constant in comparison to Washington Aqueduct.

Table 4-1: Coefficients and goodness-of-fit statistics for the linear model for long-term trend in production for Equation (4-1).

Statistic	**Fairfax Water (w/o Loudoun Water)**	**WSSC Water**	**Washington Aqueduct**	**Loudoun Water[1]**
Intercept, *b*	136.8	170.3	164.7	19.3
Slope, *m*	-0.001	-0.002	-0.007	0.001
Coefficient of Determination, R^2	0.004	0.03	0.3	0.07
Standard Error, SE	23.3	15.9	17.5	5.6
Standard Deviation, SD	23.4	16.1	20.2	5.7
Mean, $\bar{Y}$ (2005-2018)	134.2	165.9	147.2	21.9

[1] Loudoun Water data is total consumption and not total production.

The last point on the long-term trend line, *x'*, is the long-term stationary mean, $\hat{Y}(x')$, to which all the residuals are added to form the trended time series (see Figure 4-1 and Figure 4-2). The result is a demand series that represents current conditions from which forecasts can be made and from which model parameters can be estimated. The point on the regression line corresponding to the most recent observation can be represented by Equation 4-2,

$$\hat{Y}(x') = mx' + b$$ *Equation 4-2*

where *x′* is the time index of the most recent observation, which is 5113 and corresponds to December 31, 2018. Table 4-2 shows that the linear formula in Equation 4-2 produces a long-term stationary mean that is close to the 2018 mean annual production from the data, except in the case of Washington Aqueduct.

Table 4-2: Comparison of the 2015 and 2020 ICPRB studies' long-term stationary means (MGD).

Supplier	2020 Linear $\hat{Y}(x')$ using 2005-2018	2018 Mean $\bar{Y}$ Production from data
Fairfax Water (w/o Loudoun Water)	131.7	132.6
WSSC Water	161.6	163.1
Washington Aqueduct	129.7	138.2
Loudoun Water	24.4	23.3

4.4 Monthly Mean Production

Daily variation in demand was chosen as the criterion variable for the multiple regression analyses. This variable was computed from the detrended production data by using monthly production factors and the long-term stationary means. Definitions describing how this was done follow:

Monthly production factors are the ratios of average monthly production to average annual production, where the averaging period is 2005 through 2018. These are used to disaggregate annual production into monthly production. Values are provided in Table 4-3.

Long-term monthly means are the product of monthly production factors and the long-term stationary means from Table 4-2. Values are provided in Table 4-3.

Daily variation in demand is the residual difference between the detrended daily production data and the long-term monthly means. The two time series are compared in Figure 4-3 and Figure 4-4.

Using daily variation as the criterion variable enables simulations of potential daily differences from future monthly productions. When the daily variation estimates are added back to the monthly disaggregation of the annual production forecast the result is the daily production forecast.

Table 4-3: Production factors and monthly means by supplier for years 2005-2018.

	Average Monthly Production Factors				Long-term Monthly Means, MGD			
Month	**Fairfax Water (w/o Loudoun Water)**	**WSSC Water**	**Washington Aqueduct**	**Loudoun Water**	**Fairfax Water (w/o Loudoun Water)**	**WSSC Water**	**Washington Aqueduct**	**Loudoun Water**
January	0.88	0.95	0.94	0.77	115.6	154.2	122.4	18.9
February	0.85	0.94	0.95	0.78	112.3	152.3	123. 7	19.0
March	0.86	0.93	0.93	0.79	112.7	150.1	120.4	19.3
April	0.93	0.95	0.95	0.92	122.1	154.1	123.8	22.6
May	1.02	1.01	0.99	1.05	134.9	163.0	128.4	25.6
June	1.15	1.08	1.08	1.26	150.9	173.8	140.3	30.9
July	1.23	1.12	1.15	1.36	161.4	180.5	148.7	33.2
August	1.20	1.10	1.12	1.31	158.1	177.9	145.5	32.0
September	1.13	1.06	1.07	1.18	148.4	170.9	138.3	28.9
October	0.99	0.98	0.98	0.96	130.9	158.8	126.9	23.4
November	0.89	0.94	0.93	0.82	117.2	152.2	120.1	20.1
December	0.87	0.93	0.90	0.78	114.4	150.4	117.1	19.0
Annual					131.7	161.6	129.7	24.4

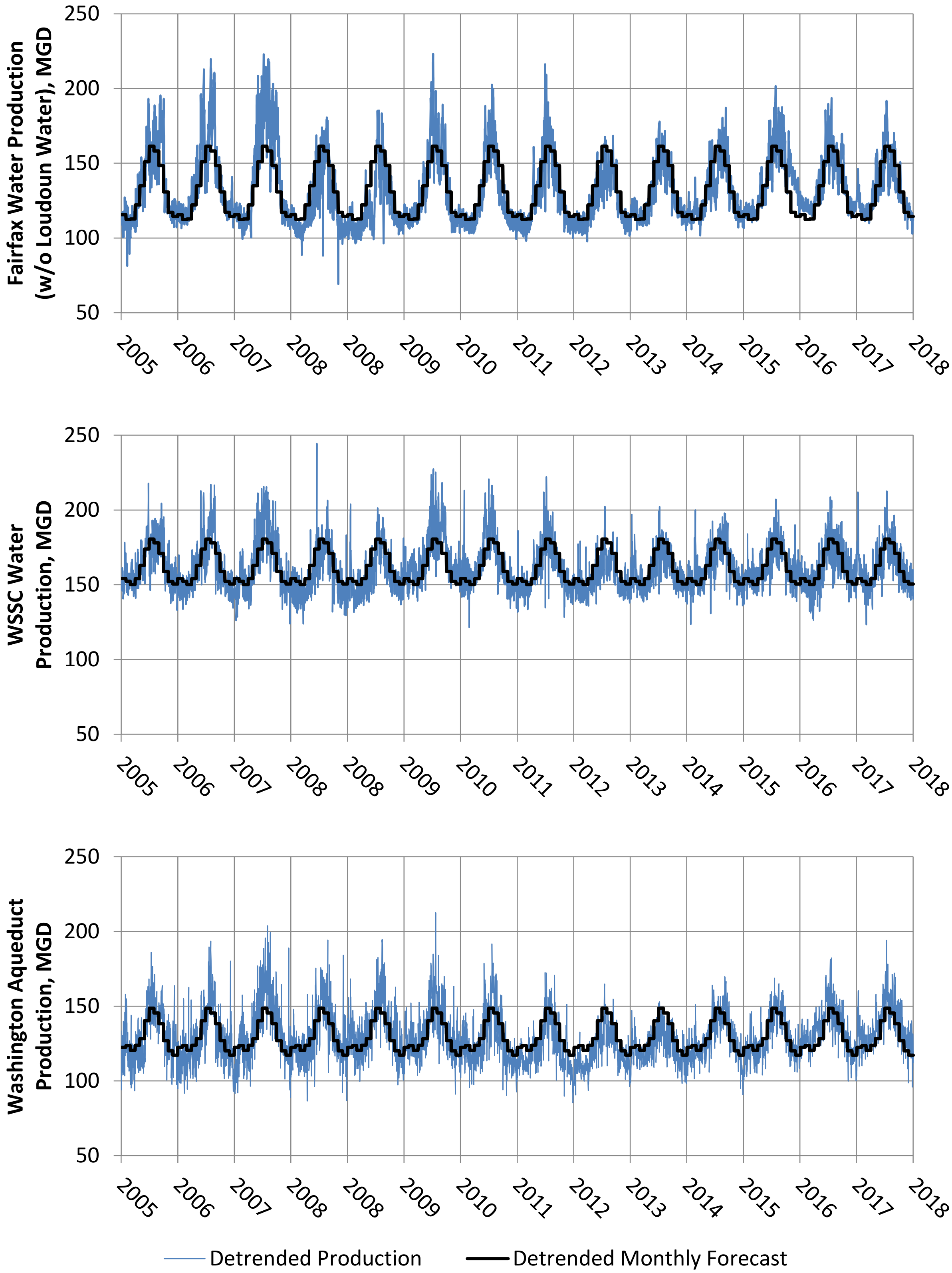

Figure 4-3: CO-OP supplier daily production data, detrended and compared to the monthly disaggregation of the long-term stationary mean.

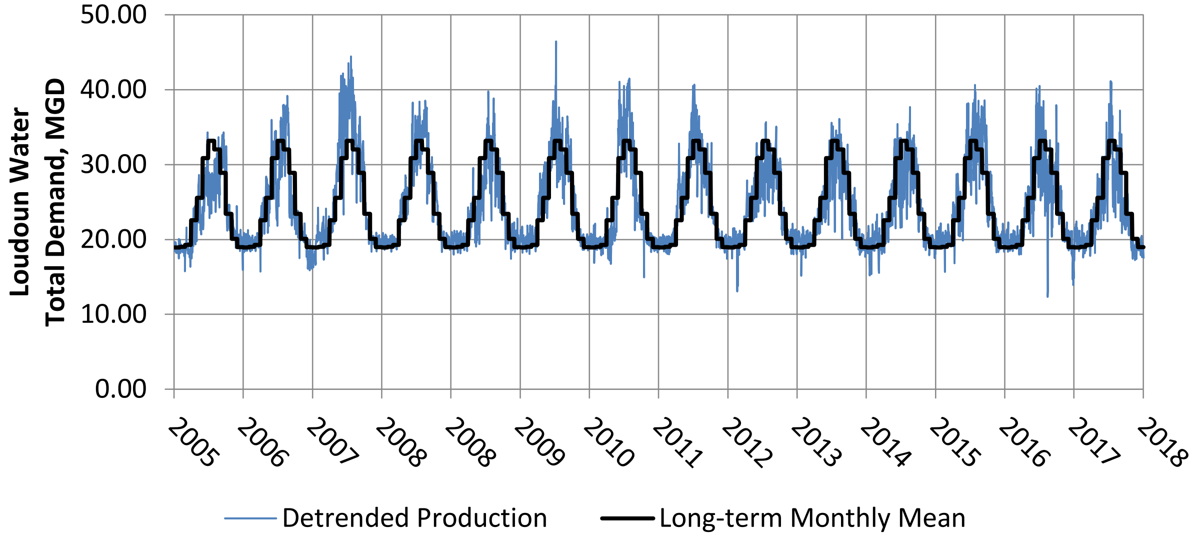

Figure 4-4: Loudoun Water daily total demand, detrended and compared to the monthly disaggregation of the long-term stationary mean.

4.5 Regression Models

Seasonal multiple least squares regression analyses for daily variation explain the differences seen between daily demand and monthly average conditions. A generic form of a regression equation is as follows:

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

where t is a time index representing the day of the time series, the criterion variable Y_t is the predicted daily variation in demand on day t, and the k predictor variables are $x_{1,t}, \ldots, x_{k,t}$. 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.

The dependent variable Y is taken as the departure of detrended daily demand from detrended monthly average conditions. Variables examined as explanatory variables in the regression for the WMA water suppliers include temperature, both forecast and lagged by one through five days, precipitation, both forecast and lagged by one through five days, day of week (Sunday, Monday, Tuesday…etc.), and the number of days in a row without significant rainfall (defined as less than 0.15 inches).

The data are evaluated for non-linearity in the response of demand to the independent variables for all water suppliers. Plots of demand versus forecast temperature, temperature, and temperature lagged one day show that demand has a non-linear response to temperature, with a breakpoint occurring at 85 ^{o}F. Demand rises at a slower rate from 30 ^{o}F through 85 ^{o}F than it does from 85 ^{o}F and higher. This non-linear response is stronger during the spring and fall months compared to the summer months, however, the response is present for all three seasons. For temperatures lagged more than one day, there is almost no non-linear response between demand and temperature. Therefore, to model this non-linear behavior, forecast temperature, temperature, and temperature lagged one day are broken into piece-wise linear segments at the 85 ^{o}F breakpoint, with different regression coefficients applied to temperatures greater than and less than 85 ^{o}F.

An evaluation of variance relative to precipitation for forecast precipitation, current day's precipitation, precipitation lagged by one day, and precipitation lagged by two and four days illustrate that demand is a non-linear function of precipitation, with a breakpoint ranging from 0.2 inches (WSSC Water) to 0.3 inches (Fairfax Water, Washington Aqueduct). The regression model inputs are modified to reflect this non-linear trend by assigning any precipitation greater than 0.2 inches a value of 0.2 inches for WSSC Water, and by assigning any precipitation greater than 0.3 inches a value of 0.3 inches for Fairfax Water and Washington Aqueduct. The same nonlinear responses assumed in Fairfax Water inputs are assumed for Loudoun Water.

Finally, an evaluation of the number of days in a row without significant precipitation with demand shows a similar non-linear response for all four WMA suppliers. Demand increases linearly for periods of one to twelve days and does not increase for days greater than twelve. This suggests after nearly two weeks without rain, water demand reaches an equilibrium point without additional increase in demand for further days without rainfall. To model this behavior, when the number of days in a row without significant precipitation is greater than twelve, it is assigned a value of twelve as inputs to the regression model.

Backward stepwise regression methods are used to calibrate Equation 4-3. Predictor variables are 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 set of seasonal regression models include a version of Equation 4-3 that simulates spring (March, April, and May), summer (June, July, and August), and fall (September, October, November) daily water demand. A regression equation was attempted but a meaningful relationship could not be found for the winter season. Table 4-4, Table 4-5, and Table 4-6 summarize the different coefficients used in Equation 4-3 for the respective spring, summer, and fall seasons for this study. Figure 4-5 shows scatterplots of detrended production of the four suppliers versus predicted demand from the sets of regression models. These four graphs indicate that the regression models do a reasonable job predicting intermediate demands but tend to under-predict the highest demands and over-predict the lowest demands.

Table 4-4: Spring (March, April, May) regression coefficients for Equation (4-3).

Independent Variable	**WSSC Water**	**Washington Aqueduct**	**Fairfax Water (w/o Loudoun Water)**	**Loudoun Water**
Intercept, b_0	-2.29	-16.81	-5.77	-0.66
Maximum daily temperature >85 ^oF, one-day forecast	0.02		0.05	
Maximum daily temperature >85 ^oF	0.12	0.04	0.14	0.02
Maximum daily temperature <85 ^oF	0.05		0.06	
Maximum daily temperature >85 ^oF, one day prior	0.07	0.17	0.06	0.01
Maximum daily temperature <85 ^oF, one day prior		0.11		
Daily precipitation, one-day forecast			-5.99	-2.57
Daily precipitation, actual	-1.51		-3.64	-0.72
Daily precipitation, one day prior	-2.48	-2.60	-1.72	-0.36
Daily precipitation, two days prior	-1.67		-1.23	
Day of week – Monday	-1.78	5.60	1.30	1.38
Day of week – Tuesday	-4.38	8.34	-3.90	1.06
Day of week – Wednesday	-3.76	8.59	-1.32	1.17
Day of week – Thursday	-5.78	8.76	-3.46	0.96
Day of week – Friday	-4.76	8.42	-2.17	0.89
Day of week – Saturday	-3.69	4.69	-1.54	
No. of days in a row without significant precipitation	0.35	0.35	0.67	0.09
Standard Error of Estimate	7.86	9.60	8.80	2.20
Standard Deviation of Criterion Series	9.14	10.71	10.91	2.53
Coefficient of Determination (R^2)	0.27	0.20	0.36	0.25

Table 4-5: Summer (June, July, August) regression coefficients for Equation (4-3).

Independent Variable	**WSSC Water**	**Washington Aqueduct**	**Fairfax Water (w/o Loudoun Water)**	**Loudoun Water**
Intercept, b_0	-148.11	-110.24	-177.83	-38.88
Maximum daily temperature >85 °F, one-day forecast	0.32		0.43	0.12
Maximum daily temperature <85 °F, one-day forecast	0.35		0.48	0.12
Maximum daily temperature >85 °F	0.80	0.40	1.01	0.17
Maximum daily temperature <85 °F	0.82	0.39	1.04	0.18
Maximum daily temperature >85 °F, one day prior	0.51	0.56	0.39	0.07
Maximum daily temperature <85 °F, one day prior	0.52	0.54	0.41	0.07
Maximum daily temperature, two days prior		0.16	0.15	0.06
Daily precipitation, one-day forecast			-20.28	-3.41
Daily precipitation, actual			-7.54	-2.00
Daily precipitation, one day prior	-5.62	-2.78	-3.04	-0.77
Day of week – Monday	3.25	11.60	6.43	1.99
Day of week – Tuesday		16.03	-2.70	0.77
Day of week – Wednesday	2.72	16.38	5.23	1.95
Day of week – Thursday		15.94		0.81
Day of week – Friday	2.54	16.29	5.48	1.62
Day of week – Saturday		6.33		
No. of days in a row without significant precipitation	1.10	0.89	1.00	0.20
Standard Error of Estimate	11.33	12.13	16.17	3.36
Standard Deviation of Criterion Series	14.83	15.70	20.96	4.37
Coefficient of Determination (R^2)	0.42	0.41	0.41	0.42

Table 4-6: Fall (September, October, November) regression coefficients for Equation (4-3).

Independent Variable	**WSSC Water**	**Washington Aqueduct**	**Fairfax Water (w/o Loudoun Water)**	**Loudoun Water**
Intercept, b_0	-3.56	-19.38	-6.88	-0.66
Maximum daily temperature >85 °F, one-day forecast			0.05	
Maximum daily temperature >85 °F	0.11	0.09	0.15	0.02
Maximum daily temperature <85 °F	0.05	0.07	0.08	
Maximum daily temperature >85 °F, one day prior	0.05	0.13	0.04	0.01
Maximum daily temperature <85 °F, one day prior		0.08		
Daily precipitation, one-day forecast			-11.05	-3.60
Daily precipitation, actual			-2.78	-0.93
Daily precipitation, one day prior	-2.59	-2.15		
Day of week – Monday		8.05		0.87
Day of week – Tuesday	-5.25	9.58	-5.79	
Day of week – Wednesday	-4.33	9.42	-2.00	0.62
Day of week – Thursday	-5.85	10.24	-5.50	
Day of week – Friday	-4.90	9.70	-3.82	0.35
Day of week – Saturday	-6.53	2.43	-4.19	
No. of days in a row without significant precipitation	0.56	0.36	0.74	0.09
Standard Error of Estimate	8.49	10.23	12.31	2.39
Standard Deviation of Criterion Series	10.10	11.79	14.65	2.77
Coefficient of Determination (R^2)	0.30	0.25	0.30	0.26

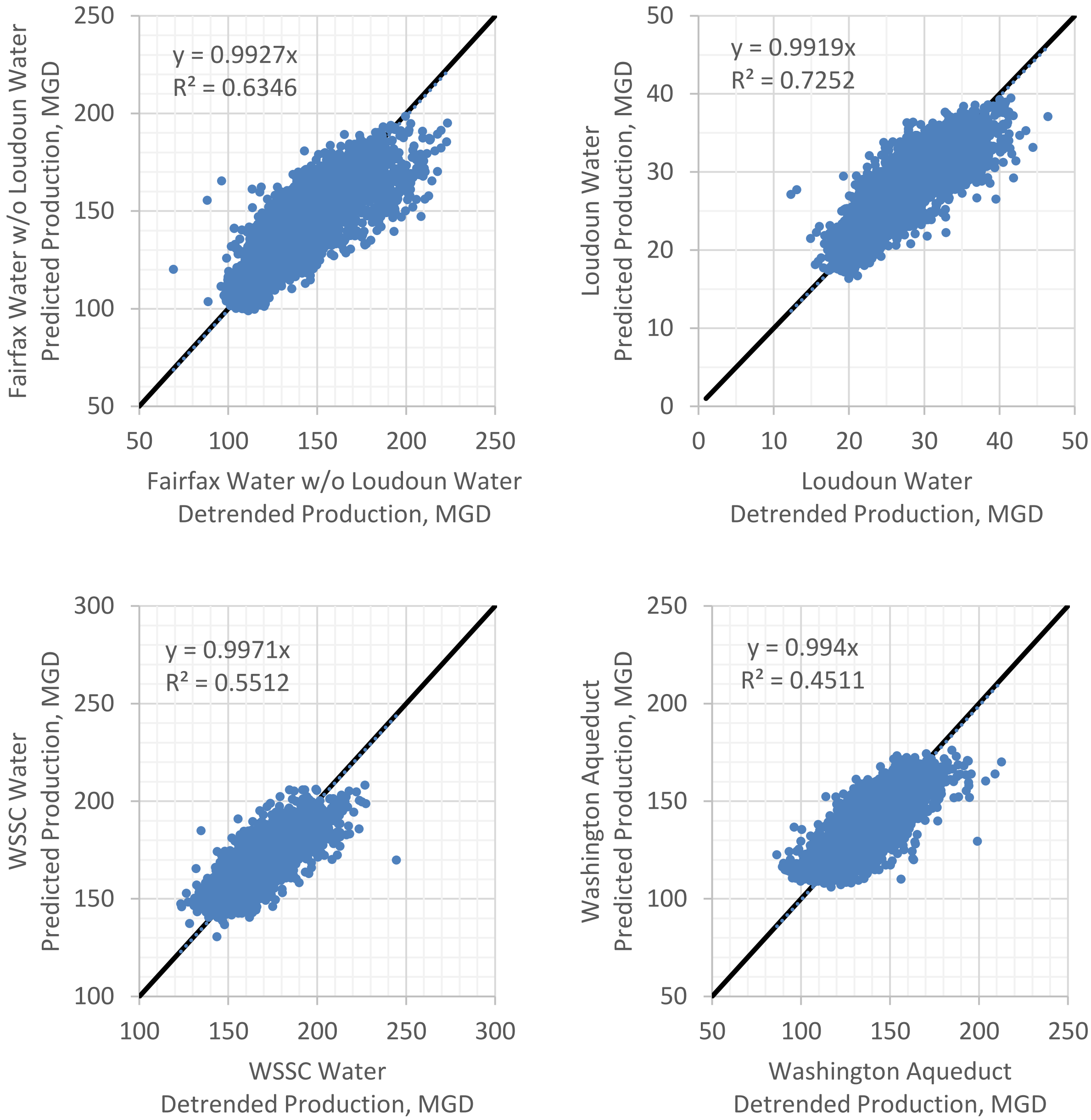

Figure 4-5: Regression model results compared with detrended actual data for the CO-OP suppliers and Loudoun Water.

4.6 ARIMA MODEL

The ARIMA model is used to help simulate the autocorrelations observed in demand time series because demand today is a good predictor of demand tomorrow. In Equation 4-4 the error term, N_t, from Equation 4-3 is separated into a random and a non-random component:

$$N_t = ARIMA_t + e_t \qquad \text{Equation 4-4}$$

where $ARIMA_t$ is the non-random portion of N_t calculated by the ARIMA process at time *t*, and e_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 all four suppliers combined.

The data used for the ARIMA analysis covers 1288 days between January 1, 2005 and December 31, 2018 (summer months only) and is the prediction error calculated from the daily sum of Fairfax Water (without Loudoun Water), Washington Aqueduct, WSSC Water, and Loudoun Water.

The R free software environment and programming language for statistical computing and graphics (supported by the R Foundation for Statistical Computing) is used to select the ARIMA model. Functions in the R package "stats v3.6.2" are applied in this analysis.[11] The selected model is classified as an ARIMA(*p*,*d*,*q*) model, where: *p* is the number of autoregressive terms, *d* is the number of non-seasonal differences needed for stationarity, and *q* is the number of lagged forecast errors in the prediction equation. This program fits coefficients to the selected model:

$$N_t = AR_1\, N_{t-1} + AR_2\, N_{t-2} + MA_1\, e_{t-1} + e_t$$ *Equation 4-5*

where AR_1 and AR_2 correspond to a *p* of two, and MA_1 corresponds to a *q* of one. The differencing term *d* is set to zero because of the previous detrending of the input data (Section 4.3). Table 4-7 summarizes the statistical significance of the terms of the chosen forecasting model. The *p*-values for the AR_1, AR_2, and MA_1 terms are all less than 0.05 and are, therefore, significantly different from zero at the 95% confidence level. The estimated standard deviation of the input random variable, e_t, equals 20.77.

Table 4-7 also summarizes the performance of the selected model in fitting the historical data. It displays: (1) the root mean square error (RMSE), (2) the mean absolute error (MAE), (3) the mean error (ME). The first two statistics measure the magnitude of the errors. A better model will give a smaller value. The last statistic measures bias. A better model will give a value close to zero.

Table 4-7: Summer ARIMA(2,0,1) model for the four suppliers.

	AR_1	AR_2	MA_1
Coefficient	1.24	-0.26	-0.76
Standard Error	0.05	0.05	0.04
T-statistic	23.10	-5.40	-18.45
p-value	< 2.2e-16	6.63E-08	< 2.2e-16
Root Mean Square Error (RMSE)			20.77
Mean Absolute Error (MAE)			16.03
Mean Error (ME)			-0.01

[11] R Documentation on stats v3.6.2: https://www.rdocumentation.org/packages/stats/versions/3.6.2.

The ARIMA term is divided among the four suppliers based on the fraction of total detrended demand that each one has provided for the period 2005-2018. The four fractions are 0.36, 0.29, 0.29, and 0.05 for WSSC Water, Washington Aqueduct, Fairfax Water (without Loudoun Water), and Loudoun Water, respectively.

4.7 Model Demonstration

Daily demands in PRRISM are simulated by summing the daily variation predicted by the seasonal regression models; Equation 4-3 with coefficients from Table 4-4, Table 4-5, and Table 4-6; the residual error term from the ARIMA model; Equation 4-5 with coefficients from Table 4-7; and the predicted monthly demands for the forecast year. The monthly demands for the forecast year are given by the monthly production factors and the forecast of average annual demands from Table 4-3.

The model can also be used to predict demands for historical years. Figure 4-6 shows total system demand (including Loudoun Water) in dry year 2010. In this graph, actual demands (solid blue line) are compared to total demands predicted by the regression models with no random error term (thicker broken grey line), and four total demand time series predicted by the ARIMA model, designated on the graph as A1 through A4 (thinner dotted lines). These four demand time series were produced with four different time series of random errors, e_t. In comparison, the ARIMA model designated on the graph as A0 (thicker red line) uses an error term e_t calculated from the data and predictions. The graphs show how the ARIMA term maintains some of the qualitative characteristics of the time series, especially in the summer months.

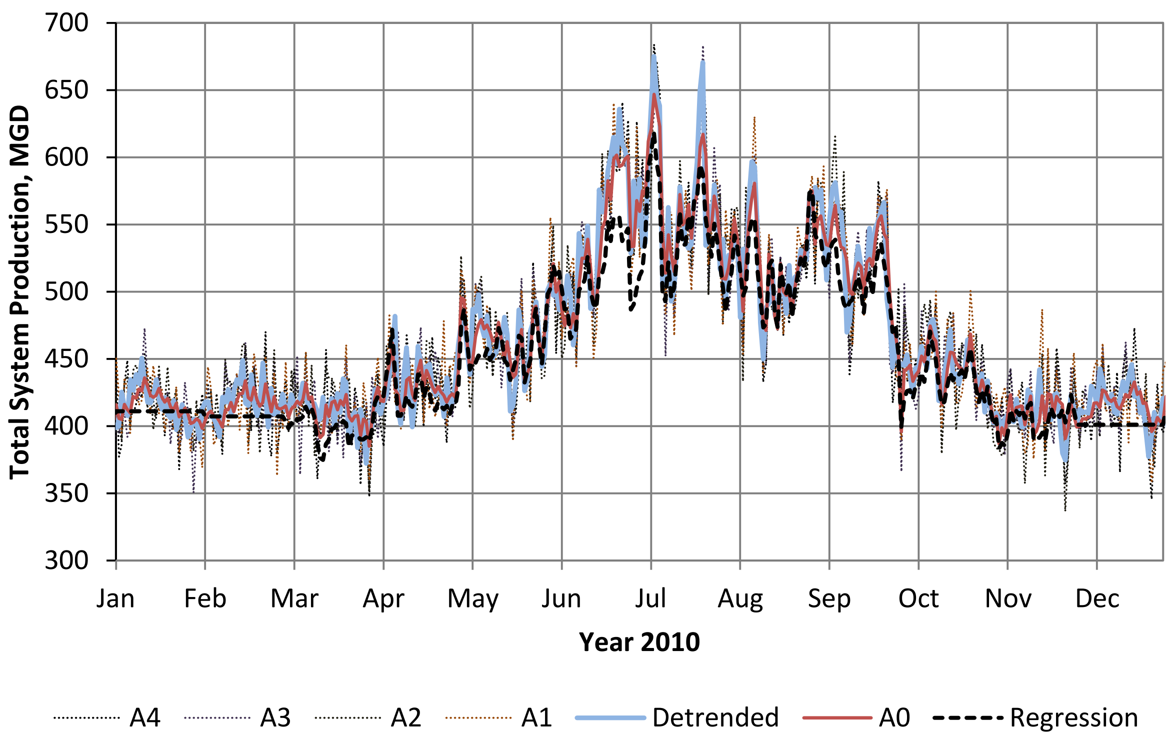

Figure 4-6: Total system demand (including Loudoun Water) for the 2010 dry year.

Table 4-8 summarizes some of the statistical characteristics of the production data, regression, and ARIMA model simulated time series for total system demand, including Loudoun Water, over the 2005-2018 historical period. Results given for the ARIMA model are averages of statistics from twelve different simulated time series, each of which was computed with a different random error time series, e_t. The ARIMA model, on average, does a good job in reproducing the system's peak-day factor as well as other time series statistics, including the 90th percentile demand and the 10th percentile demand.

Table 4-8: Comparison of statistics for total system demand time series for the period, 2005-2018.

	Detrended production data	**Predicted from regression model (with no random error term)**	**Average of 12 ARIMA model simulations**
Peak day factor	1.5	1.4	1.5
Maximum	675	647	677
Mean	447	447	447
90th Percentile	533	530	534
Median	430	428	433
10th Percentile	389	392	383

4.8 Water Use Restrictions

The imposition of water use restrictions is a management tool that may be used by states, local authorities, and water suppliers to temporarily reduce water demands during droughts or other serious situations. Restrictions can be voluntary or mandatory, depending on the severity of the drought. Such restrictions typically include the banning of lawn watering, filling of swimming pools, and operation of ornamental fountains. In 2000, the MWCOG board of directors endorsed a regionally coordinated public response plan that sets trigger levels for regional water use restrictions (MWCOG, 2001). Water use restrictions are simulated in PRRISM using the triggers that appear in Table 4-9, which provide an interpretation of the values in the MWCOG response plan. These values were also used in the 2017 alternatives study (Schultz *et al.*, 2017).

Estimates of demand reduction levels when restrictions are in place are based on past regional experience and are also provided in Table 4-9. A 5% voluntary reduction in demand is consistent with that achieved by Fairfax Water in March of 1993 during the Colonial Oil Company pipeline spill. Fairfax Water had to temporarily shut down its Potomac intake, taking all its water instead from the Occoquan Reservoir. Fairfax Water asked its customers to voluntarily reduce their water use. Average demand from February 1 through March 28 was 97.6 MGD. Demand fell to 92.6 MGD during March 29 through April 7, which is equal to a 5% reduction. It is likely that even greater reductions in demand are possible during higher demand summer months with more discretionary outdoor water uses, but to be conservative a 5% reduction is assumed for summer months and 3% for other months.

An emergency demand reduction of 15% is consistent with results in a study by Halich and Stephenson (2009) on the impact of water use restrictions in Virginia during the drought of 2002. They found that under mandatory restrictions, residential water use fell by 4.5% to 22.1%, with a reduction of 15.4% associated with a medium level of public information dissemination and a medium level of enforcement.

Table 4-9: Water use restriction triggers and assumed demand reductions.

Restriction status	Restriction trigger – level of combined storage in Little Seneca and Jennings Randolph reservoirs	Percent reduction in system demand, June through September	Percent reduction in system demand, October through May
Voluntary	< 60% of combined capacity	5	3
Emergency	< 5% of combined capacity	15	5

5 Modeling System Resources and Operations

ICPRB's planning model, PRRISM, is used in this study to evaluate the ability of the WMA water supply system, with and without potential enhancements, to meet the forecasted demands presented in Chapter 3. PRRISM simulates the day-to-day operations of the system, including daily demands of the WMA suppliers and use of the Potomac River and system reservoirs to meet those demands while maintaining river flow above the minimum environmental flow-by at Little Falls dam. The current version of PRRISM was developed using the object-oriented programming language ExtendSim™ Version 8 (Imagine That!, Inc.).

Changes are made to PRRISM on an ongoing basis to reflect new data, upgrades to the WMA system, and improved knowledge resulting from operational experience. For the current study, routine updates were made to PRRISM, as discussed in this chapter, including updates to reservoir capacities and to wastewater treatment plant return flows. In addition, as discussed in Chapter 7, the simulation of Maryland and Virginia drought stages and the resulting reductions in upstream consumptive use were added to the model.

5.1 PRRISM

PRRISM simulates daily system operations and the processes that govern water supply and demand in the system, including:

- flows in the Potomac River;
- consumptive demands of users upstream of the WMA;
- discharges from WMA supplier WWTPs into the freshwater Potomac River and Occoquan Reservoir;
- reservoir inflows, storage, and releases;
- withdrawals by WMA suppliers;
- transfers of treated water between WMA suppliers and between Fairfax Water's three service areas;
- nine-day and one-day forecasts of Potomac River flow at Little Falls; and
- potential changes in stream flows and withdrawals due to climate change.

Significant changes to the simulation of system operations were made for the 2015 water supply study and are discussed in detail by Ahmed *et al.* (2015), including the use of a one-day Little Falls flow forecast to determine the Little Seneca Reservoir water supply release rate and Occoquan Reservoir withdrawal rate and a more detailed representation of the transfer of finished water between Fairfax Water's eastern and western service areas. The ability to simulate four structural and six operational water supply alternatives were added to PRRISM for the 2017 alternatives study and are described in detail by Schultz *et al.* (2017).

5.2 Potomac River Flow

5.2.1 Flow Variability

Flow in the Potomac River is usually ample and more than sufficient to meet water supply needs and the environmental flow-by at Little Falls dam. Long-term average flow upstream of the WMA intakes is 7,789 MGD (12,050 cfs) for the years 1930-2018, based on USGS estimates for the Potomac River (adjusted) near Washington, DC.[12] Combined Potomac withdrawals by the WMA suppliers are usually in the range of 290 to 480 MGD, or approximately 4% to 6% of average adjusted flow. But flow in the Potomac is highly variable and dependent on time of year. It is typically highest in the spring and lowest during the summer and fall. The seasonal variation of flow in the Potomac River is apparent in Figure 5-1, which shows four daily statistics for historical adjusted flow values at Little Falls dam: minimum flow, 10th percentile flow, median flow, and 90th percentile flow, calculated with daily data from the 90-year period, 1930-2019. The historical minimum flow, for example, 411 MGD on September 1, is the lowest adjusted flow that ever occurred on September 1. The median adjusted flow on September 1 of 1,855 MGD is the median of the 90 flow values that have occurred on September 1. From Figure 5-1 it is evident that on most days of the year WMA needs are still comfortably below the minimum flow ever recorded for that day. The graph also shows that flow in the Potomac River has at times been below the level necessary to meet today's demands, especially in the months of August and September.

Figure 5-1 also shows WMA Potomac River demands, plus the 100 MGD environmental flow-by at Little Falls dam, that occurred in a recent drought year, 2002. The graph of 2002 flows demonstrates the high variability in river flow, even during drought. The graph also shows that new minimum flow records were set during 2002, notably in February, March and April.

The drought of record for the current WMA system occurred in 1930, when Potomac River flow was extremely low for an extended period, from mid-July through mid-December. The second most serious drought in the basin occurred in the summer of 1966, when observed flow at Little Falls dropped to its lowest recorded level, 78 MGD (121 cfs), on September 9th (corresponding to an adjusted flow of 388 MGD, or 601 cfs, on September 10th).

[12] Adjusted flow at Little Falls dam (USGS Station No. 01646502) is the flow that would have been observed in the absence of WMA withdrawals. It is computed from observed flow at Little Falls (USGS Station No. 01646500), plus the estimated sum of WMA withdrawals.

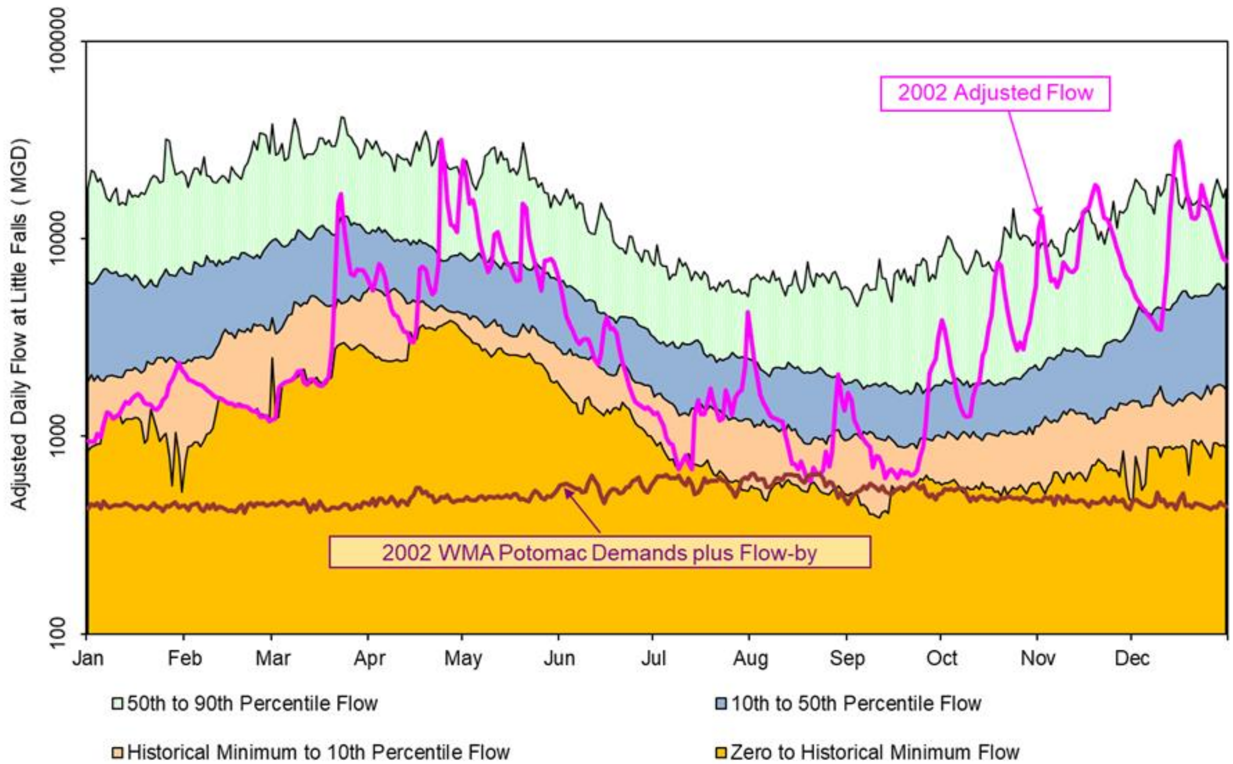

Figure 5-1: Adjusted daily flow at Little Falls dam in 2002, daily adjusted flow percentiles for 1930-2019 data, and drought year (2002) demands plus flow-by.

5.2.2 PRRISM Flow Inputs

PRRISM's simulation of daily water availability is based on input time series of Potomac River "natural" flows, that is, estimates of flows that would have occurred without the effects of withdrawals, diversions, or reservoir regulations. Historical stream flow records have been used to develop natural historical daily Potomac River flows and reservoir inflows for input into PRRISM (Hagen and Steiner, 1998a; Hagen *et al.*, 1998b; 1998c), during the period of record, which begins on October 1, 1929. Thus, PRRISM can be used to evaluate whether the current system can meet forecasted demands under hydrologic conditions which occurred in each year of the historical record, including the drought years of 1930 and 1966.

The future water availability assessment in this study is based on several different climate scenarios for each of the two planning horizons, 2040 and 2050. All the scenarios use the historical daily time series of natural Potomac River flows and reservoir inflows as a starting point. Conditions associated with each scenario are presented in Section 6.5.3.

5.2.3 Environmental Flow-By

The current environmental flow-by for the Potomac River near Washington, D.C, is based on recommendations in a 1981 study conducted by the Maryland Department of Natural Resources (1981). This study was the result of a request by the USACE to the Maryland Department of Natural Resources to make a quantitative recommendation related to a clause in the LFAA on the "amount needed for flow in the Potomac River downstream from the Little Falls dam for the purpose of maintaining environmental conditions." The study recommended a minimum daily environmental flow-by of 100 MGD at Little Falls dam. This number was subsequently incorporated into the LFAA emergency allocation. The study also contained a recommendation related to flow below Great Falls, which is located approximately nine miles above Little Falls dam. It recommended that when flow below Great Falls dropped below 500 MGD, Washington Aqueduct begin shifting its withdrawal from its intake at Great Falls to its intake at Little Falls. This "load-shift" would have the effect of increasing flow between Great Falls and Little Falls dam by the amount of the shift. Because Washington Aqueduct summer withdrawals at the time of the 1981 study were often near or at 200 MGD, this recommendation would have maintained flow between Great Falls and Little Falls dam at or near 300 MGD during low-flow periods.

A more recent study on the environmental needs of large rivers in the Potomac River basin, conducted by ICPRB, George Mason University, and the USGS for The Nature Conservancy (Cummins *et al.*, 2010), reviewed these environmental flow recommendations. This study concluded that flow at Little Falls dam should be maintained above the 100 MGD flow-by and recommended that flow between Little Falls dam and Great Falls should be above 300 MGD, and that, as a precautionary measure until more ecological monitoring data is available to improve understanding of low-flow impacts, reservoir operating procedures should give consideration to maintaining variability during extreme low-flow periods.

CO-OP conducts drought operations with the goal of maintaining daily flow at Little Falls dam above the 100 MGD flow-by and flow between Great Falls and Little Falls dam above 300 MGD. As discussed below, a substantial margin of safety of 120 MGD is simulated in the current study for Little Seneca and Occoquan operations to help ensure that flow at Little Falls stays above 100 MGD.

5.3 Reservoir Operations

This section gives an overview of operational strategies for the current WMA system, which uses the Potomac River as its primary supply and relies on the Patuxent and Occoquan reservoirs on a daily basis to supplement Potomac withdrawals, with releases made from upstream reservoirs, Jennings Randolph, and Little Seneca, when Potomac River flow is not sufficient to meet water supply needs plus the environmental flow-by at Little Falls dam. The operations of planned and proposed resources (Milestone Reservoir, Beaverdam Reservoir, Travilah Quarry, and Luck Stone Quarry B) are also discussed.

Jennings Randolph and Little Seneca reservoirs are both located upstream of the WMA water supply intakes and are used to augment flows in the Potomac River when the sum of predicted withdrawals and the environmental flow-by at Little Falls dam is greater than forecasted Potomac River flow. Since the establishment of the CO-OP system and the completion of these reservoirs in the early 1980s, water supply releases from these reservoirs have only occurred during three periods of time: summer of 1999, summer of 2002, and fall of 2010.

The Patuxent and Occoquan reservoirs are used daily in conjunction with the Potomac River intakes to meet WSSC Water and Fairfax Water demands, respectively. The water withdrawn from these reservoirs reduces the amount of water that must be withdrawn from the Potomac. During periods of drought, the Patuxent and Occoquan reservoirs are operated based on CO-OP flow forecasts in coordination with Little Seneca Reservoir to maximize water supply reliability from a systems perspective.

All system reservoirs are operated in normal years with the goal that they have a 95% probability of being at least 90% full by June 1 of each year. This practice helps ensure that these reservoirs can be used to their maximum benefit under drought conditions. More details on these reservoir operations are given below.

5.3.1 North Branch Reservoirs

Jennings Randolph and Savage reservoirs (or the "North Branch reservoirs") are located in the far northwestern corner of the Potomac River basin on the North Branch of the Potomac River (see Figure 2-1). These reservoirs are operated for four primary purposes: flood control, water quality enhancement, recreation, and water supply. Management objectives for the North Branch reservoirs have been developed by the USACE's Baltimore District Office in accordance with the reservoirs' master manuals of operations and with input from the North Branch Potomac River Advisory Committee. This committee was established in 2005 to provide a stakeholder forum regarding operations and management of the reservoirs, the surrounding public lands, and downstream flow levels (NPS, 2008).

Jennings Randolph Reservoir is the WMA system's largest storage resource, with 13.1 BG of the reservoir's conservation pool allocated to CO-OP "water supply" storage and the remaining 16.2 BG allocated to "water quality" storage. These two segments of storage are operated separately. The USACE's Baltimore District Office manages this reservoir and makes releases from water quality storage continually to meet its primary objectives, and to the greatest degree possible, to provide whitewater boating and fishing opportunities downstream along with boating and beach access on Jennings Randolph Reservoir itself. Jennings Randolph water supply storage is only used at the request of CO-OP on behalf of the CO-OP suppliers. Savage Reservoir is operated in coordination with Jennings Randolph Reservoir, with releases generally made at a one-to-five ratio for both water quality and water supply releases, but it does not have official storage allocations. Savage Reservoir also supplies water to the Town of Westernport, Maryland. The combined Jennings Randolph and Savage release is measured at the USGS stream gage (Station ID 01598500) at Luke, Maryland.

The representation of Jennings Randolph Reservoir water quality releases in the current version of PRRISM, developed in close coordination with the USACE's Baltimore District Office, is described in detail in Ahmed *et al.* (2010). PRRISM simulates all recreational and environmental storage elevation targets that are either mandated by the government or recommended by the North Branch Potomac River Advisory Committee. PRRISM simulates the USACE's balancing of competing needs for the limited water resource, including a stepped rule table to guide releases when downstream flow and reservoir elevation targets need to be abandoned during dry conditions.

During periods of drought, CO-OP can request water supply releases from the North Branch reservoirs to augment flows in the Potomac River. CO-OP determines release rates based on forecasts of flow and demands. Because the North Branch reservoirs are located some 200 miles upstream of the WMA, releases must be made approximately nine days in advance to allow for travel time downstream.

5.3.2 Use of River Flow Forecasts

Significant travel times are required for upstream reservoir releases to reach the WMA and there are also lag times required for implementation of certain operational changes. Therefore, CO-OP uses flow and demand forecasts to determine reservoir release rates and to coordinate CO-OP system operations, and this use of forecasts is simulated in PRRISM.

5.3.2.1 Nine-day forecasts of river flow

Releases from the North Branch reservoirs, Jennings Randolph and Savage, are based on nine-day forecasts of Potomac River flow at Little Falls. This flow forecast is obtained from an empirical equation for the recession of flow at Little Falls, derived from a data set of natural flows during historical periods of drought (see Ahmed *et al.*, 2015).

5.3.2.2 One-day forecasts of river flow

Releases from Little Seneca Reservoir and Fairfax Water load-shifts between Potomac River and Occoquan Reservoir withdrawals are based on one-day forecasts of Potomac River flow at Little Falls. These operations contribute to system reliability and efficiency by partially "correcting" for errors in the nine-day release. If more water than needed was released from the North Branch reservoirs nine days ago, a Fairfax Water load-shift to the Potomac can "capture" some of this excess by conserving Occoquan storage. Conversely, if not enough water was released from the North Branch reservoirs due to an erroneously high nine-day flow forecast, a Little Seneca release and Fairfax Water load-shift to the Occoquan can compensate by augmenting Potomac River flow. PRRISM's one-day forecast is similar to that currently used in CO-OP's drought operations support tools. Tomorrow's flow at Little Falls is estimated from today's flow plus a change based on recent observations at upstream gages, lagged appropriately (see Ahmed *et al.*, 2015).

One-day forecasts are also used to simulate operations of some of the planned and proposed alternatives in the system scenarios considered in Chapter 8, since it is assumed that it takes approximately one day for these operations to have an impact on river flow at Little Falls during low-flow conditions. This assumption is provisional and may be revised in future studies if new data becomes available.

One-day forecasts are used in the simulation of two of the planned or proposed structural alternatives:

- Luck quarry (Luck Stone Quarry B) releases for Potomac River low-flow augmentation
- Fairfax Water load-shifts that make use of Vulcan Quarry

One-day forecasts are used in the simulation of two of the proposed operational alternatives:

- Cooperative use of Milestone Reservoir, that is, use of this reservoir in conjunction with use of Little Seneca Reservoir
- Loudoun Water Beaverdam Reservoir releases for Potomac River low-flow augmentation

5.3.2.3 Current day river flow

Only WSSC Water's load-shifts between its Potomac River and Patuxent intakes are not based on forecasts, but rather on current day flow at Little Falls and current day demand. Thus, WSSC Water load-shifts play a key role in the WMA supply system. If flow in the river on a given day is not sufficient to meet WMA demands plus the 100 MGD flow-by at Little falls because of an error in the previous day's one-day flow and demand forecast, then a load-shift from WSSC Water's Potomac intake to its Patuxent intake can increase flow and potentially prevent a Potomac River flow deficit, that is, prevent daily flow at Little Falls from falling below 100 MGD.

Simulated use of one of the proposed structural alternatives, Travilah Quarry, is not based on a forecast but rather on current day demands and flow, similar to the Patuxent reservoirs. A release from Travilah Quarry is estimated to have a close to immediate impact on flow at Little Falls because it's assumed that it would use remotely operated valves and allow both WSSC Water and Washington Aqueduct to switch quickly from their Potomac withdrawals to the Travilah supply.

5.3.3 Proposed Operational Changes

The four proposed operational changes considered in this study were described in Section 2.3.5.2. The first two options, which are cooperative use of Milestone Reservoir and use of Beaverdam Reservoir for low-flow augmentation, assume coordinated use with Little Seneca Reservoir, and are thus based on one-day forecasts of river flow. Under the third alternative, which is improved flow forecasts, the accuracies of both the nine-day and the one-day forecasts of Potomac River flow at Little Falls are assumed to improve by 10%. The last of the group of operational alternatives is the use of Jennings Randolph water quality storage during drought emergencies. This alternative is simulated as a limited transfer of Jennings Randolph water quality storage to water supply storage in certain cases when water supply storage is low.

5.4 Effects of Sedimentation on Reservoir Capacities

Reservoir storage capacities tend to decrease with time due to the deposition of sediment. Reservoir sedimentation rates are highly variable and dependent on hydrologic conditions, with the majority of sediment deposition occurring during very large storm events. Estimates of reservoir storage capacities and sediment deposition rates of WMA reservoirs are based on recent and historical bathymetric surveys, as discussed in the sections below.

The decrease in storage capacity in the WMA water supply system, as a function of forecast year, is represented in PRRISM by means of an assumed sedimentation rate for each reservoir. Table 5-1 shows the estimated current and projected reservoir storage for current system reservoirs, along with sedimentation rates assumed in the current study. Since the publication of the 2015 water supply study (Ahmed *et al.*, 2015), only one new bathymetric survey has been conducted, a 2015 survey of WSSC Water's Patuxent reservoirs. Thus, values for usable capacity and sedimentation rates for the Patuxent reservoirs were revised, but values for the Occoquan, Little Seneca, Jennings Randolph, and Savage reservoir are unchanged from those used in the 2015 study.

5.4.1 Occoquan Reservoir

The most recent bathymetric survey of Occoquan Reservoir was conducted in 2010. A new survey is planned for 2020. Reviews of past bathymetric surveys and sedimentation rate estimates are available in a report prepared for Fairfax Water by CDM (2002). The 2010 survey found that the volume of the reservoir at full pool elevation, 122 feet above mean sea level (MSL), was 8.33 BG. This volume is larger than the volume of 8.313 BG computed in a survey conducted in 2000. The increased volume measured in 2010 indicates that at certain times sediment flushing may occur, resulting in a gain of reservoir storage capacity. A portion of Occoquan Reservoir's capacity, 0.28 BG, is located below the elevation of the invert of the lowest intake, 80 feet. Thus, the estimate of useable storage in 2010 is 8.05 BG.

The current study continues to use Fairfax Water's suggested sedimentation rate of 20 million gallons per year (MG/yr) to account for potential future fluctuations in sedimentation. This is the "low" value of the Occoquan Reservoir sedimentation rate estimated in past studies. Prior to the 2015 study (Ahmed *et al.*, 2015), CO-OP assumed a sedimentation rate of 40 MG/yr, computed from the volume lost from

1995 to 2000, determined from detailed bathymetric surveys by the Occoquan Water Monitoring Laboratory (CDM, 2002).

Table 5-1: Effects of sedimentation on reservoir storage capacities.

Reservoir	Baseline year	Usable capacity in baseline year (MG)	Projected usable capacity (MG)			Sedimentation rate (MG/yr)
			2020	2040	2050	
Occoquan Reservoir[1]	2010	8,050	7,850	7,450	7,250	20
Patuxent reservoirs[2]	2015	10,530	10,407	9,915	9,669	24.6
Little Seneca Reservoir[3]	2010	3,903	3,863	3,783	3,743	4
Jennings Randolph Reservoir - water supply[4]	2013	13,098	12,958	12,557	12,356	45 (distributed between water supply and quality storages[6])
Jennings Randolph Reservoir - water quality[4]	2013	16,295	16,120	15,621	15,372	
Savage Reservoir[5]	2005	6,241	5,971	5,611	5,431	18

[1] Baseline usable capacity and sedimentation rate from Fairfax Water (G. Prelewicz, personal communication, March 18, 2014).
[2] Baseline usable capacity and sedimentation rate from Van Ryswick and Sylvia (2015).
[3] Baseline usable capacity and sedimentation rate from Ortt, *et al.* (2011). Values will be revised upon completion of the Little Seneca Reservoir forebay dredging project.
[4] Baseline usable capacity based on the 2013 revised stage-storage curve provided by USACE's Baltimore District Office (B. Haines, personal communication, January 16, 2014).
[5] Baseline usable capacity and sedimentation rate from Kame'enui *et al.* (2005)
[6] 44.56% for water supply and 55.44% for water quality.

5.4.2 Patuxent Reservoirs

New bathymetric surveys for WSSC Water's two Patuxent reservoirs, Triadelphia and T. Howard Duckett (Rocky Gorge), were conducted in April of 2015 by the Maryland Geological Survey (MGS) on behalf of WSSC Water (Van Ryswick and Sylvia, 2015). To provide the most accurate picture of changing conditions, the 2015 surveys used the same equipment and methodologies for data collection and data processing that were used in a previous MGS survey conducted in 2004/2005 (Ortt *et al.*, 2007), in which bathymetric data was collected in May and June of 2004 for Triadelphia and in April and August of 2005 for Duckett. Sedimentation rates were estimated by comparing the 2015 combined volumes determined in the 2015 survey with those of the 2004/2005 survey.

MGS determined that the volumes of Triadelphia and Duckett reservoirs were 6.45 BG and 5.49 BG, respectively, in 2015, resulting in a combined volume of 11.94 BG. Of this volume, 0.77 BG and 0.60 BG are considered by WSSC Water to be reserved for flood storage for Triadelphia and Duckett, respectively, and 0.04 BG is considered to be unusable storage volume, a reduction from the previous value of 0.40 BG (T. Supple, personal communication, August 3, 2018). The resulting value for usable storage, referred to by WSSC Water as "normal storage" capacity is 10.53 BG.

The average annual capacity loss for Triadelphia during the period between the 2015 survey and the earlier 2004 survey was 19.6 MG (59 acre-feet, or ac-ft), and the annual loss for Rocky Gorge between its 2015 and 2005 surveys was 5.0 MG (15 ac-ft), resulting in a combined annual loss due to sedimentation of 24.6 MG (74 ac-ft). This value appears in Table 5-1 and is used in the current study's simulation modeling because it is considered to be a conservative estimate, being somewhat greater than the estimated combined annual loss of 17.5 MG (52.7 acre feet) computed over the longer time interval, based on the 2004/2005 surveys and 1954 survey.

5.4.3 Little Seneca Reservoir

The most recent bathymetric data for Little Seneca Reservoir was collected in July and August of 2010, and results are available in a study by the MGS for the Maryland Department of Natural Resources (Ortt *et al.*, 2011). These data indicated a total storage capacity of 3.922 BG at mean pool level (385 feet above MSL) and a usable capacity of 3.903 BG. This volume can be compared to a previous analysis of the pre-construction topography from 1979 and to the bathymetric survey conducted by Ocean Surveys, Inc., in 1996, which indicated a storage capacity of 3.86 BG. According to the MGS, the fact that the current capacity of the reservoir is more than the calculated capacity from the 1996 survey is likely due to the greater density of data in the 2010 survey. The sedimentation rate calculated from the pre-construction topography and the 2010 bathymetry is 4 MG/yr.

Little Seneca Reservoir has three forebays which were designed to trap sediment carried by the streams that flow into the reservoir. Based on the 2010 survey, MGS judged that these forebays were very effective in capturing incoming sediment, stating that the "forebays are performing their function of sediment trapping and are only allowing a small portion of sediment to be transported further into the reservoir." This report also indicated that the forebays were close to full. WSSC Water and the other CO-OP suppliers are committed to maintaining the effectiveness of this important system resource by dredging to remove the sediment that has collected in the forebays. The dredging project is in its planning stage, and is anticipated to take place in the mid-2020's. In preparation for the dredging project, WSSC Water will conduct a new bathymetric survey in the spring of 2020. Considering the commitment to dredge Little Seneca forebays when they become full, CO-OP may, at the completion of the dredging project, revise its estimate of the Little Seneca sedimentation rate.

5.4.4 North Branch Reservoirs

Capacities and sedimentation rates for Jennings Randolph and Savage reservoirs are unchanged from values assumed in the 2015 study (Ahmed *et al.*, 2015). Historical bathymetric survey results for Jennings Randolph Reservoir, as well as the allocation of storage between water quality and water supply, were discussed in detail in that study. Results are summarized below.

The original Jennings Randolph storage volume, at conservation pool level, was determined to be 94,700 ac-ft (30,860 MG) (USACE, 1997). After subtracting approximately 2,700 ac-ft to account for dead storage and anticipated sediment accumulation over a 100-year period (USACE, 1986), usable conservation pool storage was given as 92,000 ac-ft (29,978 MG), with 40,995 ac-ft (13,358 MG) allocated to water supply storage and 51,005 ac-ft (16,620 MG) allocated to water quality storage (Future Storage Agreement, Exhibit A, 1982). A hydrographic survey conducted in 2013 culminated in a letter from the USACE's Baltimore District Office that formalized the redistribution of the water supply and water quality storage accounts through a revised Exhibit A (USACE, 2014b). The water storage agreements between the USACE and the CO-OP suppliers contain clauses that address potential future changes in reservoir storage space due to sedimentation. These clauses state that whenever necessary, there shall be an equitable redistribution of storage space among purposes served by the project including municipal and industrial water supply. The revised Exhibit A contains a table with the following revised values:

- Total usable conservation pool storage: 90,203 ac-ft (29,397 MG)
- Water supply storage: 40,194 ac-ft (13,099 MG)
- Water quality storage: 50,009 ac-ft (16,298 MG)

These new storage distributions maintain the original proportions of conservation pool storage: 55.44% for water quality and 44.56% for water supply.

5.5 Treated Wastewater Return Flows

Most of the area's wastewater is treated at DC Water's Blue Plains Advanced Wastewater Treatment Plant, which discharges into the Potomac estuary south of Washington, DC. However, several wastewater treatment plants serving the WMA discharge treated water into waterways within the Potomac River Basin, upstream of the WMA water intakes. This treated wastewater is available for further use at downstream withdrawal points. Wastewater treatment plant (WWTP) return flows for future years are estimated and incorporated into PRRISM. The facilities considered for this analysis are WSSC Water's Seneca and Damascus Wastewater Resource Recovery Facilities (WRRF), Loudoun Water's Broad Run Water Reclamation Facility (WRF), and the Upper Occoquan Service Authority (UOSA) WWTP. The Seneca and Damascus WRRFs and the Broad Run WRF discharge into the Potomac River; the UOSA WWTP discharges upstream of the Occoquan Reservoir. Annual return flows for these facilities are listed in Table 5-2.

Wastewater return flows typically vary over the calendar year, reaching their lowest values during summer. These changes in monthly return flows are considered in PRRISM since water supply releases from the Jennings Randolph and Little Seneca reservoirs would occur during times when releases from treatment plants are at their lowest. Monthly production factors are developed to convert the projected average annual return flows (Table 5-2) to monthly return flows. Projected monthly production factors were derived from 2014 through 2018 return flow data. Lower estimates of wastewater return flow are a conservative assumption in the PRRISM model as lower return flows from these treatment plants cause higher release rates from the reservoirs. Table 5-3 shows the production factors calculated for Seneca and the Damascus WRRFs, the Broad Run WRF and the UOSA WWTP.

Table 5-2: Past and projected treated wastewater return flows (MGD) from Seneca and Damascus WRRFs, the Broad Run WRF and the UOSA WWTP to the Potomac River and Occoquan Reservoir.

Year	Seneca WRRF to Potomac River[1]	Damascus WRRF to Potomac River[1]	Broad Run WRF to Potomac River[2]	UOSA WWTP to Occoquan Reservoir[3]
2015	14.4	0.81	3.96	32.6
2020	16.18	0.88	6	35.2
2025	17.69	0.88	8	37.5
2030	18.33	0.89	9	39.1
2035	19.08	0.92	10	40.6
2040	19.93	0.94	10	42.2
2045	20.45	0.97	10	43.7

[1]Data provided by WSSC Water (K. Six, personal communication, March 2019)
[2]Data provided Loudoun Water (D. Geldert, personal communication, July 2019)
[3] Data obtained from UOSA by Fairfax Water (N. Saji, personal communication, February 2020)

Table 5-3: Monthly production factors for treated wastewater return flows for Seneca and Damascus WRRFs, the Broad Run WRF and the UOSA WWTP to the Potomac River and Occoquan Reservoir.

Month	Seneca WRRF Factors (average of 2014-2018)[1]	Damascus WRRF Factors (average of 2014-2018)[1]	Broad Run WRF Factors (minimum of 2014-2018)[2]	UOSA WWTP Factors (minimum of 2014-2018)[3]
January	0.93	0.78	0.93	0.83
February	0.97	0.93	0.94	0.91
March	0.94	0.86	0.90	0.89
April	0.93	0.87	0.91	0.90
May	0.96	0.98	0.99	0.97
June	0.97	0.98	0.93	0.98
July	0.97	0.84	0.89	0.94
August	0.95	0.79	0.82	0.92
September	0.93	0.77	0.85	0.85
October	0.91	0.78	0.92	0.88
November	0.92	0.82	0.89	0.87
December	0.97	0.88	1.00	0.92

[1]Data provided by WSSC Water (K. Six, personal communication, March 2019)
[2]Data provided by Loudoun Water (D. Geldert, personal communication, July 2019)
[3] Data obtained from UOSA by Fairfax Water (N. Sajji, personal communication, February 2020)

Wastewater discharge from the Broad Run WRF is impacted by Loudoun Water's non-potable reuse system and that impact is reflected in their Broad Run WRF discharge estimates provided in Table 5-2 (P. Kenel, personal conversation July 31, 2020). Average reclaimed demand was 1.75 MGD in 2019. Additional data from July 2020 shows reclaimed demands can range from 2 to 3.25 MGD, and with new data center customers, demand will continue to increase over the next 5 years. The main impact is an increase in Loudoun Water system demands for combined potable and non-potable water and a decrease in the Broad Run WRF discharge (due to evaporative losses by data centers). Loudoun Water did not provide the non-potable water use data in their billing records for the 2020 water supply study. However, MWCOG does include the facilities using reclaimed water as employees in the Round 9.1 forecast. Future studies may reevaluate how best to represent the effect of Loudoun Water's non-potable water use in the WMA system.

5.6 Water Production Losses

Water losses from the raw water treatment process are simulated by PRRISM. ICPRB's approach to representing these losses in past studies is discussed by Ahmed *et al.*, (2015). Treatment process losses are due to the dewatering and transport to off-site locations of the residual solid material associated with water treatment processes, which includes sediment contained in the raw water and solids from treatment process coagulants. Historically, water containing these residuals was discharged back into the source water, resulting in negligible net water loss from the water treatment process. However, water quality concerns in the 1990's led to restrictions on discharges from water treatment plants. In 1996, WSSC Water entered into an agreement with the Maryland Department of the Environment to build facilities to remove solids from its Potomac WFP discharge, with an exception for periods of high Potomac River flow. In 2015, a Consent Decree was issued requiring WSSC Water to undertake short-term measures to significantly reduce its discharge of solids to the Potomac River and to establish a long-term schedule to implement upgrades that will allow it to meet regulatory effluent limits, conditions, and waste load allocations (US District Court MD, 2015). To satisfy new USEPA permit requirements, Washington Aqueduct completed a new residuals management facility in November 2012. Fairfax Water's Griffith WTP at the Occoquan Reservoir and its Corbalis WTP on the Potomac River are relatively new, and both have residual solids management facilities. In 2012, a change occurred in the Corbalis WTP's solids processing (G. Prelewicz, personal communication, March 18, 2014). Water removed from the plant's belt filter solids processing facilities is now sent through an on-site stormwater pond to discharge through a Virginia Pollutant Discharge Elimination System permitted outfall to a nearby tributary of Sugarland Run. Prior to 2012, this water, typically less than 2% to 3% of total production, was re-cycled to the head of the plant.

Assumed production losses used in PRRISM are based on data analyses described by Ahmed *et al.* (2015). Production loss rates for all plants are assumed to be 3%, except for the Griffith WTP, where a loss rate of 10% is used.

6 Anticipating the Impact of Climate Change

To estimate future water availability, this study looks at the impact that a changing climate may have on streamflow in the Potomac basin in the forecast years, 2040 and 2050. Trends and projections indicate that on average, the mid-Atlantic states are becoming and will continue to get "wetter." But climate projections also indicate that extreme conditions, that is, floods and droughts, will become more severe in many regions of the world. The aim of the current study is to derive scenarios that reflect the expected differences in the impact of climate change on high-flow years versus low-flow years.

Meteorologists have historically characterized "normal" climate conditions based on averages taken over 30-year periods of time (World Meteorological Organization, 1989). In this study, a historical period, 1896 through 1979, is assumed to represent conditions before the onset of significant climate change in the Potomac basin. The climate projections used in this study extend from 1950 through 2099, a 150-year period that overlaps with the pre-climate change historical period. The analysis presented here compares conditions in a 30-year pre-climate change "base" period, 1950 through 1979, with conditions that have been or are projected to be experienced in subsequent 30-year periods extending from 1980 through 2099. The focus of the analysis is mean annual streamflow and changes over time in its long-term mean value and in its extreme values, as represented by percentiles, or equivalently, quantiles, as computed over 30-year intervals.

6.1 Regional Trends and Projections

According to the fourth National Climate Assessment (NCA4), the earth's average surface air temperature has risen 1.0 °C (1.8 °F) over the past century (from 1901-2016). The increase over the continental US over this same period has also been 1.0 °C, and 0.7 °C (1.2 °F) over the past several decades (USGCRP, 2017; 2018). Global average atmospheric concentrations of carbon dioxide have risen to over 400 parts per million (2016 value), a level that has not been exceeded since three million years ago, a time when both temperatures and sea levels were higher than today.

Trends in the basin states, Maryland, Pennsylvania, Virginia, and West Virginia, were reviewed in state summaries prepared for the NOAA National Centers for Environmental Information (NCEI) by the North Carolina Institute for Climate Studies (NCICS), based on analyses of data from 1901 to 2014 (Frankson *et al.*, 2017; Runkle *et al.*, 2017a; Runkle *et al.*, 2017b; Runkle *et al.*, 2017c). Since the beginning of the 20th century, average temperatures have risen by about 0.8 °C (1.5 °F) in both Maryland and Virginia, by 1.2 °C (2.0 °F) in Pennsylvania, and by less than 0.6 °C (1 °F) in West Virginia. Temperatures were exceptionally warm in the 1930's and cool in the 1960s in Maryland, Virginia, and West Virginia. In West Virginia, temperatures were highest in the 1930 and early 1950s, but since 1960 have risen about 0.6 °C (1 °F).

Trends in precipitation are mixed in the basin states. No increase in annual mean precipitation is evident for Virginia or West Virginia, though in Virginia average precipitation during the most two recent decades considered in the NCICS analyses (1995-2014) has been higher than the long-term average. Precipitation was also above average in Maryland over this period, and the number of extreme precipitation events has been highest in the most recent decade considered (2005-2014). In

Pennsylvania, the most recent five-year period in the record analyzed by NCICS, 2010-2014, was the wettest on average and had the second highest number of extreme events.

6.2 Data Sources

Data sources for the climate change analyses presented in this study are described below. They include climate projections derived from the Coupled Model Intercomparison Project Phase 5 (CMIP5) multi-model ensemble, historical climate data from the Oregon State University's PRISM Climate Group and from the National Oceanographic and Atmospheric Administration (NOAA), and USGS daily streamflow data from the USGS's National Water Information System.

6.2.1 Climate Projections

This study uses an ensemble of climate projections derived from the CMIP5 multi-model ensemble. These projections were statistically downscaled using monthly bias-correction and spatial disaggregation (BCSD) (Reclamation, 2013), available from the "Downscaled CMIP3 and CMIP5 Climate and Hydrology Projections" archive.[13] The BCSD data are monthly time series, extending from 1950 through 2099, for a grid of ⅛ degree by ⅛ degree, providing a spatial resolution of approximately 12 kilometers (km) by 12 km. The BCSD gridded data, clipped and spatially averaged over the drainage area of the Potomac basin upstream of the USGS stream gage at Little Falls Pump station near Washington, DC (38.9375 degrees north and -77.1875 degrees west), were downloaded from the archive website. The BCSD bias-correction was performed using a quantile mapping approach.

The CMIP5 model runs are based on four distinct greenhouse gas (GHG) emissions scenarios developed as part of the Intergovernmental Panel for Climate Change (IPCC) fifth assessment, which was completed in 2013-2014. Each of these scenarios, referred to as a representative concentration pathway (RCP), assumes a different change in the radiative forcing (a measure of the net energy received by the earth from the sun) in 2100 as compared to preindustrial conditions. The four representative concentration pathways are referred to as RCP2.6, RCP4.5, RCP6.0, and RCP8.5. In its most recent Special Report, The Ocean and Cryosphere in a Changing Climate (IPCC, 2019), the IPCC contrasted the potential effects of RCP2.6, described as "a low greenhouse gas emission, high mitigation future", and RCP8.5, a "high greenhouse gas emission scenario in the absence of policies to combat climate change." The other two scenarios, RCP4.5 and RCP6.0, represent futures with intermediate greenhouse gas emissions. Because there is no consensus on which RCP best represents future emissions, the current study uses projections from all four RCPs.

A total of 231 CMIP5 BCSD projections are available for the Potomac basin drainage area above Little Falls, obtained from 36 different global climate models (GCMs) constructed by 22 climate modeling groups from around the world. For each GCM, from 2 to 40 runs are available representing some or all the RCPs and one or more sets of initial climate conditions, as summarized in Appendix A.4.

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[13] Archive at: https://gdo-dcp.ucllnl.org/downscaled_cmip_projections/dcpInterface.html.

6.2.2 Historical Meteorology

Two different sets of historical climate data were used in this study: (1) data from Oregon State University's PRISM Climate Group, and (2) data from NOAA's National Centers for Environmental Information (NCEI).

The first of these datasets was accessed via the PRISM Climate Group website.[14] PRISM uses climate observations from a wide range of monitoring networks and a series of regression models to develop spatially explicit climate maps at a regional scale (Daly *et al.*, 2008). PRISM provides monthly historical past (1895-1980) and recent years (1981-2018) precipitation time series over the conterminous US at an 800 meter (m) to 4 km spatial resolution; data at 4 km resolution was used in the current study. The PRISM gridded data for monthly average precipitation and monthly average temperature were spatially averaged over the Potomac River drainage area above Little Falls for use in the climate change analysis.

The second of these datasets, the Gridded 5km GHCN-Daily Temperature and Precipitation Dataset (nClimGrid), version 1 (Vose *et al.*, 2014), is available via the NOAA NCEI webpage.[15] This dataset provides values of monthly average precipitation and monthly average, minimum, and maximum temperature beginning in the year 1895 on a grid that spans the continental United States. The data were derived from NOAA's Global Historical Climatology Network (GHCN). NClimGrid data files were downloaded for this project and values of precipitation and temperature were spatially averaged over the Potomac River drainage area above Little Falls.

6.2.3 Potomac River Flow Data

Annual time series of "natural" Potomac River flow at Little Falls were computed for the years 1896 through 2017, based on a monthly reconstruction for February 1895 through December 2017 which was based on streamflow data available from the USGS's National Water Information System website[16] (see Table 6-1). The natural flow time series are estimates of what flow at Little Falls would have been without WMA withdrawals or diversions to the C&O Canal, without the effects of the North Branch reservoirs, Jennings Randolph and Savage, and without upstream consumptive use. Little Falls monthly flows for February 1895 up through February 1930 were estimated by summing available monthly data from upstream gages at Point of Rocks, Monocacy River, Goose Creek, and Seneca Creek (see Table 6-1) and using appropriate adjustment factors. Monthly flows from 1930-03 onward were estimated based on USGS monthly Little Falls "adjusted" flows, which are the USGS's estimates of what flow would have been at Little Falls without the effects of WMA withdrawals and diversions to the C&O Canal. For October 1950 through June 1981, adjustments were made to account for the presence of Savage dam, by adding estimated inflows and subtracting outflows based on data for Stations 01596500, 01597000, and 01597500. For July 1981 to the present, adjustments were made to account for the presence of both Savage and Jennings Randolph dams, based on data for Stations 01596500, 01595500, 01595000,

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[14] PRISM Climate Group website: http://www.prism.oregonstate.edu/

[15] NOAA NCEI webpage: https://data.nodc.noaa.gov/cgi-bin/iso?id=gov.noaa.ncdc:C00332

[16] USGS National Water Information System: https://waterdata.usgs.gov/nwis/

and 01598900. For January 1930 to the present, adjustments were made to eliminate the estimated impact of consumptive water use upstream of the WMA intakes by use of the following simple piecewise linear model: annual consumptive use in 1930 was assumed to be 0 MGD and it increased linearly until 2010, when it was 74.6 MGD. After 2010, annual upstream consumptive increased at a constant rate of 0.7 MGD/year (see Ahmed *et al.*, 2015).

Table 6-1: Gages used for reconstruction of "natural" flow at Little Falls.

USGS gage station	Station no.	Period of record	Drainage area, square miles
Potomac River at Little Falls, adjusted	01646502	1930-03-01 to present	11560
Potomac River at Point of Rocks	01638500	1895-02-01 to present	9651
Monocacy River	01642000	1896-08-01 to 1930-09-29	665
Monocacy River at Jug Bridge	01643000	1929-10-01 to present	1117
Goose Creek near Leesburg	01644000	1930-01-01 to present	332
Seneca Creek at Dawsonville	01645000	1930-09-26 to present	101
Savage River near Barton	01596500	1948-09-18 to present	49.1
Savage River below dam	01597500	1948-10-01 to present	106
Crabtree Creek near Swanton	01597000	1948-09-17 to 1981-09-30	16.7
North Branch Potomac River at Kitzmiller	01595500	1949-10-01 to 1985-09; 2003-10 to present	225
North Branch Potomac River at Steyer	01595000	1956-07-01 to present	73.1
North Branch Potomac River at Luke	01598900	1949-10-01 to present	406

6.3 Potomac Basin Climate Projections

Trends in the climate projections for the Potomac basin were investigated by looking at changes in long-term statistics calculated for five 30-year intervals comprising the 150-year simulation period, 1950 to 2099. After first computing mean annual precipitation and temperature for each year in the 150-year simulation period for each of the 231 climate projections, long-term statistics, including long-term means, were computed for each run for each of the following five 30-year periods:

- 1950-1979 – representing baseline conditions
- 1980-2009 – recent conditions
- 2010-2039 – current conditions
- 2040-2069 – includes study forecast years, 2040 and 2050
- 2070-2099 – long-term forecast period

6.3.1 Filtering the Projections

A filtering step was performed to eliminate climate runs with trends over the historical record which deviated significantly from observations. For each run, the change in long-term mean precipitation in the Potomac basin from the baseline period, 1950-1979, to the recent period, 1980-2009, were compared with the observed change computed from the nClimGrid dataset. The nClimGrid dataset was selected for this part of the analysis because it is relied on for use in trend analyses (USGCRP, 2017). A run was discarded if the simulated difference and the observed difference were found to be unequal according to a hypothesis test at the 5% significance level. The same procedure was applied to changes in mean temperature. After the application of this filtering procedure, 224 out of the original 231 runs remained in the climate projections ensemble. The seven runs that failed the filtering test all had projected changes in mean temperature that exceeded the observed change by an amount that was statistically significant; no runs failed the filtering test based on projected changes in mean precipitation.

6.3.2 Trends in Projected Precipitation and Temperature

Changes over time in long-term means and standard deviations of projected precipitation and temperature, for the Potomac River drainage area above Little Falls, appear in Table 6-2. These statistics were computed for each of the five 30-year intervals in the simulation period based on the complete ensemble of 224 filtered BCSD projections, resulting in a sample of annual mean values, for each 30-year interval, of n = 30 x 224 = 6720 years. This table also includes statistics calculated from the PRISM historical dataset. The means and standard deviations of projected precipitation and temperature in the study baseline period, 1950-1979, are quite close to those in the historical period, 1896-1979, supporting the argument that the base period is a reasonable representation of pre-climate conditions in the Potomac basin.

Projected long-term mean precipitation in Table 6-2 can be seen to steadily rise over the 150-year simulation period of the BCSD projections, from 985 millimeter per year (mm/year) (38.8 inches/year) for the base period, 1950-1979, to 1089 mm/year (42.9 inches/year) for 2040-2069 and 1110 mm/year (43.7 inches/year) for 2070-2099, increases of 10.6% and 12.7%. Similarly, values of long-term mean temperatures increase from 10.94 ^{o}C (51.7 ^{o}F) in the base period to 13.57 ^{o}C (56.4 ^{o}F), and 14.41 ^{o}C (57.9 ^{o}F) for the future periods, 2040-2069 and 2070-2099, increases of 2.6 ^{o}C (4.7 ^{o}F), and 3.5 ^{o}C (6.3 ^{o}F), respectively.

Water supply planners are particularly interested in projected changes in extreme conditions. The fact that the standard deviations of both annual precipitation and temperature rise over time in Table 6-2 is an indication that extreme conditions will occur more frequently according to the BSCD projections. Changes in extreme years can also be investigated by looking at changes in “percentile” values calculated over the long-term, which for this study, is represented by the five 30-year intervals described above. The percentile value is the value below which a given percentage of a sample falls. For example, 75% of the values in a sample are below the 75th percentile value. Percentiles values are closely related to quantile values, which are used later in this chapter in discussions of annual flow. A quantile value is the percentile value divided by 100. Table 6-3 gives selected percentile values of projected annual precipitation and temperature. These were again computed over the five 30-year intervals using as a sample set equal to the entire ensemble of 224 filtered BCSD projections. Results in Table 6-3 indicate, according to the BCSD projections, that temperature is expected to rise, as expected, but precipitation is also expected to rise, even for percentiles representing extremely dry years.

Finally, projected changes in climate are compared by RCP category. Figure 6-1 and Figure 6-2 show projected trends in long-term mean precipitation and temperature by RCP. To construct the first graph, statistics were computed by first grouping the values of long-term mean precipitation for each 30-year period by RCP. Five statistics were then calculated: the minimum value, maximum value, and the 10th, 50th, and 90th percentile values of long-term means. A similar graph was constructed from the long-term mean temperature values.

It is clear from these graphs that average precipitation and temperature are both projected to rise in the Potomac basin for all RCP categories. In the case of precipitation, differences between runs in the same RCP grouping are greater than differences between RCPs, though by the 2080's runs in RCP2.6 tend to indicate the least increase and runs in RCP8.5 the greatest increase. In the case of temperature, RCP8.5 runs tend to indicate increases more than a degree higher than RCP2.6 runs by the year 2050, and by 2085, there is no longer much overlap between runs based on RCP2.6 and those based on RCP8.5, with the majority of the RCP2.6 runs indicating that temperature will begin declining.

Table 6-2: Annual precipitation and temperature for the Potomac basin – long-term means and standard deviations from BCSD filtered projections.

	Precipitation			**Temperature**		
Time interval	**Mean, mm/year (inches/year)**	**Change in mean from study base period, percent**	**Standard deviation, mm/year (inches/year)**	**Mean, °C (°F)**	**Change in mean from study base period, °C (°F)**	**Standard deviation, °C (°F)**
From historical data (PRISM)						
1896-1979	991 (39.0)	0.6	128 (5.0)	11.19 (52.1)	0.3	0.60 (1.1)
From ensemble of 224 BCSD filtered projections						
1950-1979 (study base period)	985 (38.8)	0.0	138 (5.4)	10.94 (51.7)	0.0 (0.0)	0.60 (1.1)
1980-2009	1011 (39.8)	2.6	145 (5.7)	11.45 (52.6)	0.5 (0.9)	0.67 (1.2)
2010-2039	1052 (41.4)	6.8	154 (6.1)	12.55 (54.6)	1.6 (2.9)	0.76 (1.4)
2040-2069	1089 (42.9)	10.6	164 (6.5)	13.57 (56.4)	2.6 (4.7)	0.99 (1.8)
2070-2099	1110 (43.7)	12.7	169 (6.7)	14.41 (57.9)	3.5 (6.2)	1.49 (2.7)

Table 6-3: Percentile values of annual precipitation and temperature, computed from 30-year intervals for ensemble of 224 filtered runs.

	Precipitation, mm/year (inches/year)			Temperature, °C		
	Percentile			Percentile		
Time interval	**1st**	**50th**	**99th**	**1st**	**50th**	**99th**
1950-1979	702 (27.6)	978 (38.5)	1333 (52.5)	9.5 (49.1)	10.9 (51.6)	12.3 (54.1)
1980-2009	720 (28.3)	1006 (39.6)	1390 (54.7)	9.8 (49.6)	11.4 (52.5)	13.1 (55.6)
2010-2039	732 (28.8)	1043 (41.1)	1444 (56.9)	10.9 (51.6)	12.5 (54.5)	14.4 (57.9)
2040-2069	743 (29.3)	1079 (42.5)	1513 (59.6)	11.5 (52.7)	13.5 (56.3)	16.1 (60.0)
2070-2099	756 (29.8)	1101 (43.3)	1555 (61.2)	11.4 (52.5)	14.3 (57.7)	16.2 (61.2)

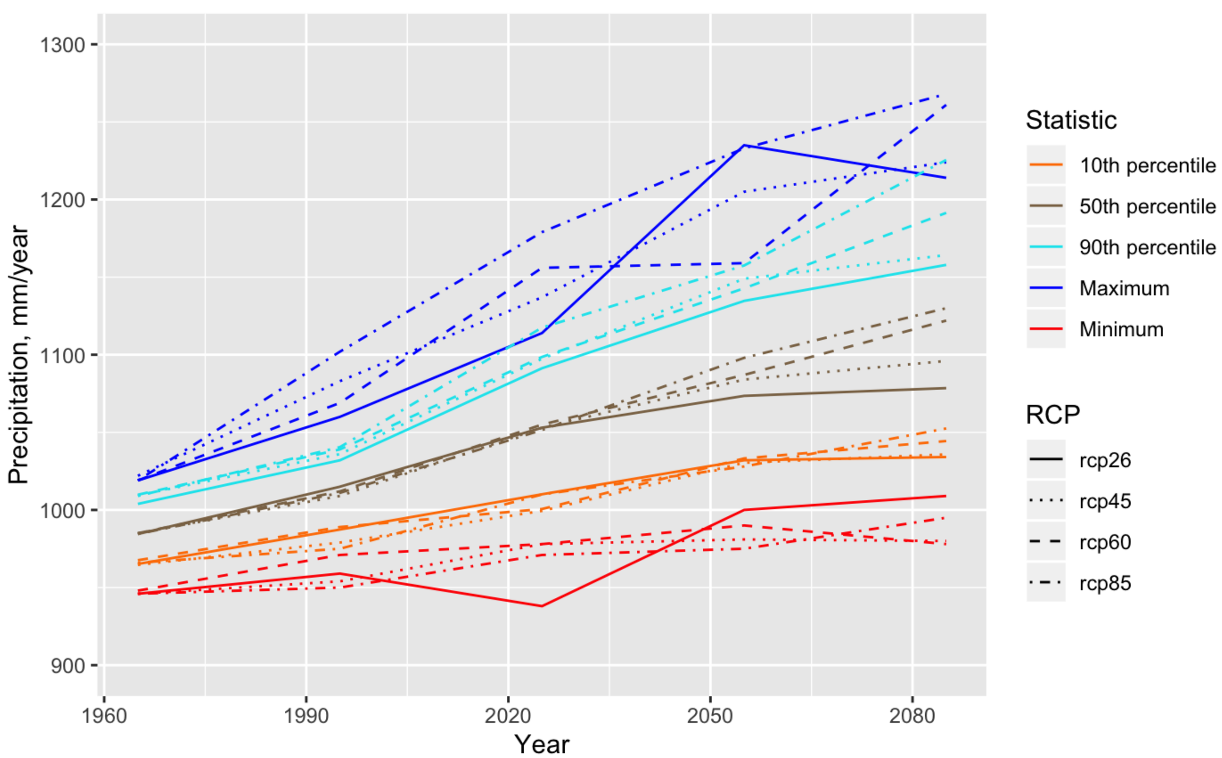

Figure 6-1: Statistics for long-term mean precipitation, by RCP, from filtered BCSD projections.

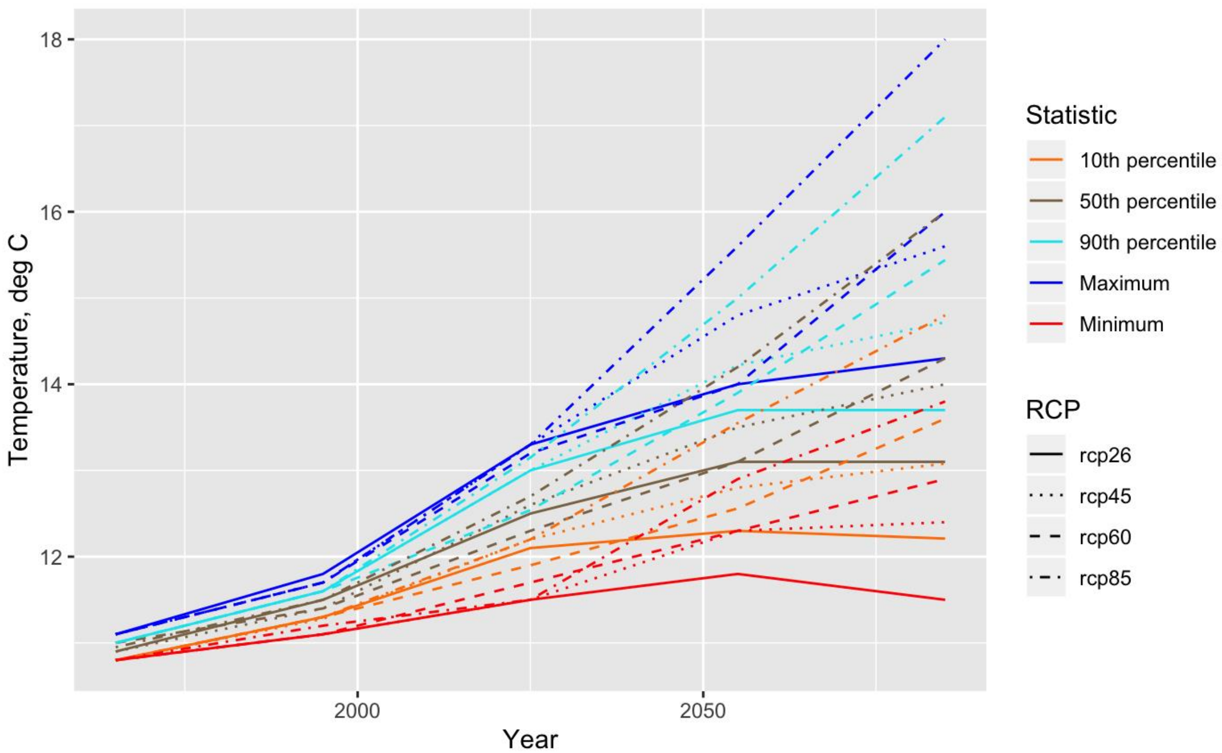

Figure 6-2: Statistics for long-term mean temperature, by RCP, from filtered BCSD projections.

6.4 Potomac Basin Streamflow

6.4.1 Climate Response Function

The response of annual streamflow to changes in climate was determined using natural Potomac River flow at Little Falls, derived from historical observations, and the PRISM dataset of observed climate, both described above. The PRISM dataset was used because it was found to significantly outperform the nClimGrid dataset in terms of its ability to predict annual Potomac River flow. Multiple least squares regression was used to predict mean flow, Q_i, from mean temperature, T_i, and mean precipitation, P_i, in a given year, i. Following Milly *et al*. (2018), a term representing lagged flow, Q_{i-1}, is included in the regression equation to represent the effect on flow of conditions in the prior year. In addition, a nonlinear precipitation term is included because it is found to improve predictions in very high-flow and low-flow years. The flow and precipitation variables in the equation are written in fractional form, Q_i/Q_0 and P_i/P_0, respectively, where Q_0 = 337 mm/year and P_0 = 991 mm/year are defined as the means of annual flow and precipitation in the historical base period, 1896-1979.[17] The temperature term is a

[17] Annual flow for the 11,560 square mile Potomac drainage area above Little Falls is converted from cfs to mm using the conversion factor 0.02983.

difference, $T_i - T_0$, where T_0 = 11.19 °C is the mean temperature over the historical base period. The regression equation is

$$Q_i / Q_0 = \beta_1 \, Q_{i-1} / Q_0 + \beta_2 \, (T_i - T_0) + \beta_3 \, P_i / P_0 + \beta_4 \, (P_i / P_0)^2 \qquad \textit{Equation 6-1}$$

where

i = calendar year, from 1896 through 2017

Q_i = mean annual natural Potomac River flow at Little Falls in year, i (mm/year)

T_i = mean annual temperature in the Potomac watershed above Little Falls in year, i (°C)

P_i = mean annual precipitation in the Potomac watershed above Little Falls in year, i (mm/year)

Regression coefficients, β_1 through β_4, along with statistics from the regression analysis, are given in Table 6-4. The coefficient of determination for the regression model is 0.98. All regression coefficients were significant at the 90% significance level.

Table 6-4: Regression coefficients for climate response function based on historical data.

	β_1	β_2	β_3	β_4
Coefficient	0.144	-0.051	-0.204	1.039
Standard Error	0.045	0.025	0.137	0.107
p-value	0.001	0.020	0.069	0.000

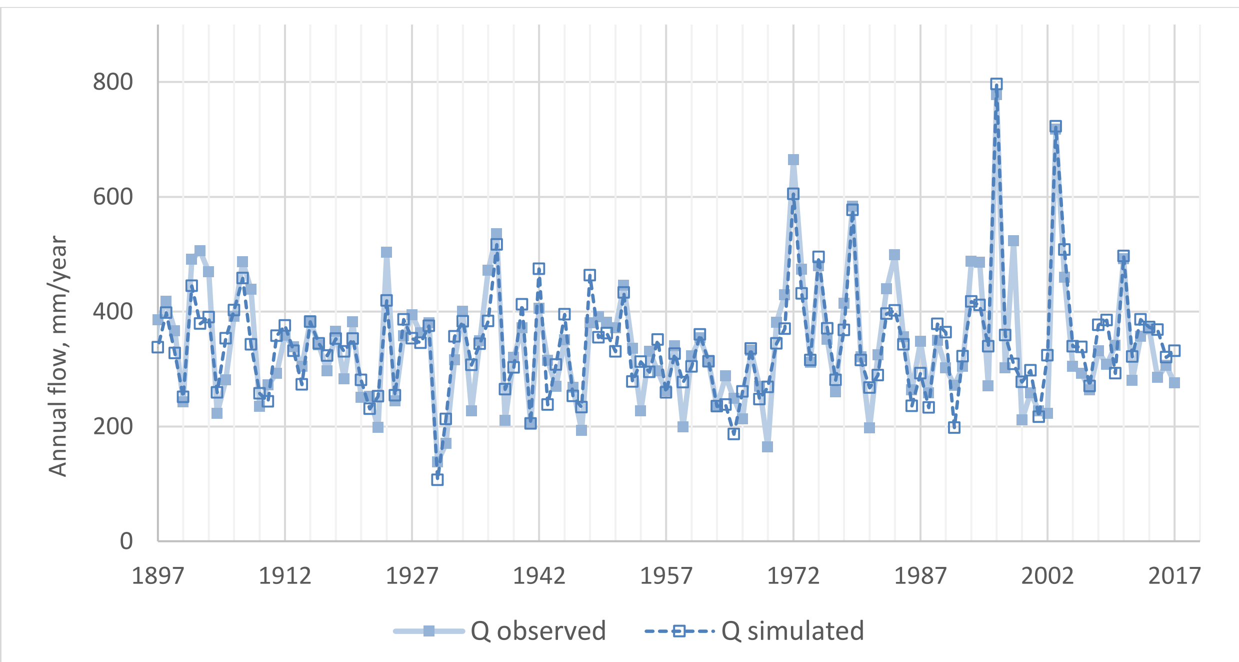

Figure 6-3: Comparison of actual annual natural Potomac River flow at Little Falls, derived from observations, compared to flows predicted by the regression equation.

A comparison of actual and predicted annual flows is shown in Figure 6-3. The correlation coefficient of actual flows and predicted flows is 0.88 and the Nash-Sutcliffe Efficiency coefficient is 0.77.

Results above indicate that the climate response function, using actual annual temperature and precipitation values as inputs, provides a reasonably good match to the time series of actual annual natural Potomac River flows derived from USGS flow observations. To further assess the methodology used in this study, the statistical properties of the ensemble of flows generated using the BCSD climate projections for the 1950-1979 base period are compared with those of actual flows by means of quantile plots, which are sample approximations to the underlying cumulative distribution functions. Quantile plots are constructed from a given sample set of size n by ranking sample values, x_i, from smallest to largest and assigning the smallest a rank of r=1 and the largest a rank of r=n (see Helsel and Hirsch, 2002). The p^{th} quantile value of a variable, x, is the value of the variable which is not exceeded by a fraction, p, of the sample points. The sample values are then plotted, from smallest to largest, where the y-axis gives the quantiles and the x-axis gives the quantile values. A sample quantile, as discussed above, is equivalent to the corresponding percentile, where percentile = quantile*100. More formally, the quantile function is defined as the inverse of the cumulative distribution function, F, where for a random variable X, F(x) is the probability, p, that X is less than the value, x, or $F(x) = Prob(X < x) = p$. Then the quantile function, q(p), can be expressed as $q(p) = F^{-1}(p) = x$. A variety of methods are used to compute probabilities for quantile plots based on an empirical sample (Helsel and Hirsch, 2002). In this study we use the Weibull formula, where $p = r/(n+1)$.

The quantile plots of actual and predicted annual flows are computed for the period for which conditions in the Potomac basin are judged to be minimally affected by climate change, that is, within the 1896-1979 historical period. Results are shown in Figure 6-4. In this figure, the quantile plot of actual annual natural Potomac River flows, derived from USGS observations, for the 84-year historical period, is compared with the quantile plot of the entire ensemble of predicted annual flows from all of the 224 filtered BCSD projections, for the 30-year base period, 1950-1979. Also shown in the graph is the quantile plot of actual annual natural Potomac River flows for the base period. This figure indicates that the quantile plot of the flows predicted from the BCSD ensemble matches quite well with the plot of actual flows in the historical period. In addition, the quantile plot of actual flows in the 30-year base period matches reasonably well to the plot of actual flows in the 84-year historical period.

Though comparisons of actual and predicted time series plots and actual and predicted quantile plots both indicate that the climate response function provides a reasonably good model of annual Potomac River flow, this function does under-predict the lowest annual flow in the historical record, the flow of 1930. The observed mean annual flow in 1930 is 138 mm and the flow predicted by the climate response function is 107 mm, a 22% difference. The under-prediction of flow for the drought of record is a limitation of the climate response function. However, the quantile scaling methodology used in this study (see Section 6.5) to some degree overcomes this limitation by basing predictions of future flows on proportional changes of quantile values rather than on projected changes in the absolute values of flows, as discussed below.

A limitation of the climate response function coefficients in Table 6-4 is that because they are based on historical data, many of the values of annual precipitation and temperature in the climate projections are outside the range of the sample set used to derive the coefficients. To help confirm that the coefficients are reasonable, they can be compared with coefficients based on results from ICPRB's 2010 study, Part 2 (Ahmed *et al.*, 2013). In that study, the Chesapeake Bay Program (CBP) Watershed Model, Phase 5.2, was run with sets of inputs from 18 climate projections for 2040 provided by the USGS's National Research Program for the CBP. A reanalysis was conducted of output from the 18 Watershed Model runs done for that study, based on natural Potomac River flow, temperature, and precipitation averaged over the 12-year simulation period. Coefficients for a climate response function based on the CBP Watershed Model output are given in Table 6-5. Because these represent the response of "long-term" mean flows to changes in climate, the coefficient for lagged flow, β_1, is not included in the model.

Results in Table 6-5 are consistent with those in Table 6-4. All coefficients in Table 6-5 are within two standard errors of those in Table 6-4. Most importantly, the coefficient for the response of streamflow to temperature, β_2, in Table 6-5, -0.074, is within one standard error of the coefficient in Table 6-4, -0.051. The magnitude of the temperature coefficient derived from the CBP model output is higher than that derived from the historical data. However, the CBP Watershed Model, Phase 5.2, uses the Hamon model to simulate evapotranspiration, and comparisons of evapotranspiration models suggest that Hamon may over-simulate the response of streamflow to temperature (Milly and Dunne, 2017).

Table 6-5: Regression coefficients for climate response function based on CBP Watershed Model output.

	β_2	β_3	β_4
Coefficient	-0.074	-0.26	1.24
Standard Error	0.008	0.07	0.06
p-value	0.000	0.001	0.000

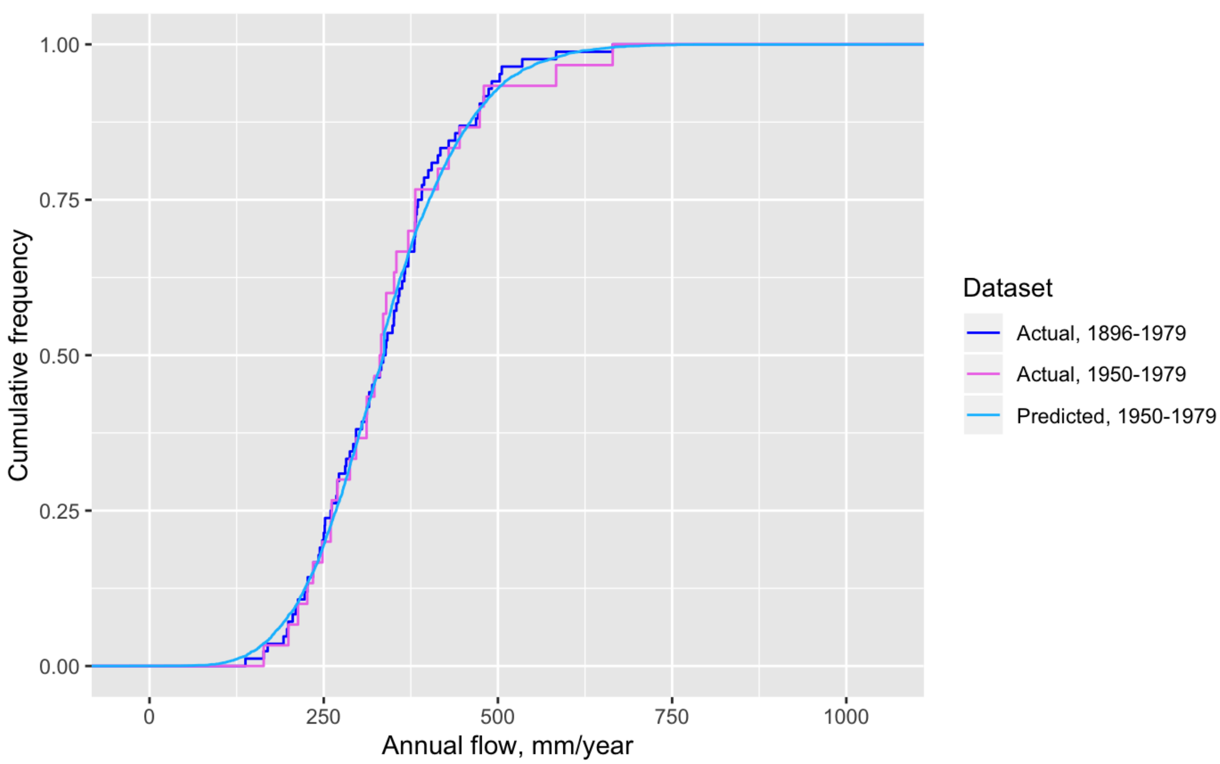

Figure 6-4: Comparison of quantile plots of observed and predicted natural Potomac River flow at Little Falls for pre-climate change historical periods.

6.4.2 Trends in Projected Flow

The climate response function, Equation 6-1, was used to obtain projections of natural annual Potomac River flow at Little Falls, using projected temperature and precipitation values from each of the 224 filtered BCSD climate projections, for each year in the 150-year period, 1950-2099. To investigate changes over time, long-term means and other statistics were computed, again using the five 30-year intervals of the simulation period to represent long-term conditions. Statistics were calculated based on the complete ensemble of 224 filtered BCSD projections. Table 6-6 gives means, standard deviations, selected quantile values of projected annual flows, and corresponding statistics from the historical record of actual flows for comparison purposes. For example, in Table 6-6 for the time interval, 2040-2069, the quantile value corresponding to quantile, 0.02, is 130 mm/year, indicating that for the sample consisting of projected flows for all of the 30 years of all of the 224 projections, 98% of the annual flow values exceed 130 mm/year and 2% of the values are less than or equal to 130 mm/year. Figure 6-5 shows projected trends in the 1st, 10th, 50th, 90th, and 99th percentile values (corresponding to the 0.01, 0.10, 0.50, 0.90, and 0.99 quantile values). Both the table and the figure indicate that for quantiles computed using the climate response function and the full ensemble of filtered BCSD projections, the lowest percentile annual flow values (corresponding to drought years) decrease over time while the highest percentile annual flow values (corresponding to very wet years) increase over time.

Table 6-6: Long-term statistics for projected natural Potomac River flow at Little Falls, mm/year.

Dataset	Time interval	Mean	Standard deviation	Quantiles for natural annual Potomac River flow, mm/year						
				0.01	0.02	0.10	0.50	0.90	0.98	0.99
Observed	1896-1979	337	100	159	168	216	337	473	551	597
Simulated based on all filtered BCSD projections	1950-1979	338	104	122	143	212	335	475	584	618
	1980-2009	347	114	118	143	210	340	493	606	649
	2010-2039	360	124	119	139	210	349	523	654	702
	2040-2069	370	135	102	130	207	360	543	681	745
	2070-2099	369	143	82	110	196	358	552	704	766

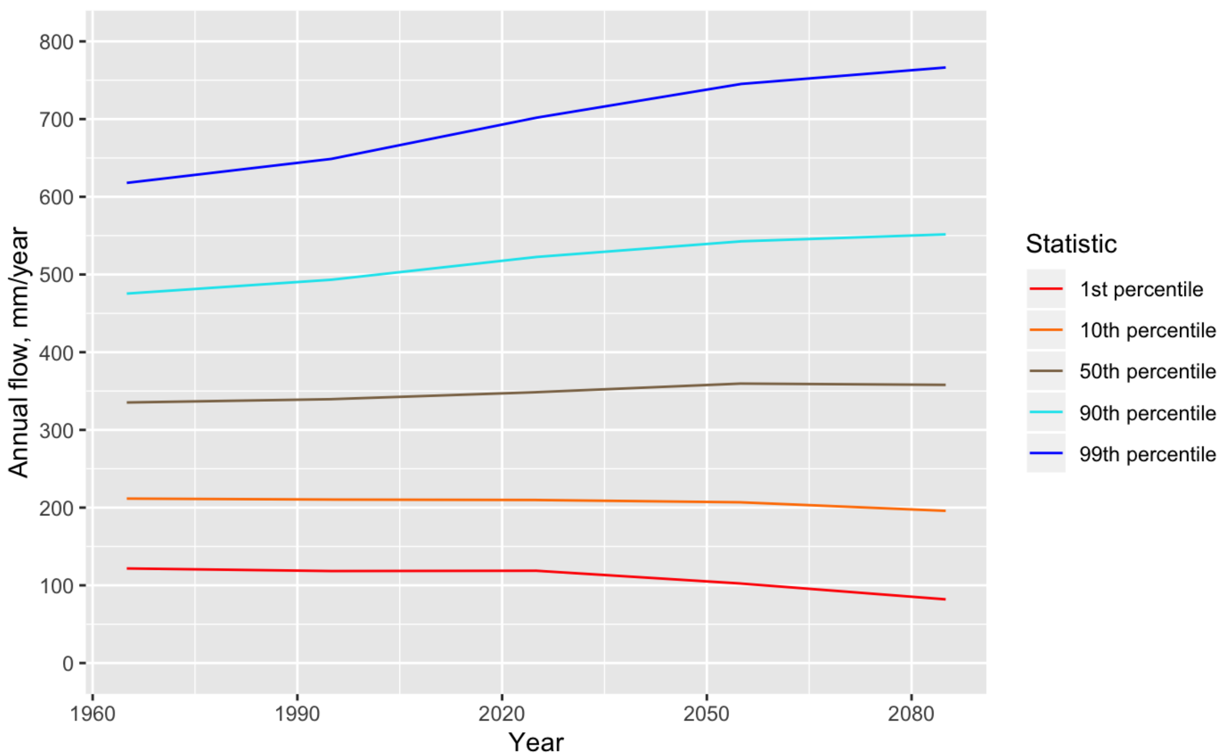

Figure 6-5: Trends in percentile values of projected natural Potomac River flow at Little Falls.

6.5 Future Changes in Streamflows

This section describes the methodology used to develop sets of streamflows representing future water availability in the Potomac basin, allowing the construction of planning scenarios for daily natural Potomac River flows and reservoir inflows. A quantile scaling approach is applied to compute flow-dependent scale factors for mean annual streamflows for each forecast period of interest. Quantile methods are sometimes used to help correct biases in climate projections because they provide adjustments to the full range of quantile (or equivalently, percentile) values of a variable, such as precipitation, instead of simpler adjustments that just correct the mean and variance. Below we describe how quantile scaling is used in the current study to determine the projected fractional change in future annual flow, for each flow quantile, as measured from its value in a pre-climate change era. These fractional changes, by flow quantile, are then applied as scale factors to mean annual flow in each year of the historical record, allowing spatial and temporal disaggregation to the daily time step and to other streamflow locations in the basin. This method of spatial and temporal disaggregation to the daily time step follows Nowak *et al.* (2010), though in the current study no stochastic sampling step is included.

6.5.1 Quantile Scale Factors for Mean Annual Streamflows

Quantile scaling is used to compute flow-dependent scale factors for mean annual streamflows for each forecast period of interest. This approach is based on calculated quantile values of projected annual natural Potomac River flow at Little Falls computed from long-term time series, which in the case of this study are 30 years in length. Example quantile values appear in Table 6-6 above, where the base period, 1950-1979 represents pre-climate change conditions. Here the random variable, X, is annual natural Potomac River flow at Little Falls. Then for a given forecast period, *f*c, and probability, *p*, the scale factor, $S_{fc}(p)$, is defined as the ratio of the quantile value for flow in the forecast period, $q_{fc}(p)$ to that in the base period, $q_{base}(p)$, that is

$$S_{fc}(p) = \frac{q_{fc}(p)}{q_{base}(p)}$$ *Equation 6-2*

For example, if the forecast period of interest is the 2040-2069 time interval, the scale factor for the 0.50 quantile can be computed from flow quantile values in Table 6-6 as $S_{2040\text{-}2069}(0.50) = q_{2040\text{-}2069}(0.50)/q_{base}(0.50)$ = 360/335 = 1.075. Thus, in this example, it is predicted that the 0.50 quantile (the median value) for annual flows will increase by a factor of 1.075 in the period, 2040-2069, as compared to the 1950-1979 pre-climate change base value, that is, there will be a 7.5% increase.

Table 6-7 below gives quantile scale factors for the four 30-year time intervals following the 30-year base period, 1950-1979. These scale factors were computed from the combined set of annual flows from a pooled sample of all 224 filtered BCSD projections. It is evident from this table that flows in low-flow years are projected to decrease in the future, whereas flows in the mid-range flow years are projected to rise and flows in the high-flow years are projected to rise quite significantly.

Table 6-7: Quantile scale factors for 224 BCSD projection ensemble, for each 30-year time interval.

	Base period	**Forecast period**			
Flow quantile	**1950-1979**	**1980-2009**	**2010-2039**	**2040-2069**	**2070-2099**
0.005	1.00	0.91	0.97	0.81	0.55
0.010	1.00	0.97	0.98	0.84	0.67
0.020	1.00	1.00	0.98	0.91	0.77
0.050	1.00	1.01	1.01	0.97	0.88
0.100	1.00	0.99	0.99	0.98	0.92
0.250	1.00	1.00	1.02	1.03	1.01
0.350	1.00	1.01	1.03	1.05	1.04
0.500	1.00	1.01	1.04	1.07	1.07
0.650	1.00	1.04	1.08	1.12	1.12
0.750	1.00	1.05	1.08	1.13	1.14
0.900	1.00	1.04	1.10	1.14	1.16
0.950	1.00	1.05	1.12	1.18	1.18
0.980	1.00	1.04	1.12	1.17	1.20
0.990	1.00	1.05	1.14	1.21	1.24
0.995	1.00	1.04	1.12	1.22	1.27

6.5.2 Sources of Uncertainty in Predicting Future Flows

The quantile scale factors provide a tool to investigate changes in future streamflow due to projected changes in climate. However, the values of the scale factors are subject to considerable uncertainty. Two sources of uncertainty are discussed below: uncertainty reflected in the range of climate projections used in this study, and uncertainty due to prediction errors of the climate response function used to predict annual streamflow based on annual temperature and precipitation.

6.5.2.1 Uncertainty due to the wide range of climate projections

Results in Table 6-7 were computed from the full ensemble of 224 filtered BCSD projections. To better illuminate the wide range of potential future flow conditions predicted by climate models, the 224 flow time series were ordered and placed into groups of roughly equal size based on mean flow calculated over the 2040-2069 time interval. These groups are denoted as “Very Dry”, “Dry”, “Average”, “Wet”, and “Very Wet”, where the Very Dry group of projections had the lowest values of mean flow in 2040-2069, and the Very Wet group had the highest values of mean flow in this period. Quantile scale factors were computed from pooled samples of runs in each of these five groups of projections for the 2040-2069 forecast period. Results appear in Table 6-8, along with scale factors computed from the ensemble of all 224 projections, for comparison purposes.

The large range of uncertainty in future flow conditions due to the range in climate projections is evident in the results appearing in Table 6-8. The projected change in flows during a drought of a severity expected to occur approximately once every 100 years is represented by the scale factor for the

0.01 flow quantile. In Table 6-8, the scale factors for the 0.01 flow quantile are 0.64, 0.84, and 0.88, for the respective Very Dry, Dry, and Medium groups of runs, implying that flows in a future severe drought may be 36%, 16%, or 12% lower than flows that occurred historically. On the other hand, the scale factors for the 0.99 flow quantile for the Wet and Very Wet groups indicate that flows in a severe drought could be significantly higher, by 13% or by as much as 32%, due to the impact of climate change.

Table 6-8: Quantile scale factors for the 2040-2069 forecast period, reflecting uncertainty in downscaled global climate model projections.

	Groups of projected flow time series, with grouping based on mean flow in 2040-2069					
Flow quantile	**Very Dry**	**Dry**	**Medium**	**Wet**	**Very Wet**	**Ensemble of all flow time series**
0.01	0.64	0.84	0.88	1.13	1.32	0.84
0.02	0.67	0.87	0.93	1.13	1.35	0.91
0.05	0.76	0.90	1.00	1.13	1.26	0.97
0.10	0.79	0.92	1.04	1.12	1.21	0.98
0.25	0.83	0.98	1.06	1.13	1.24	1.03
0.35	0.87	1.00	1.06	1.14	1.24	1.05
0.50	0.90	1.02	1.09	1.15	1.25	1.07
0.65	0.95	1.06	1.11	1.18	1.27	1.12
0.75	0.96	1.05	1.13	1.17	1.29	1.13
0.90	0.96	1.06	1.13	1.18	1.32	1.14
0.95	0.96	1.09	1.16	1.22	1.30	1.18
0.98	0.97	1.11	1.16	1.23	1.29	1.17
0.99	0.98	1.16	1.18	1.22	1.32	1.21

6.5.2.2 Uncertainty due climate response function prediction errors

The climate response function, Equation 6-2, is a simple but reasonably successful model for predicting annual streamflow based on annual temperature and precipitation. However, the uncertainties in the model coefficients, represented by the standard errors in Table 6-4, lead to uncertainties in the flow predictions. Most importantly, changes in the temperature coefficient, β_2, have a significant effect on the low-flow values of the quantile scale factors. To represent this uncertainty, quantile scale factors for the 2040-2069 forecast period were computed using values of the temperature coefficient which were one standard error less than or greater than the value estimated by the regression analysis, $\beta_2 = -0.051$, that is, $\beta_2 = -0.051 - 0.025 = -0.076$ and $\beta_2 = -0.051 + 0.025 = -0.026$. The resulting sets of quantile scale factors for the future flows in the 30-year period, 2040-2069, appear in Table 6-9. Results in this table show that differences are most pronounced for the lower flow quantile values, and least pronounced for the high quantile values. For example, the scale factors for the 0.01 quantile range from 0.60 to 1.07, indicating that changes in annual flows in extreme drought years may range from -40% to +7%. On the other hand, results in Table 6-9 for the 0.99 quantile scale factors, which range from 1.16 to 1.25, indicate that flows in extremely wet years may increase from 16% to 25% due to climate change.

Table 6-9: Range of quantile scale factors for 2040-2069 forecast period, reflecting uncertainty in streamflow response to temperature.

	Flow scale factors for 2040-2069		
Flow quantile	**Temperature coefficient one SE less than regression model value $\beta_2 = -0.076$**	**Temperature coefficient from regression model: $\beta_2 = -0.051$**	**Temperature coefficient one SE greater than regression model value $\beta_2 = -0.026$**
0.01	0.60	0.84	1.07
0.02	0.69	0.91	1.10
0.05	0.81	0.97	1.11
0.10	0.84	0.98	1.11
0.25	0.93	1.03	1.12
0.35	0.96	1.05	1.14
0.50	1.00	1.07	1.15
0.65	1.05	1.12	1.19
0.75	1.06	1.13	1.19
0.90	1.09	1.14	1.20
0.95	1.13	1.18	1.23
0.98	1.12	1.17	1.22
0.99	1.16	1.21	1.25

6.5.3 Planning Scenarios for Future Climate and Streamflow

Six different scenarios for future climate and streamflow in the Potomac basin are used in this study to assess the future reliability of the WMA water supply system, three scenarios for each of the two forecast years, 2040 and 2050. The scenarios reflect the range of uncertainty in future flow conditions due to uncertainty in our knowledge of the response of streamflow to increasing temperatures. Conditions associated with each scenario are given in Table 6-10, below.

The altered climate scenarios use quantile scale factors that were computed from the combined set of annual flows from all 224 filtered BCSD projections, as was done for the results in Table 6-7. However, the 2040 – altered climate scenario is based on scale factors computed using a 30-year forecast period centered around 2040, that is, 2025-2054, and the 2050 – altered climate scenario is based on a forecast period centered around 2050, that is, 2035-2064.

Table 6-11 presents results similar to those in Table 6-10, but it gives changes in recent and current precipitation, temperature, and flows as predicted by the climate response function and ensemble of filtered BCSD projections for a recent 30-year period centered around 1995, and also for what might be viewed as the current period, centered around 2025. Values in the three columns under 1995 are used to “remove” the influence of climate change from the 30-year period, 1980-2009, in order to augment the pre-climate change historical record, 1896-1979 to a longer time series, 1896-2009. This procedure is described in more detail below. Values in the three columns under 2025 provide a range of predictions, based on the methodology used in this study, for the impact of climate change on conditions in the period in which we are now living.

Results in Table 6-10 are used to construct the six planning scenarios, which are used as input into the PRRISM water supply planning model, and consist of daily time series representing temperature, precipitation, natural Potomac River flow at Little Falls, and reservoir inflows. All future scenarios are derived from the historical daily record of precipitation, temperature, and streamflows in the Potomac basin, from January 1, 1896 through December 31, 2009. The climate time series are constructed by applying the constant change factor, given in Table 6-10, to the historical daily precipitation time series and by adding the constant delta change value to the historical daily temperature time series. The flow time series are constructed with methodology similar to the spatial and temporal disaggregation procedure used by Nowak *et al.* (2010) for annual streamflow, by applying the flow-dependent quantile scale factors to daily streamflow values, based on the quantile value of the mean annual flow.

To apply the quantile scale factors to the historical daily flow records, the annual mean flow values of natural flow at Little Falls are first sorted and each year’s quantile is computed. For example, the lowest mean annual flow in the historical record occurred in 1930, the year of the historical drought of record for the WMA system. Thus, 1930 is assigned a quantile of 1/(114 + 1) = 0.0087, where 114 is the total number of years in the period, 1896-2009. The second lowest annual flow occurred in 1969, so it is assigned a quantile of 2/(114 + 1) = 0.0174. The highest annual flow occurred in 1996, so it is assigned a quantile of 114/(114 + 1) = 0.9913. The quantiles in Table 6-10 range from 0.005 to 0.995, but only include selected intermediary values. Linear interpolation between these intermediary values is used to determine scale factors for all of the quantiles associated with the 114 years in the historical time series. For example, for the 2040 altered climate Medium Flows scenario, the scale factor for the year 1930 is computed by linearly interpolating between the scale factors for the 0.005 and 0.010 quantiles, 0.86 and 0.91, resulting in a scale factor of 0.90 for daily flows in this year.

The flow-dependent scale factors in some of the columns of Table 6-10 are not monotonically increasing functions of quantile, as might be expected, but rather, exhibit a certain degree of “noise”. This small random variation is due to the significant variation present in the ensemble of BCSD temperature and precipitation projections as well as the relatively short length of the period (30 years) used to compute “long-term” statistics in this study. This noise is only on the order of 1%, and it was decided that attempting to remove it via a smoothing procedure would result in little benefit.

Table 6-10: Planning scenarios for precipitation, temperature, and regional streamflow.

		2040 (2025-2054)			**2050 (2035-2064)**		
		Lower Flows	**Medium Flows**	**Higher Flows**	**Lower Flows**	**Medium Flows**	**Higher Flows**
Precipitation	Constant change factor	1.08[1]			1.10[3]		
Temperature	Constant delta change, °C	2.2[2]			2.5[4]		
Quantile scale factors for annual flows	0.005	0.63	0.86	1.10	0.55	0.83	1.10
	0.01	0.73	0.91	1.08	0.65	0.87	1.07
	0.02	0.79	0.96	1.11	0.72	0.93	1.10
	0.05	0.87	1.01	1.12	0.83	0.98	1.11
	0.10	0.89	1.00	1.10	0.86	0.98	1.10
	0.25	0.95	1.03	1.11	0.93	1.03	1.12
	0.35	0.97	1.04	1.11	0.96	1.04	1.13
	0.50	0.99	1.05	1.11	1.00	1.06	1.13
	0.65	1.04	1.09	1.15	1.04	1.10	1.18
	0.75	1.05	1.10	1.15	1.06	1.12	1.18
	0.90	1.07	1.11	1.16	1.08	1.14	1.19
	0.95	1.09	1.14	1.18	1.12	1.17	1.21
	0.98	1.08	1.12	1.16	1.12	1.16	1.20
	0.99	1.11	1.14	1.18	1.14	1.18	1.23
	0.995	1.11	1.15	1.19	1.17	1.21	1.25

[1]Based on the ratio of mean precipitation from the ensembled of filtered BCSD projections for 2025-2054 and 1950-1979.
[2]Based on the difference between mean temperature from the ensembled of filtered BCSD projections for 2025-2054 and 1950-1979.
[3]Based on the ratio of mean precipitation from the ensembled of filtered BCSD projections for 2035-2064 and 1950-1979.
[4]Based on the difference between mean temperature from the ensembled of filtered BCSD projections for 2035-2064 and 1950-1979.

Table 6-11: Recent and current scenarios for precipitation, temperature, and regional streamflow.

		1995 (1980-2009)			2025 (2010-2039)		
		Lower Flows	**Medium Flows**	**Higher Flows**	**Lower Flows**	**Medium Flows**	**Higher Flows**
Precipitation	Constant change factor	1.03[1]			1.07[3]		
Temperature	Constant delta change, °C	0.5[2]			1.6[4]		
Quantile scale factors for annual flows	0.005	0.86	0.91	0.98	0.77	0.97	1.14
	0.01	0.92	0.97	1.00	0.83	0.98	1.10
	0.02	0.94	1.00	1.02	0.85	0.98	1.10
	0.05	0.98	1.01	1.03	0.91	1.01	1.10
	0.10	0.97	1.00	1.02	0.92	0.99	1.07
	0.25	0.97	1.00	1.01	0.96	1.02	1.08
	0.35	0.99	1.01	1.02	0.97	1.03	1.08
	0.50	1.00	1.01	1.03	1.00	1.04	1.08
	0.65	1.03	1.04	1.06	1.04	1.08	1.12
	0.75	1.03	1.05	1.06	1.05	1.08	1.12
	0.90	1.03	1.04	1.05	1.07	1.10	1.13
	0.95	1.03	1.05	1.06	1.09	1.12	1.15
	0.98	1.02	1.04	1.05	1.09	1.12	1.15
	0.99	1.03	1.05	1.07	1.11	1.14	1.17
	0.995	1.03	1.04	1.05	1.11	1.13	1.15

[1]Based on the ratio of mean precipitation from the ensembled of filtered BCSD projections for 1980-2009 and 1950-1979.
[2]Based on the difference between mean temperature from the ensembled of filtered BCSD projections for 1980-2009 and 1950-1979.
[3]Based on the ratio of mean precipitation from the ensembled of filtered BCSD projections for 2010-2039 and 1950-1979.
[4]Based on the difference between mean temperature from the ensembled of filtered BCSD projections for 2010-2039 and 1950-1979.

As mentioned above, the 84 years of the historical record that approximate an unaltered climate in the Potomac basin, 1896-1979, were augmented with the 30-year record, 1980-2009, by first "removing" the impact of climate change using the scale factors that appear in Table 6-11 in the columns under "1995." The 114-year historical record, 1896-2009, was first used in the sorting step and computation of quantiles describe above, then precipitation, temperature, and flows unaltered by climate were estimated by dividing values for 1980-2009 by the scale factors in the table (and subtracting the delta change from the temperature time series). After these steps, the 114 annual flows, now all unaltered by climate, were re-sorted and quantiles recalculated. Because the 1995 flow-dependent change factors were all fairly close to 1.0 and fairly slowly varying for quantiles greater than 0.05, as were all scale factors for 1980-2009, this procedure was judged to be reasonable given the accuracy of the calculations used in this study.

6.5.4 Impact of Climate Changes on the Drought of Record

For reference, the impact of climate change on a future drought corresponding to the historical 1930 drought of record is presented here. As discussed above, changes in daily flows for a given year are based on that year's quantile for annual flows, computed from the 114-year historical record, 1896-2009. The quantile for 1930 is 1/(114 + 1) = 0.0087. Linear interpolation is used to compute changes for a given annual flow quantile from the scale factors appearing in Table 6-10. Scale factors for daily flows in the 0.0087 quantile are derived from the scale factors for the 0.005 and 0.01 quantiles. Results for the 2040 and 2050 scenarios are as follows:

- 2040: change in daily flows in the 1930 drought of record year is -30%, -10%, and +9% for the Lower Flows, Medium Flows, and Higher Flows scenarios, respectively.
- 2050: change in daily flows in the 1930 drought of record year is -38%, -14%, and +8% for the Lower Flows, Medium Flows, and Higher Flows scenarios, respectively.

The changes in flow in the three scenarios used in this study can be compared with changes used in ICPRB's 2017 alternatives study (Schultz *et al.*, 2017). In that study, flow change factors differed by season, but the same change factors were applied to all years of the historical record, including the 1930 drought of record year. For the three 2040 climate change scenarios in the alternatives study, summertime (June, July, August) flows were assumed to change by +2%, -7%, and -19%, and other month flows were assumed to change by +2%, -6%, and -14%. Thus, flows in a drought year are considerably lower in the current study's Lower Flows scenario than they were in the alternative study's most severe climate scenario. Drought year flows in the current study's Medium Flows scenario fall between the moderately severe and most severe scenario in the alternatives study.

6.6 Impact of Climate Change on WMA Demands

PRRISM's representation of daily demands includes a component based on the seasonal regression models described in Chapter 4. Because daily demand in these models depends on precipitation and temperature, simulated demand responds to changes in climate. From Section 6.5.3, mean precipitation for 2040 and 2050 is projected to increase by 8% and 10%, respectively, and mean temperature is projected to increase by 2.2 and 2.5 ^{o}C. These changes are applied to the historical daily time series used in PRRISM to simulate daily WMA demands according to the models presented in Chapter 4. The increased precipitation tends to decrease demand for water, but the increase in temperature tends to increase water demand. Table 6-12 below summarizes total mean annual and total mean July WMA demand, as simulated by PRRISM, for the forecast years, 2040 and 2050.

It is evident from these results that climate change has little effect on average annual WMA demands, which only increase by 2 MGD in 2040 and 3 MGD in 2050. But the projected rise in temperature does have an impact on summertime demands. In Table 6-12, mean July demand is predicted to rise by 16 MGD in 2040 and by 18 MGD in 2050, as compared to demands that would be expected in the absence of climate change.

Table 6-12: Simulated impact of climate change on WMA demands.

Forecast year	Assumed changes in Potomac basin climate		Demand scenario	WMA Annual demand, MGD		WMA July demand, MGD	
	Change in precipitation, percent	Change in temperature, °C (°F)		Baseline	With climate change	Baseline	With climate change
2040	8	2.16 (3.9)	Low demands	452	456	532	554
			Medium demands	501	505	590	611
			High demands	550	554	647	669
2050	10	2.5 (4.5)	Low demands	473	479	557	582
			Medium demands	528	534	622	647
			High demands	583	588	687	711

7 Estimating the Impact of Drought Management on Upstream Consumptive Use

Under state drought management plans, water use restrictions may be imposed, with the level of restrictions dependent on the severity of drought conditions. State drought management decisions, therefore, can mitigate the impact of water use on downstream users. For this study, Maryland and Virginia drought stage declarations are represented in the PRRISM model, allowing simulation of the impact of state management decisions on consumptive use of water upstream of the WMA and the resulting impact on flow in the Potomac River at WMA intakes.

Communities, farms, and industries located upstream of the WMA withdraw water from the Potomac River, its tributaries, and the basin's groundwater aquifers. A portion of the water withdrawn is subsequently returned to Potomac basin streams and aquifers. However, a portion is not returned due to evaporation, transpiration by trees and other vegetation, incorporation into products, consumption by humans or livestock, diversion to another basin, or other processes. The portion of water withdrawn that is removed and not returned to be available for downstream use is termed "consumptive demand," or equivalently in this study, "consumptive use." Upstream consumptive use decreases river flow and, therefore, reduces water availability at WMA intakes, and is represented in the PRRISM model. Estimates of current and future upstream consumptive use, at a monthly timescale, are available from ICPRB's 2015 study (Ahmed *et al.*, 2015). In the 2017 alternatives study, Schultz *et al.* (2017) evaluated the benefits of reducing upstream consumptive use and found that a 10% reduction in upstream consumptive use (amounting to an annual average of 9.6 MGD in 2040) could improve the WMA system safe summer yield by 15 MGD and increase the 5th percentile of "worst day shared storage" from 1.2 BG to 2.0 BG.

During droughts, state governments have the authority to call for voluntary and mandatory restrictions that can substantially decrease water use (*e.g.,* Kenney *et al.*, 2004, Mini *et al.*, 2015). These restrictions generally target highly evaporative water uses such as outdoor lawn watering. Existing state drought management measures in the Potomac basin effectively decrease upstream consumptive water use. Drought restrictions imposed by the States also may impact water demand in the WMA service areas as discussed in Section 4.8, which details implementation of water use restrictions through the MWCOG response plan (MWCOG, 2001). In this chapter, we attempt to capture the impact of state drought management upstream of the WMA services areas on Potomac River flow by simulating a reduction of upstream surface water withdrawals. Although drought contingency plans are in place in all states within the Potomac basin, availability of information detailing drought assessment methods restricted this analysis to Maryland and Virginia drought regions.

7.1 Current and Future Upstream Consumptive Use and Surface Water Withdrawals

Estimates of annual withdrawals and consumptive use (CU) in the upper Potomac River basin upstream of the WMA supplier intakes are presented in Table 7-1. These estimates were derived from ICPRB's consumptive use database (Ahmed *et al.*, 2015). The largest upstream users are thermoelectric power facilities, which have combined annual withdrawals of approximately 1,516 MGD.

Table 7-1: Current estimated total withdrawals and consumptive use (CU) in the upper Potomac River basin, upstream of the WMA supplier intakes (MGD).

Use type	**Use description**	**Annual average withdrawals**	**Annual average CU in a dry year**	**Summer (Jun-Jul-Aug) average CU in a dry year**
AQU[1]	Aquaculture - the raising of fish, shellfish, and other organisms that live in water	33.2	1.6	2.0
COM[1]	Commercial self-supplied users	2.0	1.2	1.5
IND[1]	Industrial self-supplied users	60.6	19.2	21.4
IRRG[1]	Irrigation of golf courses	3.1	3.2	7.4
MIN[1]	Mining, including rock quarrying	33.5	6.1	5.8
PP – Mt. Storm[1]	Thermoelectric power – Mt. Storm Power Station	1,105.9	22.1	22.5
PP – other[1]	Thermoelectric power – other facilities	409.5	8.2	9.5
PWS[1,2]	Public water supply	123.3	9.2	21.3
IRRA[3]	Irrigation – agricultural (cropland and nurseries)	7.9	7.1	21.8
LIV[3]	Livestock	16.3	12.4	12.4
SSD[3]	Self-supplied domestic use	50.8	8.1	8.1
	TOTAL	1,846.0	98.5	133.6
	TOTAL – excluding Mt. Storm[4]	740.0	76.4	111.1

[1] Based on 2005 through 2008 state withdrawal data.
[2] Analysis excluded withdrawal data for Fairfax Water, Aqueduct, WSSC, Rockville, and City of Fairfax.
[3] Based on 2010 USGS county data and Horn *et al.* (2008).
[4] Mount Storm is upstream of Jennings Randolph Reservoir and its consumptive demand is mitigated by water quality releases from both Jennings Randolph and Savage reservoirs.

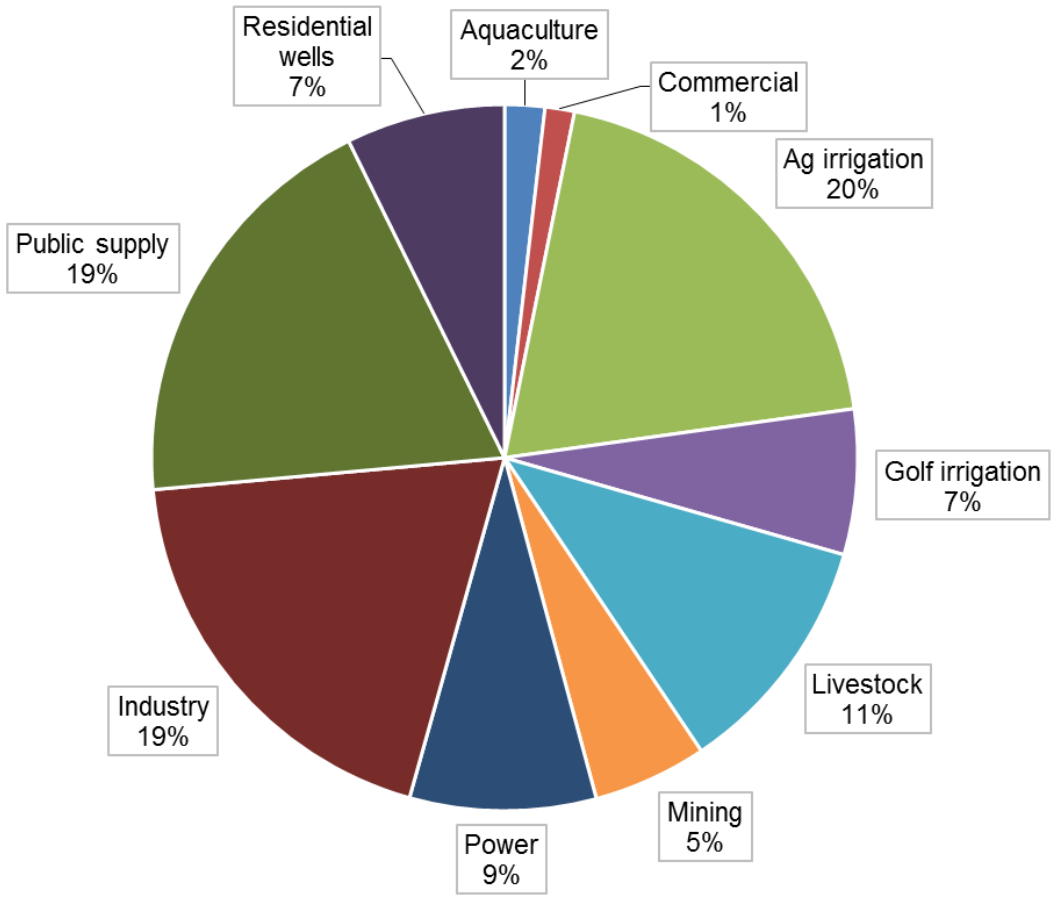

Figure 7-1: Percent summertime (June, July, August) upstream consumptive use by water use type, excluding the Mount Storm power plant.

Two facilities account for almost all of the power facility withdrawals: Dominion's Mount Storm Power Station in Grant County, West Virginia, and NRG's Dickerson Generating Station in Montgomery County, Maryland. Both of these facilities use water for once-through cooling systems. However, the consumptive use of water by power plants is more modest, since consumptive use for once-through cooling systems is relatively small. Upstream consumptive use in the summer months has the greatest impact on the WMA water supply system since demands are at their highest in the summer and flow in the river tends to be falling. The last column of Table 7-1 shows that the four water use types with the highest summertime upstream consumptive use are self-supplied industry, thermoelectric power, public water supply, and agricultural irrigation. Following Steiner *et al.* (2000), the Mount Storm Power Station's consumptive use is excluded from the total used in PRRISM to simulate the reduction in flow at Little Falls dam due to upstream consumptive use. This is because Mount Storm is located upstream of Jennings Randolph Reservoir, and its consumptive use from the North Branch of the Potomac River is mitigated by minimum water quality releases from the Jennings Randolph and Savage reservoirs to meet flow requirements at Luke, Maryland. Figure 7-1 gives a breakdown by percentage of upstream consumptive use by use type, excluding Mount Storm.

To simulate the impact of drought restrictions, reductions in surface water withdrawals in Maryland and Virginia are assumed and modeled as gains of water when drought emergency or warning stages are in effect. Estimates of current and future average annual surface water withdrawals for Maryland and Virginia are presented in Table 7-2. These estimates were derived from ICPRB's consumptive use database and are for the following use types: aquaculture, self-supplied industry, mining, golf course irrigation, self-supplied commercial, agricultural irrigation, livestock, and public water supply. Surface withdrawals from thermoelectric power generation were excluded from the analysis of drought restrictions impacts.

It should be noted that a major industrial user in the basin, a paper mill in Luke, Maryland, owned by the Verso Corporation, ceased operations in the spring of 2019. Consumptive use by the Luke paper mill is estimated to be one of the largest in the Potomac basin upstream of Little Falls dam. Based on monthly withdrawal data in ICPRB's consumptive use database, extending from 1985 through 2012, and limited discharge data, the summertime (June, July, August) consumptive use of the mill is estimated to be 18.4 MGD for the period, 2005-2008, or 48% of its corresponding withdrawals. Adjustments were not made to PRRISM simulations for this reduction in upstream consumptive use because at the time this study was conducted, the Verso Corporation was still seeking a buyer for the mill. However, if mill operations do not recommence, a significant adjustment to upstream consumptive use will be made in the upcoming 2025 water supply study.

Table 7-2: Projected current and future average annual surface water withdrawals upstream of WMA intakes.

Year	Withdrawals in Maryland (BG)	Withdrawals in Virginia (BG)
2020	86.8	41.3
2030	90.0	45.0
2040	93.2	48.7
2050	96.4	52.3

7.2 Impact of State Drought Management on Consumptive Use and Withdrawals

During droughts, state governments have the authority to call for reductions in water withdrawals by any users, thereby mitigating the impact of consumptive use and improving river flows. Maryland and Virginia maintain drought response plans defining drought stages for different levels of drought severity. Four drought levels or drought stages are considered: Normal, Watch, Warning and Emergency.

7.2.1 Modeling Drought Assessment

Daily time series are constructed of indicators representing the four drought stages for four regions of Maryland and Virginia upstream of the WMA. The time series, extending from October 1, 1929 through December 31, 2018, are composite values based on regional approximations of three individual drought indicators used by the states: precipitation, streamflow, and groundwater conditions. Information on a fourth drought indicator, regional reservoir storage levels, was not available. For this indicator, streamflow is used as a surrogate, with a 30-day delay.

The drought stage time series are used in PRRISM to provide an approximation for drought stage declarations made by the Maryland Department of Environment (MDE) and by the VADEQ. In actuality, additional information and use of best professional judgment are considered in drought stage declarations. In Maryland, the U.S. Drought Monitor and drought-related water supplier problems are also monitored (Swann, 2000). In Virginia, the Drought Management Task Force evaluates available information during its deliberations on drought stage recommendations, including Palmer Drought Severity Index, NOAA monthly and seasonal precipitation forecasts, information on impacts on agriculture (Crop Moisture Index), potential impacts on forests (Keetch-Byrum Drought Index), and operating conditions at public water works (reservoir storage) (DRTAC, 2003). Final decisions regarding drought stage declarations are made by the Virginia Drought Coordinator.

To construct the drought stage time series for Maryland, spreadsheet tools used by the MDE were applied. For Virginia, in-house tools were developed following the methods described in the Virginia Drought Assessment and Response Plan (DRTAC, 2003). Drought stages for the indicators used in this study are evaluated by comparing current conditions to long term average conditions. These indicators are evaluated on a regional basis. Drought regions are defined based on considerations of river basins, climatic divisions, physiographic provinces, major geomorphologic features and service areas of major water suppliers (DRTAC, 2003). Figure 7-2 shows the Virginia and Maryland drought evaluation regions within the Potomac basin. In Virginia, thirteen drought evaluation regions exist. Two of these regions fall within the Potomac basin upstream of the WMA: The Shenandoah Drought Evaluation Region and the Northern Virginia Drought Evaluation Region. In Maryland, there are six drought evaluation regions, with two of these regions falling within the Potomac basin upstream of the WMA: the Western Region and the Central Region.

Precipitation drought stage time series were developed at a monthly time scale. Monthly precipitation was retrieved for each of the counties in the drought regions considered from the Parameter Regression on Independent Slopes Model (PRISM) Climate Group data products. Monthly averaged precipitation was used to compute a normal precipitation series which consists of the rolling 30-year averaged precipitation. The ratio of actual monthly precipitation to normal monthly precipitation determines the drought stage. Table 7-3 shows the trigger percentages used for both Maryland and Virginia.

Streamflow drought stage time series were developed at a daily time scale. Daily streamflow data from 1929 through 2018 were downloaded from the USGS National Water Information System (NWIS) website for each of the gages determined by state drought plans and falling within the drought regions considered. Streamflow statistics for Maryland were provided by MDE and streamflow statistics for Virginia were retrieved from the USGS NWIS database.

Groundwater drought stage time series were developed at a monthly time scale. Field well measurements were downloaded from the USGS NWIS website for each of the wells considered in state drought plans for the drought regions considered. Monthly averaged levels were calculated from field measurements and compared to values equivalent to the 25th, 10th, and 5th percentiles of historical records. These historical record statistics were from the USGS NWIS database.

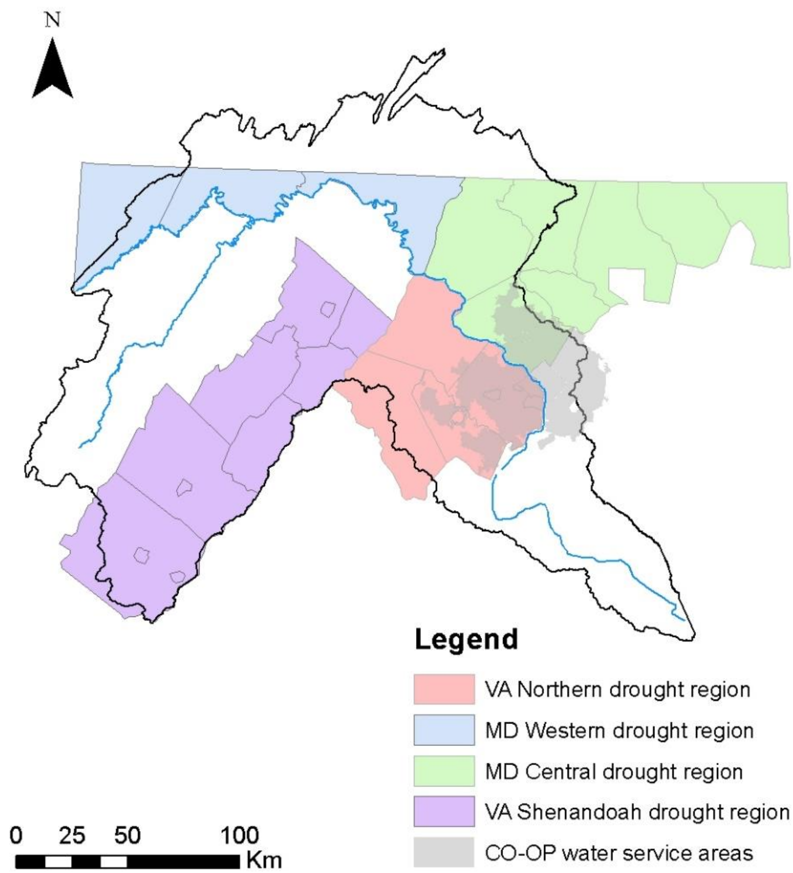

Figure 7-2: Drought evaluation regions included in the drought management impact analysis for Maryland and Virginia.

Table 7-3: Drought indicators, sources and triggers for Maryland and Virginia.

Indicator	Timescale	Data Source	Watch Trigger Percentile	Warning Trigger Percentile	Emergency Trigger Percentile
Precipitation	Monthly	PRISM	75	65	55
Streamflow	Daily	USGS NWIS	25	10	5
Groundwater	Monthly	USGS NWIS	25	10	5
Reservoir	Daily	-	-	-	-

The final drought stage is a composite of the precipitation, streamflow, groundwater, and reservoir drought stages. For a region to be placed in the "Watch," "Warning," or "Emergency" stage, two or more indicators must be in that category or a higher level. Figure 7-3 and Figure 7-4 summarize the resulting drought stages time series.

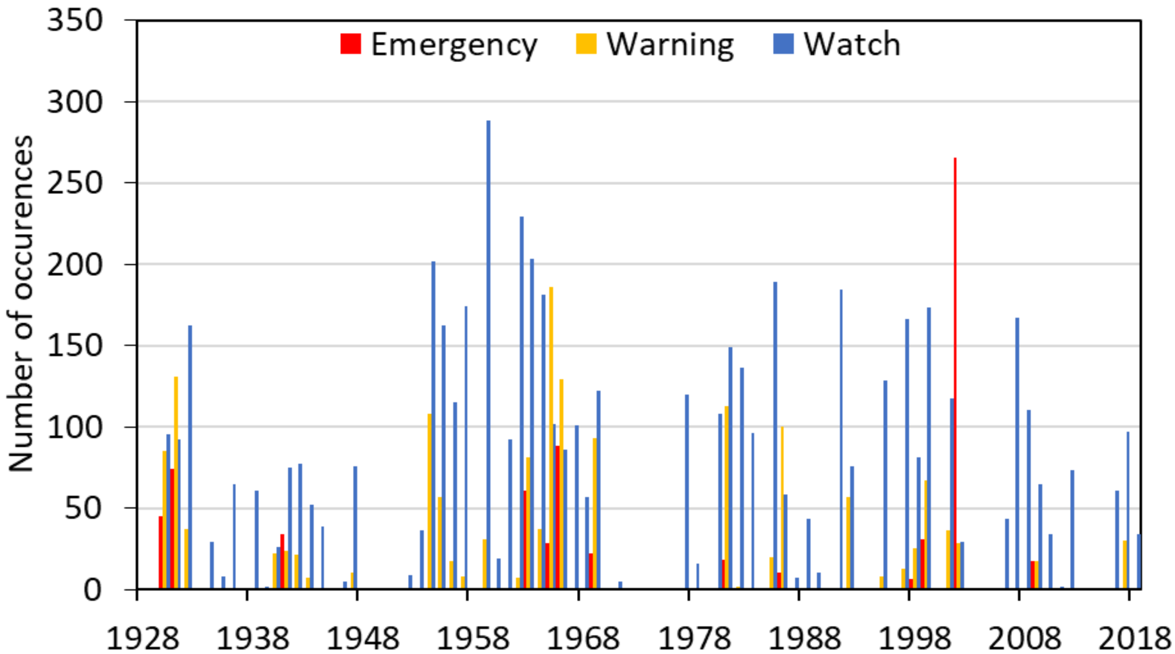

Figure 7-3: Drought time series summary in Maryland Central Region.

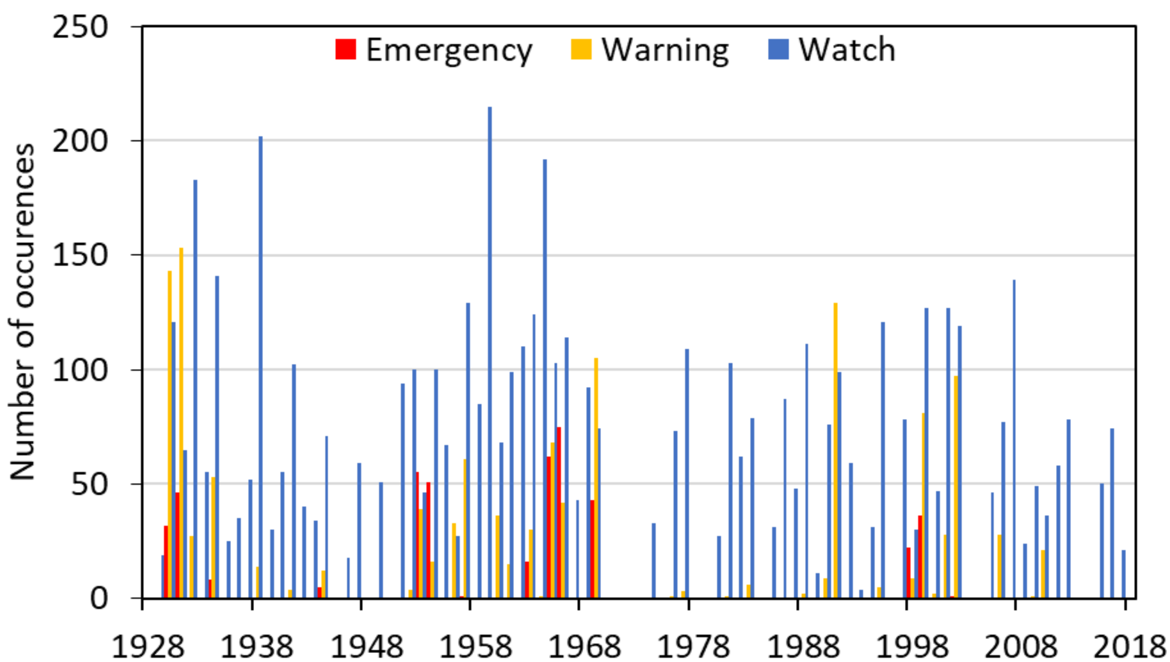

Figure 7-4: Drought time series summary in Maryland Western Region.

7.2.2 Modeling Drought Response

Occurrence of each drought stage (Watch, Warning, Emergency), triggers responses that vary by state, and by the nature and impact of the drought (DRTAC, 2003). The assumption is made that a drought watch stage may not lead to significant reduction in upstream water use. A drought warning stage may result in reductions in water use of 5% to 10%. During a drought emergency stage, mandatory water restrictions may result in water use reductions of 10% to 15% (DRTAC, 2003). Table 7-4 shows conservative estimates for upstream water withdrawal reduction percentages used by the current study.

Table 7-4: Percentage of reduction in surface water withdrawals.

Drought Status	Reduction in Demand
Normal	0%
Watch	0%
Warning	5%
Emergency	12.5%

7.2.3 Results

Reductions in surface water withdrawals by 5% during a drought warning stage and 12.5% during a drought emergency stage lead to a reduction of 1% in average upstream surface water withdrawals through the simulation period 1930 through 2009. For the year 1930, reductions in surface water withdrawals during summer months (June to September) were 12 MGD when considering medium and lower flow climate scenarios and 6 MGD for the higher flow climate scenario. Reductions in summer withdrawals were largest in 1999 when they reached 14 MGD for the lower flow climate scenario (Table 7-5).

These reductions in upstream withdrawals translate to improvements in river flow upstream of the WMA intakes. When state drought management measures are simulated using PRRISM, 1930 results indicate that average Potomac River flow from June through September increases by 6 to 12 MGD and minimum flow above WMA intakes improves by 10 to 18 MGD during a severe drought. PRRISM results also indicate that state drought management plans lead to increases in minimum storage levels in CO-OP system reservoirs experienced over the course of a severe drought.

Table 7-5: Simulated mean summer month reductions in surface water withdrawals (MGD) due to upstream drought management.

Drought Year	Higher flows	Medium flows	Lower flows
1930	6	12	12
1966	8	9	12
1999	12	13	14
2002	9	10	10
All years	1	1	1

8 Resource Analysis

The ability of the WMA system resources to meet future water demands is evaluated with CO-OP's water supply planning model, PRRISM. A scenario planning approach is used to investigate system performance under a plausible range of future conditions. Scenario planning is a tool often applied to help inform decisions regarding future infrastructure, especially under significant uncertainties such as the impact of climate change. Scenarios enable planners to test the robustness of alternatives and may assist in achieving stakeholder consensus.

In the current study, nine scenarios are used to represent ranges of uncertainties in the impact of climate change on water availability in the Potomac basin and in future WMA water demand. For each scenario, PRRISM simulations are conducted for four different configurations of the WMA system: a system with current and planned resources, and a system that has been enhanced with three different combinations of operational and structural alternatives recommended in the 2017 alternatives study (Schultz *et al.*, 2017).

8.1 Future Conditions Scenarios

Nine planning scenarios are constructed to assess the future performance of the WMA water supply system. The scenarios represent future conditions which span plausible ranges of uncertainty in future demand and hydrologic conditions. They are comprised of combinations of three demand scenarios, based on the uncertainty of the forecasts for total WMA demands, and three flow scenarios, based on the uncertainty of the response of streamflow to rising temperature, as described below.

8.1.1 Demand Scenarios

Forecasts of average annual WMA demands, computed using MWCOG Round 9.1 demographic projections, were presented in Chapter 3, along with the standard errors of the forecasts. Annual forecasts, combined with seasonal and daily variations in demand described in Chapter 4, are used in PRRISM to generate time series of daily withdrawals for a specified forecast year.

Three scenarios are used to represent WMA water demand in the future, based on results in Table 3-24. A medium demand scenario is based on the forecasts computed using the methods described in Chapter 3, and low and high scenarios are based on the forecasted demands and an estimated range of uncertainty represented by plus or minus one standard error (±SE). Under the assumption that a forecast is a random variable with a normal distribution, this range represents approximately a 68% confidence interval for the forecast value. The range, ±SE was selected for this study, rather than, for example, a 95% confidence interval, to avoid demand scenarios that might be viewed as extreme by stakeholders. Values for the WMA demand forecast standard errors, expressed as a percent of the forecast values, are also given in Table 3-24: ±9.7% for the 2040 forecast and ±10.4% for the 2050 forecast. The three demand scenarios are:

- <u>Low Demands</u>: total WMA demand is 453 MGD in 2040 and 474 MGD in 2050, based on forecasted annual demands multiplied by 0.903 for 2040 and by 0.896 for 2050
- <u>Medium Demands</u>: total WMA demand is 501 MGD in 2040 and 528 MGD in 2050, based on forecasted annual demands computed by the methods described in Chapter 3

- High Demands: total WMA demand is 550 MGD in 2040 and 583 MGD in 2050, based on forecasted annual demands multiplied by 1.097 for 2040 and by 1.104 for 2050

Daily demands simulated in PRRISM are also influenced by temperature and precipitation according to the models presented in Section 4.5, and thus respond to climate change, as described in Section 6.6.

8.1.2 Flow Scenarios

PRRISM simulates on a daily basis the water available to meet regional needs: Potomac River flows and reservoir inflows. Three scenarios are used to represent the impact of future climate on water availability in the Potomac basin. These scenarios span a range of uncertainty of the response of streamflow to rising temperature.

Chapter 6 describes the development of scale factors representing changes in flows due to climate change. All three flow scenarios incorporate the uncertainty of the global climate model projections, because all three are derived from 224 sets of BCSD temperature and precipitation projections for the Potomac basin. The scale factors are based on the projected changes in flow quantiles computed from a 30-year forecast period centered around the forecast year 2040, or 2050, from those computed for the 30-year base period, 1950-1979. The scale factors are a function of average annual flow and are lower for low-flow years and higher for high-flow years.

As discussed in Chapter 6, a climate response function was used to predict mean annual streamflow from mean annual temperature and precipitation. The coefficients of the response function were estimated using a least squares regression analysis of annual flow, temperature, and precipitation data over the historical record, 1896-2017. The scale factors derived in Chapter 6 for the quantiles representing the low flows present in drought years are most sensitive to changes in the temperature coefficient in the climate response function. This coefficient was estimated from the regression analysis to be $ß_2$ = -0.051, with a standard error of 0.025. The three flow scenarios were constructed using plus and minus one standard error to represent the range of uncertainty of the temperature coefficient. These three scenarios are described below, where comparisons are given to the “pre-climate change” base period, 1950-1979. The descriptions below gives representative results for annual flow quantiles from Table 6-10, where “extremely wet” represents changes in the 0.99 quantile, “typical” the 0.50 quantile, and “extremely dry” the 0.01 quantile of annual flow:

- Lower Flows: in this scenario, streamflows are quite sensitive to rising temperatures ($ß_2$ = -0.076)
    - flows in extremely wet years in 2040 and 2050 are 11% and 14% higher, respectively, than in the base period
    - flows in a typical year in the forecast period are about the same as in the base period
    - flows in extremely dry years in 2040 and 2050 are about 27% and 35% lower, respectively, than in the base period
- Medium Flows: streamflows are moderately sensitive to rising temperatures ($ß_2$ = -0.051)
    - flows in extremely wet years in 2040 and 2050 are 14% and 18% higher, respectively, than in the base period
    - flows in a typical year in 2040 and 2050 are 5% and 6% higher, respectively, than in the base period

  - flows in extremely dry years in 2040 and 2050 are 9% and 13% lower, respectively, than in the base period
- Higher Flows: streamflows are not greatly affected by rising temperatures (β_2 = -0.026)
  - flows in extremely wet years in 2040 and 2050 are 18% and 23% higher, respectively, than in the base period
  - flows in a typical year in 2040 and 2050 are 11% and 13% higher, respectively, than in the base period
  - flows in extremely dry years in 2040 and 2050 are 8% and 7% higher, respectively, than in the base period

8.2 Future WMA System

Results are presented on the performance of four different potential future configurations of the WMA water supply system. The configurations are listed below, in order of increasing level of enhancement.

- Baseline: Current system + Milestone Reservoir + Vulcan Quarry, Phase 1
- Baseline + Ops: Baseline + four recommended operational alternatives
- Baseline + Ops + Travilah: Baseline + Ops + Travilah Quarry
- Baseline + Ops + Travilah + Luck: Baseline + Ops + Travilah + Luckstone Quarry B

These future system configurations are based on the phased recommended options presented in the 2017 alternatives study (Schultz *et al.*, 2017). The Baseline configuration represents a future system that includes current resources and two additional resources which are acquired and planned to be in place by 2040: Loudoun Water's Milestone Reservoir and Fairfax Water's Vulcan Quarry, Phase 1. The second scenario, Baseline + Ops, represents a baseline system along with implementation of the four operational alternative recommended in the alternatives study and described in Section 2.3.5: i) operation of Milestone Reservoir in conjunction with Little Seneca Reservoir instead of in conjunction with Jennings Randolph Reservoir, ii) use of Loudoun Water's Beaverdam Reservoir for low-flow augmentation, iii) improvement in the accuracy of 1-day and 9-day river flow forecasts by 10%, and iv) use of Jennings Randolph water quality storage for water supply purposes during drought emergencies. The third configuration, Baseline + Ops + Travilah, assumes that Travilah Quarry is acquired and converted to a raw water storage facility by 2040, and is operated as a shared regional resource. The final configuration, Baseline + Ops + Travilah + Luck, assumes that the Luck Stone Quarry B has also been added to the regional system by 2040, and that water stored in this quarry is available to augment Potomac River flows during droughts.

8.3 Performance Metrics

CO-OP's PRRISM model was used to evaluate the ability of the future WMA system to meet the dual challenges of rising demands and climate change. A single PRRISM "run" for a given forecast year simulates WMA system daily operations over an 80-year period representing a range of conditions that might occur in a future climate. WMA withdrawals are based on forecasted demands, with a weather-dependent daily variation, as discussed in Chapter 4. Daily river flows and reservoir inflows are based on values from historical data, altered as described in Section 6.5.3 to reflect projected changes in climate. PRRISM provides a suite of summary statistics calculated from this sample of over 29,220 days in the 80-

year simulation period. One of the years in this sample, based in part on 1930 historic data (the WMA's "drought of record"), represents conditions in a prolonged severe drought. A second year, based in part on 1966 historic data, represents conditions in a short but severe drought. Any two different PRRISM simulations, each consisting of 80 years, are different because of the random component of the daily demand model. Results reported in this study are calculated by averaging the summary statistics from a set of 100 PRRISM runs.

Evaluations were done for each of the nine future conditions scenarios for both forecast years, 2040 and 2050, resulting in a total of 72 PRRISM run sets. The summary tables containing the full set of summary statistics for the 72 runs appear in Appendix A.5 along with a list and description of each of the statistics.

Four summary statistics are used as key performance metrics in this study:

- Percent years with no Potomac flow deficits: the percentage of years in the simulation period in which flow in the Potomac River at Little Falls is above 100 MGD (the Little Falls flow-by) on every day of the year, that is, in which combined WMA Potomac water supply needs and the environmental flow-by at Little Falls is always met.
- Percent years with emergency restrictions: the percentage of years over the simulation period in which emergency water use restrictions are implemented on one or more days of the year. In this study, emergency restrictions are assumed to be implemented when combined water supply storage in Jennings Randolph and Little Seneca reservoirs is below 5% of the combined capacity.
- Maximum 1-day Potomac flow deficit (MGD): the maximum shortfall in meeting combined WMA Potomac water supply needs and the Little Falls environmental flow-by on any single day of the simulation period.
- Minimum Travilah Quarry storage (BG): the minimum storage in Travilah experienced over the course of the simulation period.

The first two of these, percentage of years with no Potomac River flow deficits and percentage of years with emergency restrictions, are adopted from the 2017 alternatives study (Schultz *et al.*, 2017), where they were used to define that study's evaluation metrics. The third statistic, maximum Potomac River deficit in a single day, gives an indication of the severity of system failures, for scenarios in which they occur. The last statistic, minimum Travilah Quarry storage, is of interest to stakeholders because of the dual role that Travilah is expected to play in the WMA water supply system: as a backup supply in case of an emergency spill and as a resource to mitigate drought. Reductions in Travilah storage during drought reduce this reservoir's ability to serve as a backup supply in case of a spill.

8.4 Results

PRRISM was used to assess the performance of the WMA water supply system under all nine future conditions scenarios for all four potential future system configurations. Summaries of 2040 and 2050 results appear below in Table 8-1 and Table 8-2. In these tables, values are given for the four performance metrics described above in Section 8.3 for each future scenario and each future system configuration. Tables with a complete set of summary statistics for each run set are given in Appendix A.5.

Results in Table 8-1 and Table 8-2 are color-coded to indicate WMA system performance. In the current study, the definition of "reliable" WMA system performance is based on values of the first two of the PRRISM system performance metrics listed in Section 8.3, and follows the numerical criteria used in the

2017 alternatives study (Schultz *et al.*, 2017). That is, the system is considered reliable if the percent years with no Potomac River flow deficits is greater than or equal to 99.88% and the percent years with emergency water use restrictions is less than or equal to 0.06%. Using this definition, the color-coding in Table 8-1 and Table 8-2 is as follows:

- GREEN – denotes reliable performance,
- YELLOW – denotes marginal performance, if one or both of the reliability criteria are not met but the maximum Potomac deficit on a single day is very small (averaging 1 MGD or less), and
- RED – denotes system failure, that is, an inability of the system to meet combined WMA water supply and environmental flows in the event of severe drought.

Table 8-1: 2040 PRRISM values for: Percent years with no Potomac River deficits, Percent years with emergency restrictions, Maximum 1-day Potomac River flow deficit, Minimum Travilah Quarry storage.[1]

	Higher Flows			**Medium Flows**			**Lower Flows**		
	Low Demands	Medium Demands	High Demands	Low Demands	Medium Demands	High Demands	Low Demands	Medium Demands	High Demands
Baseline	**100.00% 0.00% 0 MGD NA**	**100.00% 0.00% 0 MGD NA**	**100.00% 0.01% 0 MGD NA**	**100.00% 0.00% 0 MGD NA**	**100% 0.85% 0 MGD NA**	**99.68% 2.54% 7 MGD NA**	**98.79% 2.50% 55 MGD NA**	**98.75% 2.53% 107 MGD NA**	**98.31% 3.45% 177 MGD NA**
Baseline + Ops	**100.00% 0.00% 0 MGD NA**	**100.00% 0.00% 0 MGD NA**	**100.00% 0.00% 0 M GD NA**	**100.00% 0.00% 0 MGD NA**	**100.00% 0.00% 0 MGD NA**	**99.95% 0.90% 0 MGD NA**	**99.11% 1.66% 17 MGD NA**	**98.75% 2.50% 83 MGD NA**	**98.71% 2.50% 168 MGD NA**
Baseline + Ops + Travilah	**100.00% 0.00% 0 MGD 7.7 BG**	**100.00% 0.00% 0 MGD 7.7 BG**	**100.00% 0.00% 0 MGD 7.7 BG**	**100.00% 0.00% 0 MGD 7.7 BG**	**100.00% 0.00% 0 MGD 7.7 BG**	**100.00% 0.04% 0 MGD 7.7 BG**	**100.00% 0.00% 0 MGD 7.5 BG**	**100.00% 0.00% 0 MGD 4.3 BG**	**100.00% 0.26% 0 MGD 1.6 BG**
Baseline + Ops + Travilah + Luck	**100.00% 0.00% 0 MGD 7.7 BG**	**100.00% 0.00% 0 MG 7.7 BG**	**100.00% 0.00% 0 MGD 7.7 BG**	**100.00% 0.00% 0 MGD 7.7 BG**	**100.00% 0.00% 0 MGD 7.7 BG**	**100.00% 0.00% 0 MGD 7.7 BG**	**100.00% 0.00% 0 MGD 7.7 BG**	**100.00% 0.00% 0 MGD 6.6 BG**	**100.00% 0.05% 0 MGD 2.1 BG**

[1] GREEN denotes reliable performance, YELLOW denotes marginal performance, and RED denotes system failure – in the event of severe drought.

Table 8-2: 2050 PRRISM values for: Percent years with no Potomac River deficits, Percent years with emergency restrictions, Maximum 1-day Potomac River flow deficit, Minimum Travilah Quarry storage.[1]

	Higher Flows			**Medium Flows**			**Lower Flows**		
	Low Demands	Medium Demands	High Demands	Low Demands	Medium Demands	High Demands	Low Demands	Medium Demands	High Demands
Baseline	**100.00% 0.00% 0 MGD NA**	**100.00% 0.00% 0 MGD NA**	**100.00% 1.40% 0 MGD NA**	**99.99% 1.25% 0 MGD NA**	**99.29% 2.51% 21 MGD NA**	**98.32% 3.54% 127 MGD NA**	**98.61% 2.54% 143 MGD NA**	**97.49% 3.66% 220 MGD NA**	**96.00% 4.54% 287 MGD NA**
Baseline + Ops	**100.00% 0.00% 0 MGD NA**	**100.00% 0.00% 0 MGD NA**	**99.99% 0.00% 0 MGD NA**	**100.00% 0.00% 0 MGD NA**	**99.95% 1.60% 0 MGD NA**	**98.99% 2.50% 54 MGD NA**	**98.75% 2.50% 134 MGD NA**	**98.71% 2.50% 248 MGD NA**	**97.89% 2.50% 312 MGD NA**
Baseline + Ops + Travilah	**100.00% 0.00% 0 MGD 7.7 BG**	**100.00% 0.03% 0 MGD 7.7 BG**	**100.00% 0.00% 0 MGD 7.7 BG**	**100.00% 0.00% 0 MGD 7.7 BG**	**100.00% 0.03% 0 MGD 7.7 BG**	**100.00% 0.00% 0 MGD 7.3 BG**	**100.00% 0.13% 0 MGD 0.8 BG**	**99.61% 2.50% 69 MGD 1.0 BG**	**98.75% 2.50% 263 MGD 0 BG**
Baseline + Ops + Travilah + Luck	**100.00% 0.00% 0 MGD 7.7 BG**	**100.00% 0.00% 0 MGD 7.7 BG**	**100.00% 0.00% 0 MGD 7.7 BG**	**100.00% 0.00% 0 MGD 7.7 BG**	**100.00% 0.00% 0 MGD 7.7 BG**	**100.00% 0.00% 0 MGD 7.6 BG**	**100.00% 0.03% 0 MGD 2.8 BG**	**99.93% 2.34% 12 MGD 1.9 BG**	**98.77% 2.50% 239 MGD 0 BG**

[1] GREEN denotes reliable performance, YELLOW denotes marginal performance, and RED denotes system failure – in the event of severe drought.

8.4.1 Baseline System

The Baseline system represents the status quo, that is, a future system consisting of current resources with the addition of only two relatively small reservoirs: Loudoun Water's Milestone Reservoir and Fairfax Water's Vulcan Quarry, Phase 1. These facilities are included in the Baseline case because both have progressed beyond the planning stage.

Study results indicate that the Baseline system would experience moderate stress in a severe drought in 2040 under the Medium Flows/Medium Demands scenario, with emergency water use restrictions imposed on WMA households and businesses and with reservoir storage falling to extremely low levels. The Baseline system would perform well in 2040 in the Medium Flows/Low Demands scenario and in all of the Higher Flow scenarios, but under the Medium Flows/High Demands scenario and all of the Lower Flows scenarios it would fail to meet combined WMA water demands and environmental flows.

In 2050, with the rise in forecasted demands, a similar pattern emerges, but with more serious expected shortages of water. In a severe drought the Baseline system would perform well in two of the Higher Flows scenarios, but experience difficulties, ranging from moderate to extreme, the Higher Flows/High Demands scenario and under all the Medium and Lower Flows scenarios. Under all the Lower Flows scenarios the system would be unable to meet combined WMA water demands and environmental flows.

8.4.2 Benefits of the Operational Alternatives

In the Baseline + Ops scenario, it is assumed that all four of the operational alternatives recommended in ICPRB's 2017 alternative study (Schultz *et al.*, 2017) have been implemented. In that study, the combined effects of the four operational alternatives was found to be significant, ranging from 25 to

80 MGD depending on the climate change scenario, in terms of one of that study's performance metrics, system safe summer yield.

The benefits of adding the operational alternatives are only modest for the Higher Flows scenarios, where the system already performs well, though they improve minimum reservoir storages, and, in the case of the 2050 Higher Flows/High Demands scenario, eliminate the occurrence of emergency restrictions. For the Lower Flows scenarios, the system's Baseline configuration fails to meet WMA needs, and the addition of operational alternative is not able to remedy this.

The value of the operational alternatives is most notable in the Medium Flows scenarios, where in 2040 they are able to eliminate emergency restrictions for the case of Medium Demands and elevate system performance to reliable. In the case of 2040 High Demands, they reduce the magnitude of the maximum Potomac deficit to close to 0 MGD, thus elevating system performance to marginal. In 2050, the addition of the operational alternatives reduces the maximum deficit to essentially zero in the Medium Demands scenario, elevating system performance to marginal.

8.4.3 Benefits of Travilah Quarry

Consistent with results of the 2017 alternatives study (Schultz *et al*., 2017) Travilah Quarry is highly effective at mitigating drought. This is due to its size as well as its proximity to the WMA intakes, which allow shifts to Travilah Quarry to have an almost immediate impact on river flow at Little Falls, reducing the system's dependence on flow forecasts. If Travilah Quarry becomes a regional water supply storage resource, it will serve two purposes: as a backup supply in case of an emergency spill event that contaminates the Potomac River supply and as a supplemental supply during drought. To support both purposes, an operational policy will need to be developed, with the input of stakeholders, to balance the use of Travilah Quarry and use of Little Seneca Reservoir during low-flow conditions. In this study a preliminary strategy was used: for a given scenario, the margin of safety for a Little Seneca release was adjusted to a value that used Little Seneca storage as much as possible, while avoiding emergency restrictions and system failure.

Results in Table 8-1 and Table 8-2 indicate that if Travilah Quarry were added to the Baseline system with operational alternatives, the WMA water supply would be reliable for all but the most severe conditions scenario in 2040, the Lower Flows/High Demands scenario, and for all but the three Lower Flows 2050 scenarios. For seven out of nine of the 2040 scenarios and six out of the nine 2050 scenarios, Travilah storage is largely preserved throughout even a severe drought, remaining near its capacity of 7.8 BG. However, in 2040 for the Lower Flows with Medium Demands and High Demands scenarios, storage in Travilah falls to 4.3 BG and 1.6 BG, respectively, on at least one day of a severe drought. In 2050, for all the Lower Flows scenarios, it is 1 BG or less on at least one day of a severe drought.

8.4.4 Benefits of the Luck Quarry

Loudoun Water plans to have the Luck Stone Quarry B operational by 2040 as a raw water storage facility. In this study, it is assumed that Quarry B ("Luck") will be used as a regional resource, with releases made to augment Potomac River flow during droughts. The last rows of Table 8-1 and Table 8-2 show system performance with the combined benefits of the operational alternatives, Travilah Quarry, and Luck Stone Quarry B.

The Luck quarry benefits the WMA system in two different ways, depending on the conditions scenario. For the 2040 Lower Flows/High Demands scenario and the 2050 Lower Flows/Low Demands scenario, the addition of Luck quarry storage elevates system performance from marginal to fully reliable. But in several other scenarios in which system performance is fully reliable or marginally reliable with just Travilah Quarry, the Luck quarry's role is to conserve storage in Travilah Quarry so that additional water is available in case of a spill event. This is the case in 2040 for the Lower Flows/Medium Demands and High Demands scenarios, where without the Luck quarry, storage in Travilah Quarry falls as low as 4.3 BG and 1.6 BG, respectively, during a severe drought, but only to 6.6 BG and 2.1 BG, respectively, when the Luck quarry is added to the system, resulting in an additional 2.3 BG, and 0.5 BG, respectively, of storage in Travilah Quarry available for spill mitigation. The same situation arises in the 2050 Lower Flows/Low Demands scenario, where storage in Travilah Quarry is predicted to fall as low as 0.8 BG. But the addition of the Luck quarry raises Travilah minimum storage to 2.8, a 2 BG increase.

Study results indicate that by 2050, taking into account the uncertainties in future demands and in the impact of climate change on regional streamflows, the WMA may have a need for additional resources, beyond the recommended options of the 2017 alternatives study (Schultz et al., 2017). PRRISM simulates system failures for two 2050 scenarios: the Lower Flows/Medium Demands and the Lower Flows/High Demands scenarios, even in the presence of the Travilah and Luck quarries. Resource options above and beyond those considered in the current study are available, as discussed at the end of Chapter 9.

8.4.5 System Performance Assuming No Climate Change

To provide continuity with results in past ICPRB water supply studies, PRRISM was used to assess the performance of the future WMA system with no impact of climate change on WMA demands and no impact of climate change on Potomac River flows or reservoir inflows. Simulations were conducted with the Medium Demands scenarios for the Baseline system in 2040 and 2050 and for the Baseline + Ops system in 2050. The full set of PRRISM summary statistics for these three sets of runs are given in Appendix A.5. Selected results appear below in Table 8-3.

Table 8-3: Selected PRRISM run summary statistics, assuming no impact of climate change.

	2040 Baseline	2050 Baseline	2050 Baseline + Ops
Percent years with no Potomac River flow deficit	100.00%	100.00%	100.00%
Maximum amount of Potomac River flow deficit allocated in a single day, MGD	0.0	0.0	0.0
Percent years with voluntary water use restrictions	3.70%	3.91%	3.74%
Percent years with emergency water use restrictions	0.00%	0.14%	0.00%
Minimum reservoir storage, BG			
Little Seneca Reservoir	1.3	0.6	1.2
Jennings Randolph water supply account	4.6	2.4	4.7
Jennings Randolph water quality account	2.8	2.6	2.6
Patuxent reservoirs	0.00	0.00	0.0
Occoquan Reservoir	1.9	1.9	1.5
Milestone Reservoir	0.8	0.6	0.6
Vulcan Quarry, Phase 1	0.1	0.1	0.1
Little Seneca Reservoir and Jennings Randolph Reservoir water supply, combined	5.9	3.0	5.9

As is evident from Table 8-3, if climate change has no impact on future demands or streamflows in our region, the performance of the Baseline WMA water supply system during a severe drought is reliable in 2040, according to the definition of reliability in Section 8.4. On the other hand, the performance of the Baseline system in 2050 is marginal, because, though no Potomac River flow deficits occur in the simulation, the percent years with emergency water use restrictions is 0.14%, which is greater than the criteria for reliability, 0.06%. However, as indicated by the results in the last column of Table 8-3, the addition to the system of the four operational alternatives elevates system performance back to reliable and brings most of the summary statistics in Table 8-3 back to values close to those achieved in 2040.

9 CONCLUSION

This study presents forecasts of WMA water demand and water availability out to the year 2050 and evaluates whether a future WMA water supply system can meet forecasted demands in the years 2040 and 2050. Nine planning scenarios represent the uncertainty in future water demand and water availability. For each planning scenario, four different configurations of the future system are evaluated, representing the current/planned set of system resources (Baseline) and three potential configurations of the system with enhancements recommended by the 2017 alternatives study (Schultz *et al.*, 2017). The study aims to provide decision-makers with information to assist them in determining future infrastructure needs.

9.1 SUMMARY OF DEMAND AND AVAILABILITY FORECASTS

Forecasts of average annual water demand are developed by combining recent water use information derived from billing data provided by the suppliers and their wholesale customers, information on the current and future extent of the areas supplied, and the most recent demographic forecasts (Round 9.1) from MWCOG. Average annual demand in the WMA, including Rockville, was 455 MGD in 2018, and this is projected to increase to 501 MGD by 2040 (a 10% increase) and to 528 MGD by 2050 (a 16% increase). This study's estimates of current annual demand and forecasted annual demand are considerably lower than values from ICPRB's 2015 study (Ahmed *et al.*, 2015), continuing a pattern of falling demand forecasts in each successive water supply study since the USACE's 1963 study. The current study includes an estimate of the uncertainty in the demand forecasts based on the standard error of the forecasts. The standard errors for the 2040 and 2050 forecasts are 9.7% and 10.4%, respectively, of the forecast values.

Forecasts of water availability are based on a large ensemble of spatially downscaled and bias-corrected global climate model projections for temperature and precipitation in the Potomac basin. A climate response function, developed from the historical record using multiple least squares regression, uses these to predict mean annual Potomac River flow from projected annual precipitation and temperature. A quantile scaling approach is applied to obtain flow-dependent change factors for future annual streamflow for the entire simulation period of the climate projections, 1950 through 2099. The change factors for the lowest flow years are particularly sensitive to the climate response function's temperature coefficient, and the uncertainty in the temperature coefficient is used to define three flow scenarios which represent uncertainty in future water availability due to climate change.

9.2 FUTURE CONDITIONS SCENARIOS

The ability of future WMA system configurations to meet future demands is tested using nine plausible planning scenarios formed from combinations of three demand scenarios and three flow scenarios. Uncertainty in future demands is represented by the demand forecast value plus or minus one standard error. Uncertainty in future Potomac basin streamflows is represented by three sets of river flow and reservoir inflow time series: a scenario constructed using the climate response function, and two scenarios based on altered climate response functions, created by adding plus or minus one standard error of the function's temperature coefficient.

9.3 System Evaluations

The ability of the WMA system to meet future water demands is evaluated with CO-OP's water supply planning model, PRRISM. For each planning scenario, PRRISM simulations are conducted for four different configurations of the WMA system: a system with current and planned resources (Baseline system), and a system that has been enhanced with combinations of operational and structural alternatives recommended in the 2017 alternatives study (Schultz *et al.*, 2017). Detailed output from the PRRISM runs is provided in Appendix A.5.

9.3.1 System Performance under the Nine Planning Scenarios

Values for key performance metrics from the PRRISM simulations for 2040 are given in Table 8-1. These results indicate that the WMA Baseline system, consisting of current resources with the addition of Loudoun Water's Milestone Reservoir and Fairfax Water's Vulcan Quarry, Phase 1, would experience moderate stress in the event of a severe drought in 2040 under the Medium Flows/Medium Demands scenario, with Emergency water use restrictions imposed on WMA households and businesses and with reservoir storage falling to extremely low levels. However, implementation of the suite of four recommended operational alternatives alleviates this stress and elevates system performance during a severe drought to reliable. Under all the 2040 Lower Flows scenarios, the operational alternatives are not sufficient, and the addition of Travilah Quarry is necessary to avoid system failure in a severe drought.

In 2050, with the rise in forecasted demands, a similar pattern emerges (Table 8-2), but with more serious expected shortages of water. In a severe drought, the Baseline system performs well in simulations under two of the Higher Flows scenarios, but experiences difficulties, ranging from moderate to extreme, under all other scenarios. The implementation of the four operational alternatives improves system performance significantly under the Medium Flows/Medium Demands scenario and two other scenarios. With Travilah Quarry, the system performance is elevated to reliable or marginal under three additional scenarios. However, even with both the Travilah and Luck quarries in place, PRRISM simulations indicate that during a severe drought, the system is unable to meet WMA water demands plus the Little Fall flow-by under two of the Lower Flows scenarios.

9.3.2 System Performance Assuming No Impact from Climate Change

To provide continuity with results of past ICPRB studies (e.g. Ahmed *et. al.*, 2010; 2015), this study also evaluates WMA system performance under the assumptions that climate change has no impact on future demands and it has no impact on future water availability. PRRISM simulations are conducted using the historical record of daily flows, precipitation, and temperature as inputs, with the Medium Demands scenarios. Because the historical time series of natural daily flow at Little Falls includes the drought of record of 1930 and the drought of 1966, the "no climate change" model runs provide an assessment of how well the WMA system would perform with forecasted demands during a reoccurrence of these historic droughts. In terms of the planning scenarios described in Section 8.1, the no climate change runs fall somewhere between the Higher Flows and the Medium Flows scenarios.

The "no climate change" results appear in Table 8-3. PRRISM simulations indicate that if climate change has no impact on future demands or streamflows in our region, the Baseline WMA water supply system performs reliably during a severe drought, as defined in Section 8.4, in 2040, but performance is marginal in 2050. However, as indicated by the results in the last column of Table 8-3, the addition to the system of the four operational alternatives elevates system performance back to reliable and brings most of the summary statistics in the table back to values close to those achieved in 2040.

9.3.3 Ensuring a Reliable Water Supply

System performance results for the nine planning scenarios provide a range of plausible outcomes for the WMA water supply systems that may occur in the event of a severe drought in a future altered by climate change. No one scenario in this study is presented as more or less likely than another. None the less, individual stakeholders may view one or more of the scenarios as most appropriate to help guide infrastructure planning decisions as they try to strike a balance between risks and costs. Some may view the Medium Flows/Medium Demands scenarios as most useful, deeming them more “likely” than other scenarios in that they fall in the middle of the flow and demand projections. Others may prefer to take a more conservative approach and use the Low Flows/High Demands scenarios as a guide for planning decisions, since they provide the most severe tests of system performance.

The WMA’s regional agreements, the LFAA and WSCA, specify a 20-year horizon for infrastructure planning decisions regarding new shared resources for the cooperative system. The nine 2040 scenarios indicate that the four operational alternatives recommended in ICPRB’s 2017 alternative study (Schultz *et al.*, 2017) ensure reliable system performance for the Medium Flows/Medium Demands scenario. The addition of Travilah Quarry ensures reliable, or in one case marginal, performance for all nine planning scenarios. In the most severe of the nine 2040 scenarios (Lower Flows/Higher Demands), annual WMA demand reaches 550 MGD and a drought occurs with streamflows 30% lower than those of the 1930 drought of record. The four operational alternatives and Travilah Quarry were among the measures recommended in the 2017 study, and stakeholders are actively working toward achieving the necessary consensus and identifying funding sources to implement them, with Travilah Quarry envisioned to serve as a dual purpose regional facility to mitigate the risks of both spills and drought in the Potomac River.

The nine scenarios for 2050 provide a look at potential resource needs at the end of the 30-year planning horizon. Results indicate that if droughts become much more severe, the WMA system may be unable to meet combined water supply needs and the environmental flow-by at Little Falls even if all of the recommended options of the 2017 alternatives study are implemented, including Travilah Quarry and Luck Stone Quarry B. This possibility is represented by the 2050 Lower Flows climate change scenario, in which a drought occurs in a year with streamflows 38% lower than that experienced during the 1930 drought of record. Resource options above and beyond those considered in the current study are available. For example, construction of a reverse osmosis membrane water treatment plant drawing from the Occoquan estuary was the subject of a preliminary engineering study by CDM on behalf of Fairfax Water (CDM, 2004) and was shown in the 2017 alternatives study to provide significant benefits to the WMA system in terms of system safe yield. Benefits from the alternatives considered in the current study, for example, use of Jennings Randolph water quality storage in drought emergencies, might be increased if better strategies are developed for their implementation, perhaps through use of optimization techniques in the PRRISM planning model. Also, new regional resource options have been proposed.

Stakeholders may want to wait for more information to help gage the likelihood of the 2050 Lower Flows climate scenario. ICPRB’s next water supply study, planned for 2025, will reassess the potential impact of climate change on regional streamflow based on additional data on climate and flow trends and projections. If it’s determined that steps need to be taken to address the risk of an extreme low flow scenario, engineering studies will be conducted for new resource options so that they can be simulated and evaluated for effectiveness in future water supply planning studies.

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