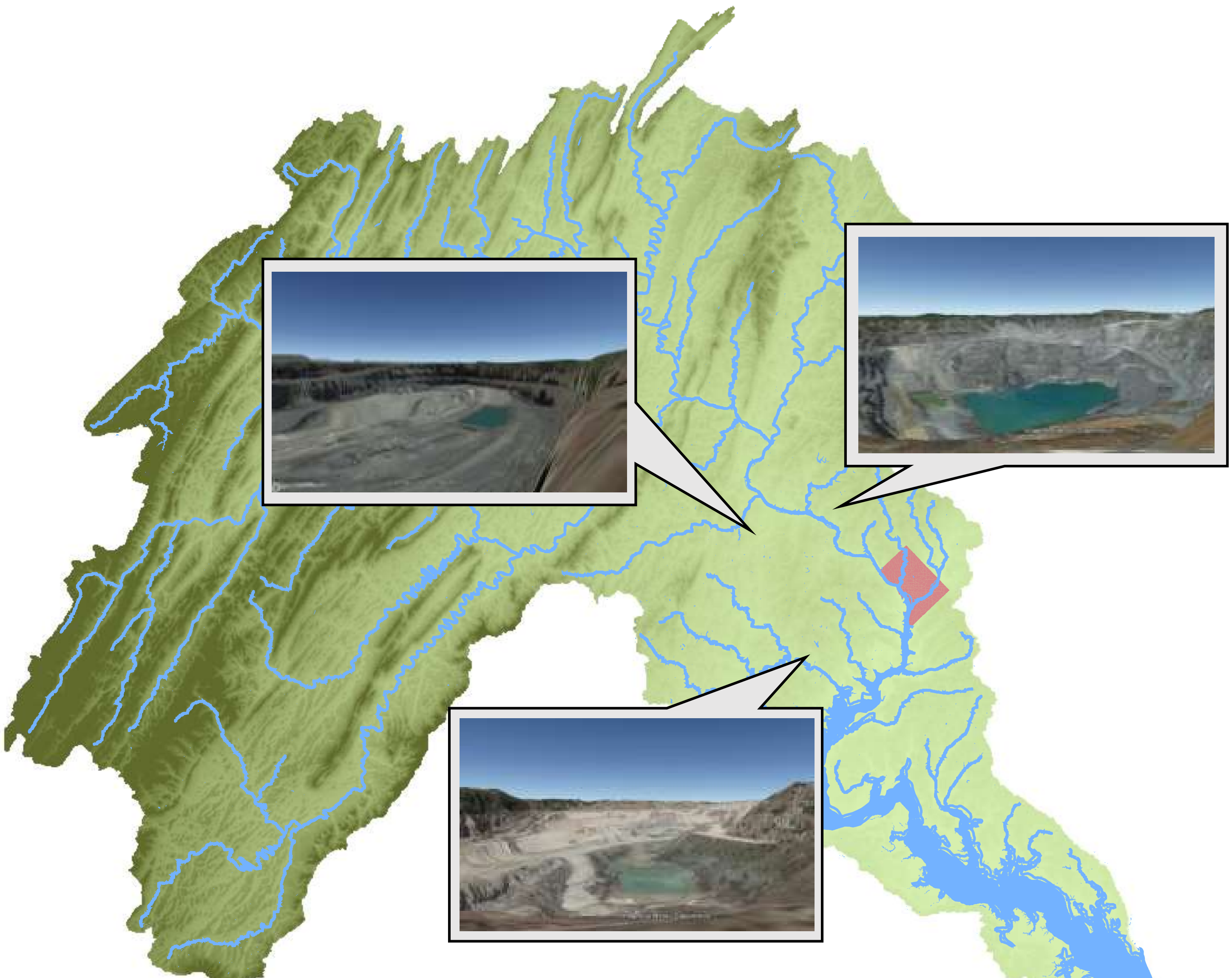
Washington Metropolitan Area Water Supply Alternatives

Meeting the Challenges of Growth and Climate Change

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



August 2017
ICPRB Report No. 17-3

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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Table of Contents

Table of Appendices

Table of Tables

Table of Figures

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Disclaimer

List of Abbreviations

BG	Billion gallons
CO-OP	ICPRB's Section for Cooperative Water Supply Operations on the Potomac
CU	Consumptive use
DC Water	District of Columbia Water and Sewer Authority
DSS	Decision Support System
FC	Forecasts
FW or Fairfax Water	Fairfax County Water Authority
GCM	General circulation model
ICPRB	Interstate Commission on the Potomac River Basin
JRR	Jennings Randolph Reservoir
LFAA	Low Flow Allocation Agreement
LW	Loudoun Water
MG	Million gallons
MGD	Million gallons per day
MOS	Margin of safety
MWCOG	Metropolitan Washington Council of Governments
PRRISM	Potomac Reservoir and River Simulation Model
R^2	Coefficient of determination
RO	Reverse osmosis
RMSE	Root mean square error
SA	Service area (for distribution of treated water to customers)
SSSY	System safe summer yield
USACE	U.S. Army Corps of Engineers
USGS	U.S. Geological Survey
VWP	Virginia Water Protection
WDSS	Worst day shared storage
WMA	Washington, D.C., metropolitan area
WSCA	Water Supply Coordination Agreement
WSSC	Washington Suburban Sanitary Commission
WTP	Water treatment plant
WWTP	Wastewater treatment plant

Executive Summary

The Washington, D.C., metropolitan area (WMA) is fortunate to have a highly reliable water supply system and a suite of supply alternatives to help meet the future challenges of population growth and climate change. The three major regional suppliers participate in a cooperative system of water supply planning and management which includes coordination and use of shared resources during droughts, regular joint planning studies, and agreement to share in the cost of new resources when the need arises. This study, by the Section for Cooperative Water Supply Operations on the Potomac (CO-OP) of the Interstate Commission on the Potomac River Basin (ICPRB), was conducted to assist the suppliers in the selection of new resources and operational measures to address the need for additional water supplies by 2040, as identified in a recent planning report (Ahmed *et al.*, 2015). This study also provides information on potential alternatives for the year 2085 to help ensure that options are available over a longer planning horizon. Alternatives have been evaluated according to their capabilities to increase future system reliability in the face of growing WMA demands, decreasing river flows due to upstream consumptive use, and the potential impacts of climate change.

Current System

The WMA's primary source of water is the Potomac River. To augment river flow during drought, the area also relies on upstream reservoirs, Jennings Randolph, Savage, and Little Seneca. Three off-Potomac reservoirs in the Occoquan and the Patuxent watersheds are used on a daily basis. Current resources, including Loudoun Water's Quarry A, planned for operation in 2022, and proposed alternatives are shown in Figure ES-1 (numbers matching names in box on next page).

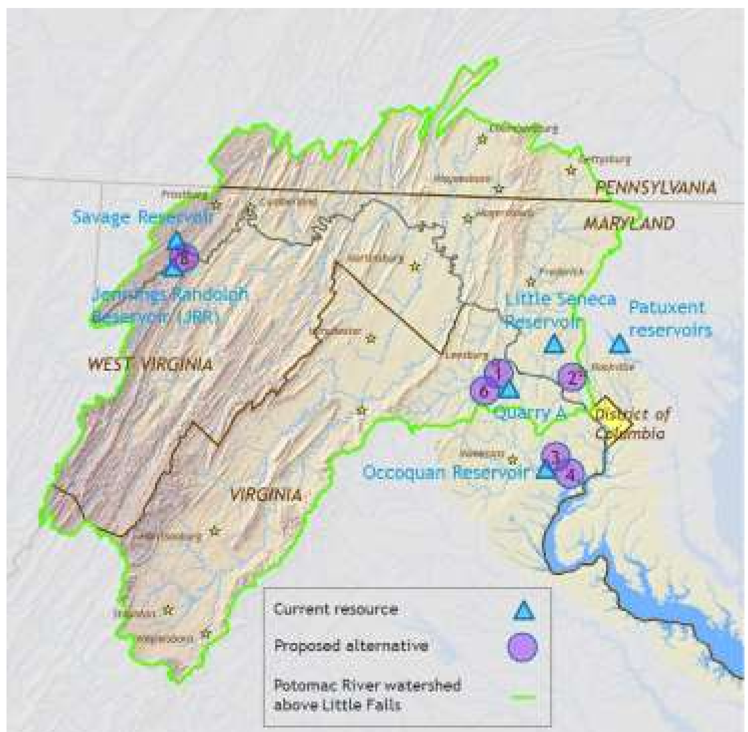


FIGURE ES-1: POTOMAC RIVER BASIN

The WMA's three major suppliers are Washington Aqueduct, Fairfax Water, and Washington Suburban Sanitary Commission (WSSC). Washington Aqueduct, a Division of the U.S. Army Corps of Engineers, provides water to the District of Columbia via the District of Columbia Water and Sewer Authority and to some Virginia suburbs. Fairfax Water serves most of the northern Virginia suburbs and WSSC primarily serves the Maryland suburbs in Montgomery and Prince George's counties. Collectively, these suppliers obtain approximately three quarters of their water from intakes on the Potomac River. In the near future, a fourth supplier, Loudoun Water, will initiate withdrawals from the Potomac River to meet a portion of its demand. Additionally, they will complete construction of the necessary infrastructure to store water in a retired quarry, "Quarry A", for use during droughts. Loudoun

Water also recently has acquired Beaverdam Reservoir, which could be used during droughts for Potomac River low flow augmentation.

Proposed Alternatives

The alternative options for augmenting future supply, listed in the box to the right, are both structural and operational. The locations of the structural alternatives and some of the operational alternatives are indicated by number on Figure ES-1. Many have been the subject of past investigations by the WMA suppliers. Although some of the structural alternatives would provide water directly to only one or two WMA suppliers, all would provide regional benefits by increasing Potomac River flow. All structural alternatives would require significant investments in new infrastructure which would in most cases include new underground conduits to transfer raw and/or treated water from one part of the WMA system to another. The operational alternatives on the other hand would require little or no investment in costly infrastructure. They would, however, entail some costs, associated with new cooperative agreements, and/or contracts between water suppliers, and/or investment in research to develop new operational tools and policies.

WMA Water Supply Alternatives
(numbering matches labels in Figure ES-1)

Structural Alternatives

1. Luck Stone quarries in Loudoun Co., Virginia
   i. Luck 1: 2.5 billion gallons in 2040
   ii. Luck 2: 6.5 billion gallons by 2085
2. Travilah Quarry in Montgomery Co., Maryland
   i. 8.5 billion gallons (assumed)
3. Vulcan Quarry in Fairfax Co., Virginia
   i. Vulcan 1: 1.7 billion gallons by 2035
   ii. Vulcan 2: >17 billion gallons by 2085
4. Reverse osmosis water treatment plant using the Occoquan Estuary as a water source

Operational Alternatives

5. Cooperative use of Quarry A
6. Use of Beaverdam Reservoir for low flow augmentation
7. Improved river flow forecasts by 10%
8. Use of Jennings Randolph water quality storage for water supply during droughts
9. Reduction in upstream consumptive use
10. More stringent regional water use restrictions

Climate Change Scenarios

According to projections from climate models, temperatures in the Potomac basin will rise whereas precipitation could rise or fall. Both temperature and precipitation have an impact on stream flows, and the range of available climate projections lead to a wide range of potential changes in water availability in the basin. This introduces tremendous uncertainty into water supply planning. ICPRB watershed modeling uses global climate model output downscaled to the Potomac basin by the U.S. Geological Survey (USGS). Results project changes in long-term average summer basin-wide stream flows ranging from -35 percent to +42 percent, with a median of +2 percent, over the period between 1995 and 2040. Between 1995 and 2085, the projected changes in average summer stream flows range from -54 percent to +36 percent, with a median of +4 percent. Water demand will also be affected by a changing climate. To take into account the uncertainty in future climate conditions, three future climate scenarios informed by past modeling results were developed for two scenarios years, 2040 and 2085. These are denoted in the table below as CC50, CC75, and CC90 (see Section 3.1 for further discussion):

SCENARIO YEAR		2040			2085	
Climate change scenario	**CC50**	**CC75**	**CC90**	**CC50**	**CC75**	**CC90**
Change in summer average basin-wide stream flow, %	+2	-7	-19	+4	-12	-23
Change in non-summer average basin-wide stream flow, %	+2	-6	-14	+3	-9	-17
Change in WMA precipitation, %	6.3	2.4	-2.9	11.3	5.4	1.4
Change in WMA temperature, °F	3.2	3.2	3.2	5.6	6.4	6.9

The future climate scenarios pose varying degrees of challenge to WMA system reliability, ranging from minor to severe. In 2040 under the CC50 scenario, stream flows actually increase slightly, yet due to increased regional demands, study results indicate that the current WMA water supply system would not be able to meet needs reliably during a severe drought. The addition to the current system of any single one of the alternatives, however, would be sufficient to ensure that needs could be met reliably under this scenario. For the most severe scenario, CC90, under which summer flows fall by 19 percent, Travilah is the only individual alternative able to meet regional needs in 2040 in case of severe drought.

A Roadmap for the Future

Recommended Strategies

2040 Strategy A:

- Step 1: Operational alternatives #5-8 by 2025
- Step 2: Vulcan 1 by 2035
- Step 3: Luck 1 + improve 1-day flow forecast by 35% by 2040

2040 Strategy B:

- Step 1: Operational alternatives #5-8 by 2025
- Step 2: Vulcan 1 by 2035
- Step 3: Travilah by 2040

2085 Strategy:

- All quarry alternatives, along with operational alternatives #5-8

In general, study results indicate that combinations of alternatives will need to be in place to ensure system reliability in the future. Over the medium-term planning horizon of 2040, two strategies for phased implementation of alternatives are recommended for consideration and future discussion (see box on the left). These two combinations of alternatives were selected in part to ensure system reliability under a moderately severe climate scenario which results in a 7 percent decrease in average summer stream flows (CC75). The strategies also consider the need to protect the region from shortfalls in the decades leading up to 2040 and the need for steps toward broader regional cooperation to help prepare for more severe challenges which may arise in the decades after 2040. Over the longer-term planning horizon, by 2085, study results indicate that most of the ten alternatives will be needed to ensure system reliability.

The 2040 Strategy A is recommended if the region chooses not to pursue acquisition of Travilah Quarry or if that facility is unavailable in the near term. As a first step, it calls for work to begin on implementation of operational alternatives 5-8 (as numbered in the box on the previous page). Completion of these four measures by 2025 would provide some degree of protection against the potential impact of climate change during the years leading up to 2040. The second step of Strategy A is implementation of Vulcan Quarry Phase 1 by 2035, which already is planned by Fairfax Water. As a final step, Strategy A calls for implementation of Luck Stone Quarry B, along with further improvements in stream flow forecasts to help realize the benefits of this additional storage, by 2040. Step 1 alone – the implementation of operational alternatives 5-8 – is sufficient for system reliability under two of the 2040 climate change scenarios, CC50 and CC75. However, even after Vulcan Phase 1 and Luck Stone Quarry B are in place, Strategy A falls somewhat short of reliably meeting 2040 demands under the most severe scenario, CC90. None the less, Strategy A may prove to be a reasonable combination of alternatives for the region. A future evaluation could conclude that Strategy A would be effective in meeting 2040 demands, *if:* it is determined that demands are growing at a slower rate than forecasted; a new generation of global climate models or use of long-term trend data for model verification shrink the range of uncertainty for changes in basin stream flows; better than anticipated increases in the accuracy of stream flow forecasts are achieved; or better operational policies can be developed.

Strategy B involves acquisition of Travilah Quarry and the construction of infrastructure to carry raw water to and from the quarry and WSSC's Potomac treatment facility and to Washington Aqueduct's

Dalecarlia and McMillan treatment plants via Aqueduct's Great Falls intake. As a part of this recommendation, implementation of operational alternatives 5-8 and of Vulcan Quarry Phase 1 are included as first steps. These initial steps would provide protection against the potential impact of climate change in the years prior to completion of the Travilah project and would help increase regional cooperation and pave the way for measures needed in the decades following 2040. Strategy B would provide the region with a reliable water supply under a wide range of potential climate conditions, including the most severe scenario considered in this study, CC90. Strategy B also could be viewed as a "no regrets" option, because even if regional stream flows do not decrease, Travilah Quarry would serve another important function for the region. The quarry could provide an alternative water supply for both Aqueduct and WSSC in case of a contamination event on the Potomac River, with a limited quantity also available to the Fairfax Water system.

Results for the second scenario year, 2085, indicate that most of the ten alternatives need to be in place to ensure reliability under the range of climate scenarios. A future system that includes operational alternatives 5-8, Vulcan 2 (with an addition of the quarry's "Main Reservoir" with 17 billion gallons of storage), Luck 2 (including the addition of Quarry C with four billion gallons), and Travilah Quarry would be able to provide a reliable supply even under the most severe climate change scenario, CC90. Of course, these results should be considered highly preliminary, and meant to aid in long-term planning conducted in an "adaptive management" framework under the assumption that CO-OP will continue to update this evaluation as new data and information become available.

Future Vulnerability to Flow Deficits

Study results highlight the future vulnerability of the WMA system to Potomac River flow deficits, that is, to river flow falling below the 100 million gallon per day minimum at Little Falls. These deficits will tend to increase and to reduce system reliability in future years, especially if rising demands are accompanied by decreases in average basin stream flows. Flow deficits may occur even on days in which the system has ample storage, due to the inherent inaccuracies in the one-day flow forecasts used to calculate Little Seneca Reservoir releases and other operational changes. Measures that were shown to be effective in reducing Potomac River flow deficits to take better advantage of available storage include:

a) use of Travilah Quarry, which because of its proximity to WSSC and Aqueduct treatment plants would be able to decrease Potomac withdrawals and quickly increase flow at Little Falls,
b) additional improvements in one-day flow forecasts, and
c) increases in minimum releases from reservoirs during droughts.

If acquisition of Travilah Quarry is not pursued in the near term, then resources need to be devoted to measures b) and c) above, in other words, to speed the improvement of one-day river flow forecasts and to develop other operational strategies to reduce the occurrence of deficits. This could be achieved by devoting more resources to CO-OP's development of its Low Flow Forecast System and by supporting research to better understand how to balance use of constant minimum releases and use of variable releases based on flow forecasts.

Cost Considerations

Available cost information on the alternatives is summarized in this study. The information, however, is incomplete, and it is not possible at this time to provide cost-benefit comparisons of the alternatives. A future step in determining the best strategy will be the development of complete and comparable cost estimates for selected alternatives.

1 Objective and Background

This study has 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) on behalf of the three major water suppliers ("CO-OP suppliers"): Fairfax County Water Authority (Fairfax Water), the Washington Suburban Sanitary Commission (WSSC), and the Washington Aqueduct (Aqueduct). The Washington, D.C., metropolitan area (WMA) is defined in this study as the District of Columbia and the portions of the city's Maryland and Virginia suburbs that are supplied water, either directly or indirectly, by the CO-OP suppliers, the City of Rockville, and Loudoun Water (see Figure 1-1).

The current study supports the long-term planning provisions of two agreements signed by the CO-OP suppliers, the *Low Flow Allocation Agreement* (LFAA, 1978, as amended by Modification 1, 1982), signed by the United States, the State of Maryland, the Commonwealth of Virginia, the District of Columbia, WSSC, and Fairfax Water; and the *Water Supply Coordination Agreement* (WSCA, 1982), signed in 1982 by the United States, Fairfax Water, WSSC, the District of Columbia, and ICPRB. Both of these agreements call for regular evaluations of the adequacy of the WMA water supply system to meet future demands. Both agreements state that, "If as a result of any such review and evaluation it is determined that additional water supplies will be required to meet expected demands, the Aqueduct, the Authority [Fairfax Water], the Commission [WSSC], and the District shall undertake negotiations to provide the required additional supplies" (WSCA, Article 10). The most recent review and evaluation of the WMA water supply system, ICPRB's *2015 Washington Metropolitan Area Water Supply Study* (Ahmed *et al.*, 2015), concluded that by the year 2040 the current system would have difficulty meeting demands if conditions similar to past severe droughts were to occur, and that under some climate change projections for our region the current system would be unable to meet demands during a severe drought.

1.1 Objective

The objective of this study is to aid the WMA suppliers in determining what changes and additions to the current water supply system are needed to allow them to meet the future challenges of growing regional demand for water and the potential impacts of climate change. Information is provided to assist them in selecting measures to address the need for additional water supplies by 2040 and to support discussions on cost-sharing. Evaluations are also conducted for the year 2085 to help ensure that options are available to meet anticipated needs over a longer planning horizon.

The study considers both potential structural measures and operational changes, many of which have been the subject of past investigations by the WMA suppliers and some of which are already in the planning or development stage. The structural alternatives considered are future use of retired quarries (Luck Stone, Vulcan, and Travilah) for raw water storage, and construction of a reverse osmosis water treatment plant on the Occoquan Estuary (RO plant). All of the structural alternatives would require substantial investments in infrastructure, including new underground conduits to transfer raw and/or treated water. The operational alternatives considered in this study, described in detail in Section 2, are: enhanced cooperation between Loudoun Water and the CO-OP suppliers in the use of Loudoun's Quarry A; use of an existing local reservoir, Beaverdam, to augment Potomac River flow during droughts; improvements in the river flow forecasts used during drought operations; use of Jennings Randolph Reservoir water quality storage during droughts; a reduction in upstream consumptive use of water; and more stringent regional water use restrictions during droughts. The operational alternatives would not require costly investments in infrastructure; however, they would require new regional cooperative agreements and/or contracts and/or investment in research and development of new operational policies and tools. Two alternatives that were the subject of previous investigations were not included in this study based on findings and considerations of suitability: Stony River Reservoir in Grant County, West Virginia, and a water supply intake in the Potomac estuary near Chain Bridge.

This study evaluates the relative benefits of each of the individual alternatives. It also evaluates the ability of selected combinations of alternatives to meet water demands in the two scenario years, 2040 and 2085, over the range of potential climate conditions.

1.2 Existing WMA Water Supply System

The WMA is served by the following water suppliers, whose service areas are shown in Figure 1-1:

- Aqueduct, a Division of the U.S. Army Corps of Engineers (USACE), serving the District of Columbia via the District of Columbia Water and Sewer Authority (DC Water); Arlington County, Virginia, via the Arlington County Department of Environmental Services (DES); and Falls Church, Virginia, via Fairfax Water.
- WSSC, 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, the City of Bowie, and DC Water.
- Fairfax Water, serving most of Fairfax County, Virginia, and other Virginia suburbs via the Prince William County Service Authority (PWCSA) and other distributors.
- City of Rockville Department of Public Works (DPW), in Montgomery County, Maryland.
- Loudoun Water, in Loudoun County, Virginia. Loudoun Water currently supplies its customers with water treated at its Goose Creek treatment plant and water purchased from Fairfax Water. In 2017 it will begin supplying a portion of its demand with water withdrawn from the Potomac River via its new intake and treated at its new Trap Rock Water Treatment Plant.

Collectively, these suppliers obtain approximately three quarters of their water from the Potomac River. The CO-OP suppliers – Aqueduct, WSSC, and Fairfax Water – participate in a cooperative system of water supply planning and management. As previously mentioned, this cooperative system is based on a set of agreements entered into more than 30 years ago: the LFAA, which specifies a formula for the allocation of water in the event of emergency shortages; the WSCA, which commits the three suppliers to operate "in a coordinated manner" during droughts to optimize the use of available resources and to construct new resources when the need has been demonstrated; and a number of shared funding agreements.

During periods of drought, CO-OP provides technical and managerial support to the CO-OP suppliers. Its responsibilities include forecasting daily demands and river flows, coordinating water withdrawals from the Potomac River and off-river reservoirs, and determining release rates from upstream reservoirs when forecasted flow in the river is not sufficient to meet expected needs. These needs include WMA demands and an environmental flow-by of 100 million gallons per day (MGD) on the Potomac River at the Little Falls dam near Washington, D.C. (USGS Station ID 01646500).

1.2.1 Water Use

According to ICPRB's 2015 water supply study (Ahmed *et al.*, 2015), the population of the WMA is currently 4.6 million and is forecast to reach 5.7 million by the year 2040, a 23 percent increase. Water demand is forecast to grow at a slower rate than population due to widespread adoption of new water saving fixtures and appliances. Average annual water demand in the WMA is estimated to increase from

486 MGD in 2015 to 545 MGD in 2040 (12 percent). Daily demand on a hot summer day is generally greater than average annual demand. Average WMA demand in July is 18 percent higher than average annual demand. Annual peak day demand for the combined WMA system (CO-OP suppliers plus Rockville and Loudoun Water) is 51 percent higher than average annual demand (a "peak day factor" of 1.51), based on 2009 through 2013 production data.

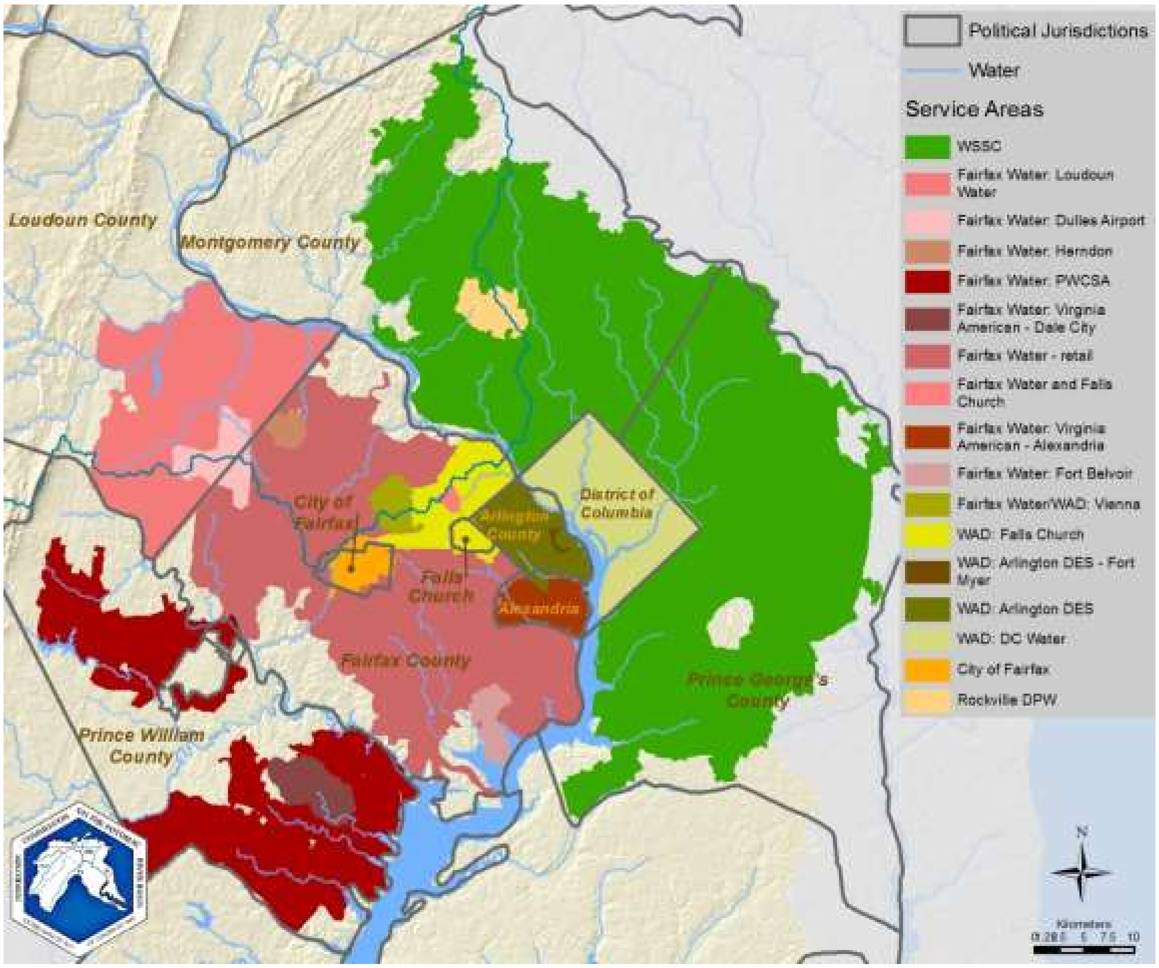


FIGURE 1-1: AREAS SERVED BY WMA SUPPLIERS AS OF 2014

1.2.2 Water Supplies

Current WMA resources are depicted in Figure 1-2. The Potomac River, whose drainage area at Little Falls dam near Washington, D.C., is 11,560 square miles, provides approximately three quarters of the region's supply. Flow in the river at Little Falls varies seasonally but usually is ample, with "adjusted flow" averaging 5.9 billion gallons per day (adjusted flow at Little Falls is measured flow adjusted by adding back the WMA withdrawals). Water in the two shared reservoirs, Jennings Randolph and Little Seneca, can be released during drought to augment natural river flow. In addition, Fairfax Water and WSSC rely daily on water stored in reservoirs outside the drainage area of the freshwater portion of the Potomac River, on the Occoquan River and the Patuxent River, respectively. Loudoun Water's Quarry A, now scheduled for completion in 2022, will be filled with water withdrawn from the Potomac River during periods of normal flow and will provide a portion of Loudoun's supply during droughts, under conditions specified in its Virginia Water Protection permit (VWP Permit No. 10-2020).

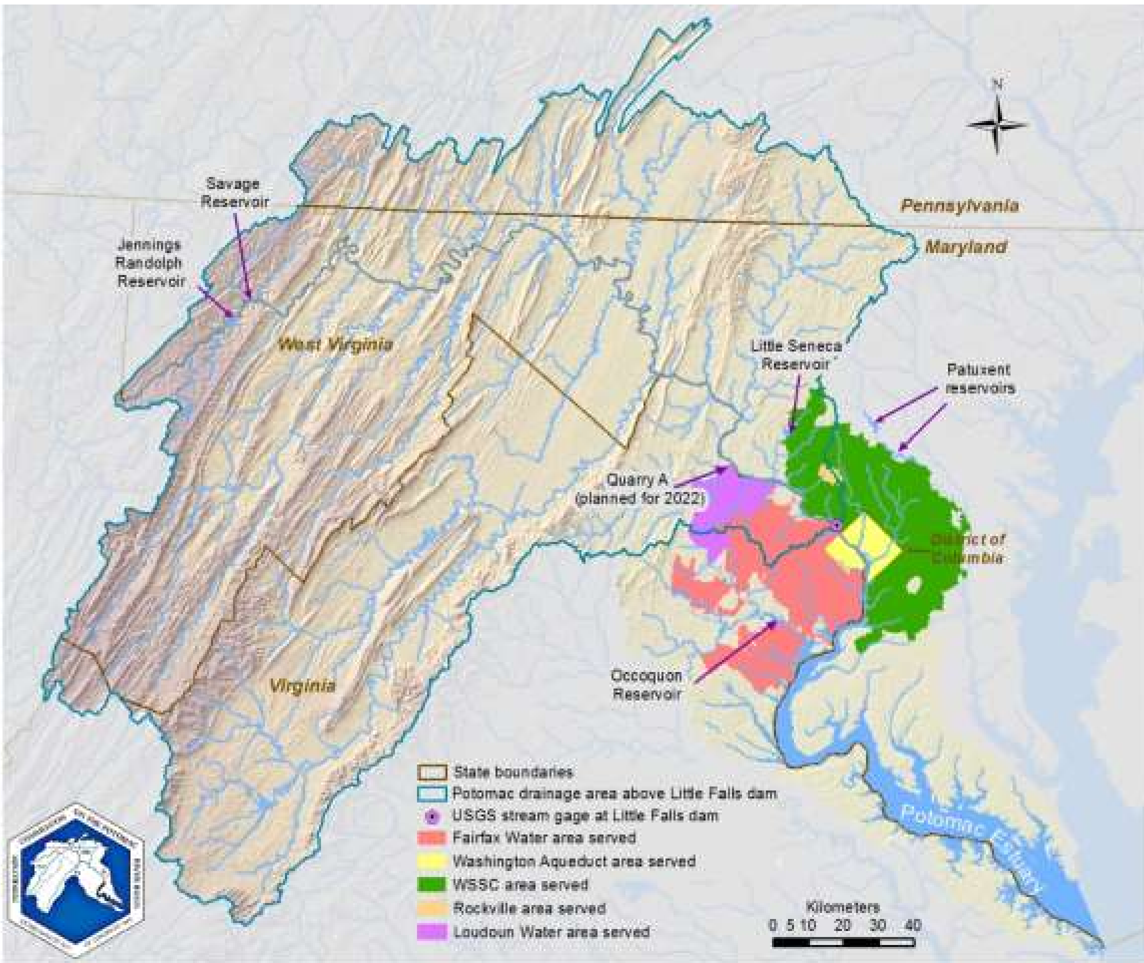


FIGURE 1-2: CURRENT WMA WATER SUPPLY RESOURCES

1.2.3 System Operations during Droughts

During droughts, CO-OP manages releases from upstream reservoirs and coordinates supplier withdrawals, in accordance with provisions of the WSCA. CO-OP's goal during drought operations is to optimize use of available resources while meeting CO-OP supplier demands, maintaining river flow at Little Falls above the 100 MGD environmental flow-by, and maintaining flow between Great Falls and Little Falls above a recommended minimum of 300 MGD. (See Ahmed *et al*., 2015 for a discussion of Potomac flow recommendations.)

Many of the decisions made by CO-OP during droughts are based on forecasts of future river flows and future demands. Nine-day forecasts are needed to determine release rates from Jennings Randolph Reservoir because a release during low flow periods takes about nine days to travel down the river and reach the WMA. One-day forecasts are required to determine the need for releases from Little Seneca Reservoir and for changes in Fairfax Waters operations, since it takes approximately one day for these operations to have an impact on flow in the river at Little Falls due to travel times and implementation lag times. Changes in operations by WSSC and Aqueduct have a much more immediate impact on Potomac River flow at Little Falls because of the proximity of their Potomac River intakes to Little Falls and their ability to implement changes quickly. CO-OP's decisions regarding these operations are based primarily on the current day's flow, as measured by the USGS gage station at Little Falls.

The key water supply operations managed by CO-OP during droughts are discussed below, and described in more detail in ICPRB's 2015 water supply study (Ahmed *et al.*, 2015). Current physical constraints of the WMA system are given in Table 1-1. These are such constraints as water treatment plant (WTP), maximum and minimum production rates and maximum flow rates of pumps and pipes that transfer raw or treated water (i.e., "finished water") from one part of the system to another.

1.2.3.1 Operations Based on Nine-Day Forecasts

Jennings Randolph Reservoir and Savage Reservoir (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 1-2). Jennings Randolph is the system's largest storage facility, with 13.1 billion gallons (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 (USACE, 2014a). Releases from these two segments of storage are tracked and accounted for separately. The USACE's Baltimore District Office manages this reservoir and makes releases from water quality storage continually to meet one of its primary objectives, water quality enhancement. To the greatest degree possible, USACE also makes releases for whitewater boating and fishing opportunities downstream along with boating and beach access on Jennings Randolph Reservoir itself. Jennings Randolph water supply storage is used only at the request of CO-OP on behalf of the CO-OP suppliers. Savage Reservoir is operated by the USACE in coordination with Jennings Randolph Reservoir, with releases generally made at a five-to-one ratio, 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, plus a small amount of local flow, is measured at the USGS stream gage (Station ID 01598500) at Luke, Maryland.

During periods of drought, CO-OP can request water supply releases from the North Branch reservoirs to augment flow in the Potomac River. 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, and CO-OP determines release rates based on nine-day forecasts of flow and demands.

1.2.3.2 Operations Based on One-Day Forecasts

Two types of system operations decisions made by CO-OP, Little Seneca Reservoir releases and Fairfax Water "load-shifts", are based on one-day flow and demand forecasts because they both take approximately one day to have an impact on flow at Little Falls dam.

Little Seneca Reservoir has a storage capacity of 3.9 BG and is located in Black Hill Regional Park in Montgomery County, Maryland. The Little Seneca dam is operated by WSSC. CO-OP can request a water supply release from Little Seneca Reservoir to augment Potomac River flow when one-day forecasts indicate that the next day's flow would otherwise be insufficient to meet demands plus the 100 MGD flow-by.

To help conserve water in Little Seneca Reservoir, CO-OP may request that Fairfax Water shift a portion of its withdrawal from the Potomac River to its off-Potomac intake at the Occoquan Reservoir. It is estimated that such a "load-shift" by Fairfax Water also takes approximately one day to increase flow at Little Falls. This is due to the travel time from their Potomac River intake to Little Falls (estimated to be 15 hours under low flow conditions) and the amount of time required to implement this operational change.

Occoquan Reservoir has a usable capacity of 8 BG and is located between Fairfax and Prince William counties in Virginia. Fairfax Water withdrawals from the Potomac River are treated at the Corbalis WTP and withdrawals from Occoquan are treated at the Griffith WTP. During normal conditions, treated water from Corbalis is primarily distributed to customers in what is referred to in this study as Fairfax Water's "Western service area" and treated water from Griffith is primarily distributed to customers in Fairfax Water's "Eastern service area." During drought operations, the implementation of a load-shift from the Potomac River to the Occoquan Reservoir (that is, a reduction in the Potomac withdrawal and a corresponding increase in the Occoquan withdrawal) requires that treated water be transferred from the Eastern to the Western service area. Conversely, a load-shift from the Occoquan to the Potomac, which may be requested to conserve Occoquan storage on days when flow in the river is more than adequate, requires a transfer of treated water from the Western to the Eastern service area. The amount of a load-shift that can be made by Fairfax Water is constrained to some extent by its ability to transfer treated water from one portion to another portion of its service area. These transfers are limited by pipe and pump capacities and other constraints, as listed in Table 1-1.

Fairfax Water demand also includes demand in a third service area, the "Central service area," which primarily consists of the City of Falls Church. Fairfax Water purchases treated water from Aqueduct and distributes it to customers in the Central service area. This water is transferred from Aqueduct's Dalecarlia and McMillan treatment plants to the Falls Church distribution system via a 35 MGD capacity pipe which runs under the Potomac River. Fairfax Water also has some capacity to transfer treated water between its Western and Central Service Areas.

1.2.3.3 Operations Based on Current Day Flow

When observed real-time flow at Little Falls approaches the 100 MGD minimum, CO-OP can request a load-shift by WSSC from the Potomac to the Patuxent, that is, a reduction in WSSC's Potomac River withdrawal and a corresponding increase in WSSC's withdrawal from the Patuxent reservoirs. WSSC's Patuxent reservoirs, Tridelphia and Howard T. Duckett, are located between Montgomery and Howard counties in Maryland. These reservoirs are operated in series and are treated in CO-OP models as a single resource with a total usable capacity of 10.2 BG. Because the travel time from WSSC's Potomac intake to Little Falls dam during low flow conditions is less than a half day and because WSSC is able to implement load-shifts rapidly, this shift in withdrawals can have an impact on current day flow.

TABLE 1-1: CURRENT WMA SYSTEM CONSTRAINTS

System resource/connections		Description
Fairfax Water		
	Potomac River intakes/Corbalis WTP (primarily for Western service area SA)	225 MGD maximum production 60 MGD minimum production
	Occoquan Reservoir intake/Griffith WTP (primarily for Eastern SA)	120 MGD maximum production 45 MGD minimum production 40 MGD maximum daily change in production
	Finished water purchased from Aqueduct (for Central SA)	35 MGD maximum via pipe from Aqueduct to Falls Church
	Transfer of finished water from Western to Eastern SA ("W to E transfer")	65 MGD maximum transfer rate
	Transfer of finished water from Eastern to Western SA ("E to W transfer")	35 MGD maximum transfer rate 10 MGD maximum daily change in transfer rate
	Transfer of finished water from Central to Western SA	+6 to -10 MGD
Loudoun Water		
	Potomac River intake/Trap Rock WTP	40 MGD maximum pump rate 20 MGD maximum treatment rate, beginning in 2017
	Discharge from Broad Run Water Reclamation Facility (indirect potable reuse)	2040: 5 MGD (influent = 12 MGD, reuse demand = 7 MGD) 2100: 6 MGD (influent = 21 MGD, reuse demand = 15 MGD)
	Quarry A as raw water storage facility	1.24 BG beginning in 2022
WSSC		
	Potomac River intake/WTP	288 MGD maximum production 100 MGD minimum production
	Patuxent reservoir intake/WTP	110 MGD maximum short-term emergency production (Future) 72 MGD maximum production (est. March 2019) 56 MGD maximum production (current) 33 MGD minimum production 10.3 MGD minimum environmental flow at Duckett dam. When storage falls below 1.0 BG: - load-shifting discontinued - withdrawal reduced to 20 MGD via intermittent WTP shutdowns
Aqueduct		
	Dalecarlia WTP	225 MGD maximum production 60 MGD minimum production
	McMillan WTP	120 MGD maximum production 60 MGD minimum production
	Pipe from Aqueduct to Fairfax Water's Falls Church service area	Allows maximum transfer of 35 MGD of finished water
Shared resources		
	Jennings Randolph Reservoir	13.1 BG water supply storage capacity 16.2 BG water quality storage at full conservation pool level
	Savage Reservoir	6.1 BG capacity
	Little Seneca Reservoir	3.9 BG capacity 1.73 cfs (1.12 MGD) minimum flow No maximum or minimum water supply release

2 Potential Water Supply Alternatives

This section of the report describes the potential structural and non-structural water supply alternatives that are evaluated, and assumptions used to represent the alternatives in the planning model used in this study, ICPRB's Potomac Reservoir and River Simulation Model (PRRISM). Many of these alternatives have been the subject of past investigations. The following four structural alternatives are considered:

1) Luck Stone quarries B and C: future use of Luck Stone quarries B and C, located in Loudoun County, Virginia, as raw water storage facilities for Loudoun Water and for releases to augment flow in the Potomac River during low flow periods, with
   a) Luck 1: 2.5 BG usable storage in Quarry B by 2035,
   b) Luck 2: 6.5 BG combined storage in quarries B and C by 2060;
2) Travilah Quarry: future use of Travilah Quarry, located in Montgomery County, Maryland, as a joint use storage facility which will increase supplies, either directly or indirectly, of all the CO-OP suppliers;
3) Vulcan Quarry: future use of Vulcan Quarry, located in Fairfax County, Virginia, as a raw water storage facility for Fairfax Water, with
   a) Vulcan 1: 1.7 BG usable storage in the Northern Reservoir by 2035,
   b) Vulcan 2: >17 BG combined storage in the Northern and Main reservoirs by 2085; and
4) Reverse osmosis water treatment plant ("RO plant"): construction of a reverse osmosis (RO) water treatment plant using the Occoquan Estuary to provide treated water for Fairfax Water.

Though most of the structural alternatives would only directly provide water to one or two WMA suppliers, they would all provide regional benefits by increasing flow in the Potomac River. All of the structural alternatives would require significant investments in new infrastructure which would in most cases include new underground conduits to transfer raw and/or treated water from one part of the WMA system to another.

The non-structural, that is, operational, alternatives considered in this study are:

5) Cooperative use of Quarry A ("Quarry A Coop"): cooperation between Loudoun Water and the CO-OP suppliers during droughts in use of Loudoun Water's Quarry A;
6) Use of Beaverdam Reservoir for low flow augmentation ("Beaverdam"): use of an existing local reservoir owned by Loudoun Water, Beaverdam, to augment Potomac River flow during droughts;
7) Improved forecasts ("FC Improvements"): improvements in the one-day and nine-day river flow and demand forecasts used during drought operations;
8) Use of Jennings Randolph Reservoir (JRR) water quality storage ("JRR WQ Storage"): use of Jennings Randolph Reservoir water quality storage for water supply purposes during droughts;
9) Reduction in upstream consumptive use ("Reduce upstream CU"): reduction in the portion of upstream withdrawals not returned to the watershed; and
10) More water use restrictions ("Increase Restrictions"): more stringent regional water use restrictions during droughts.

The non-structural alternatives would require little or no investment in costly infrastructure. However, they would all require new cooperative agreements, and/or contracts, and/or investment in research to develop new operational tools and policies.

The locations in the watershed of the structural alternatives and of Beaverdam Reservoir are shown on Figure 2-1.

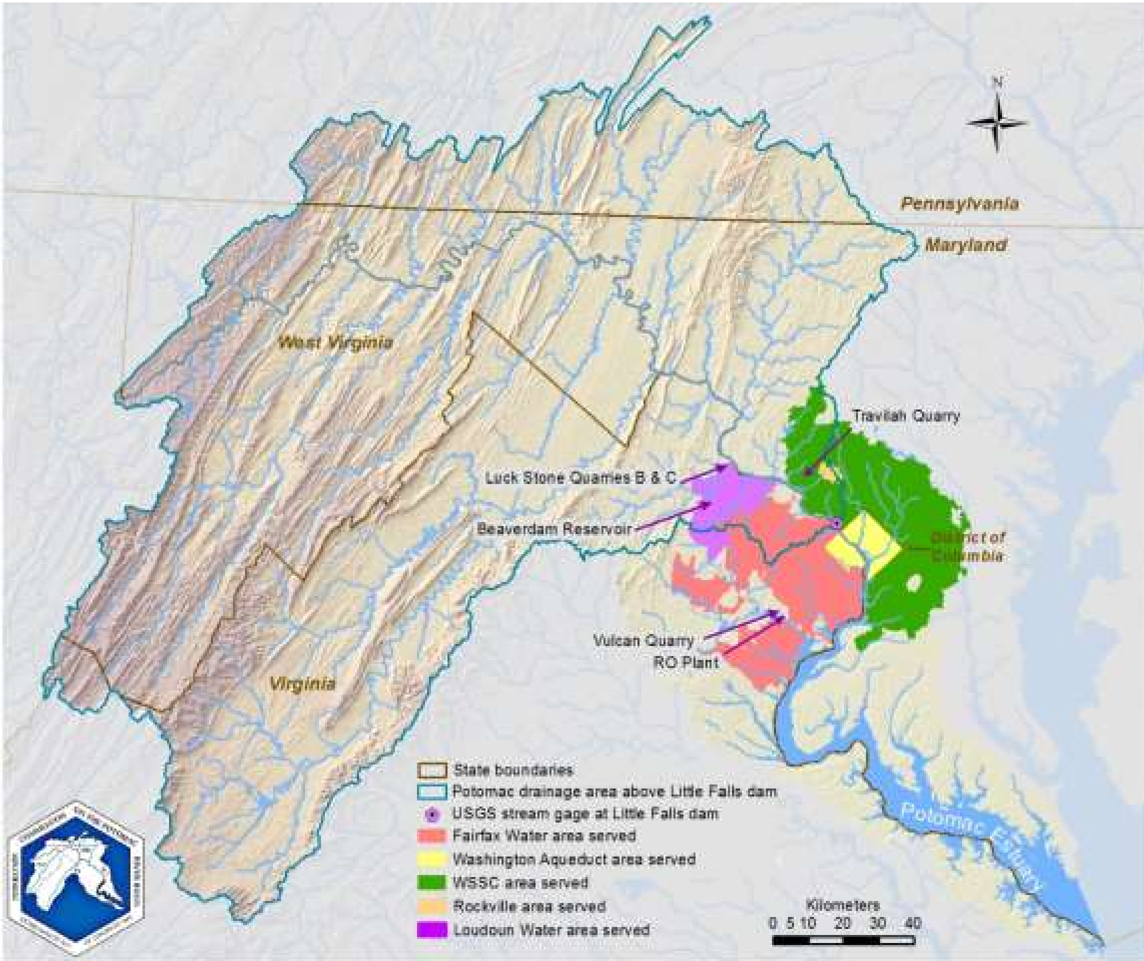


FIGURE 2-1: LOCATIONS OF THE STRUCTURAL ALTERNATIVES AND OF BEAVERDAM RESERVOIR

2.1 Luck Stone Quarries B and C

Loudoun Water and the Luck Stone Company are in the process of developing a plan for future use of two additional quarries as raw water storage facilities, referred to here as “Quarry B” and “Quarry C.” Both quarries, owned by Luck Stone, are located in Loudoun County, Virginia, adjacent to Goose Creek and near the site of Loudoun Water’s new Trap Rock WTP. Quarry B is expected to have a volume of approximately 2.5 BG when mining activities cease in 2035. 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’s new Potomac River intake. Goose Creek, a Potomac River tributary, might also provide a source of refill for these reservoirs.

Quarries B and C could be used directly by Loudoun Water, providing a raw water supply that would be treated at the Trap Rock plant. The quarries could also be used as a regional resource to augment Potomac River flow during droughts. It is assumed that this would be done via releases to Goose Creek. Though not considered in the current study, Loudoun Water is also securing easements which would make possible the future construction of tunnels to transfer water from the quarries to other WMA suppliers.

2.2 Travilah Quarry

Travilah Quarry is located in Montgomery County, Maryland, and is owned and mined by Aggregate Industries (a.k.a Bardon, Inc.). The quarry has been evaluated a number of times for its suitability for use as a water supply resource (e.g. CCJM, 2001; O'Brien & Gere Engineers, Inc., 2002). Most recently, ICPRB 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 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's Potomac River intake and a new raw water pumping station located within or adjacent to WSSC's Potomac Water Filtration Plant.

As of 2014, the volume of the quarry was 7.3 BG. The final volume available for water supply storage would depend on the result of negotiations with Aggregate Industries on topics such as the timing of acquisition and the design of remaining mining operations. Operationally, water stored in Travilah Quarry would be used during droughts or at other times when Potomac River flow is compromised (e.g. spills). Following the 2015 Black & Veatch study, it is assumed that when needed, the stored raw water would be conveyed through an underground tunnel to WSSC's Potomac treatment plant. Half of this water would be treated at WSSC's plant and half would be further conveyed by another underground tunnel to the intakes of Aqueduct's water treatment plants. Since the travel time from Travilah Quarry to the utility intakes is less than one day, this is a potentially valuable regional alternative in being able to respond quickly to water supply deficits.

2.3 Vulcan Quarry

Fairfax Water is planning to use the Vulcan Quarry, located in Fairfax County, to augment its raw water storage. Preliminary evaluations of Vulcan Quarry were conducted by CDM (2003). A description of Fairfax Water's preliminary operational plan for Vulcan Quarry is available in a report by Malcolm Pirnie (2012).

Fairfax Water has worked with the Vulcan Materials Company and with Fairfax County planning and permitting agencies to put in place a phased plan to provide additional water supply storage to meet future needs. Vulcan Materials owns and operates a granite quarry in Lorton, Virginia, located adjacent to the Occoquan Reservoir and Fairfax Water's Griffith WTP. According to Fairfax Water's two phase Vulcan Quarry Plan, Vulcan Materials will cease quarrying activities in the northern portion of the quarry (the Northern Reservoir) in the year 2035 and make a 1.7 BG volume (below the elevation of -95 feet) 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, with water in the solids waste stream recycled back to the Griffith plant. The solids waste stream contains 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 plant for treatment. A 200 million gallon (MG) volume of freeboard will remain above elevation -95 feet to provide for storage of discharge under emergency conditions. From 2035 to 2085, quarrying activities will continue in other portions of the quarry, but a "rock wall" will be left by Vulcan to segregate the Northern Reservoir from the area of active quarrying which will eventually become the "Main Reservoir."

In 2085, a new phase of the Vulcan Quarry Plan will commence. All quarrying activity will cease and the rock wall separating the Northern and the Main reservoirs will be partially demolished. At this time, the entire final volume of the quarry, up to approximately 17 BG, will be turned over to Fairfax Water for dual use as a solids disposal and raw water storage facility. At this time, two new sources of refill will be available for Vulcan Quarry: water pumped from Occoquan Reservoir and water pumped on a seasonal basis from Occoquan Bay.

2.4 Reverse Osmosis Water Treatment Plant

A study conducted for Fairfax Water by CDM (2004) evaluated the costs and benefits of a water treatment plant which uses the Occoquan Estuary as a raw water source. The facility would use a reverse osmosis (RO) membrane to treat the brackish water of the Occoquan Bay, where during drought periods, total dissolved solids levels can reach 2,500 mg/L. CDM evaluated finished water production capacities of 25 and 50 MGD.

2.5 Cooperative Use of Quarry A

Quarry A is an existing hard rock quarry owned by the Luck Stone Corporation and located along the eastern bank of Goose Creek just north of the right-of-way for the former Washington and Old Dominion Railroad in Loudoun County, Virginia. Loudoun Water is in the process of constructing a Potomac River intake and the Trap Rock Water Treatment Facility, which are planned to become operational in 2017. Loudoun plans to use Quarry A as a raw water storage facility beginning in the year 2022. These facilities received approval from the Virginia Department of Environmental Quality through the Virginia Water Protection (VWP) Individual Permit Issuance Number 10-2020 on November 27, 2012. Loudoun Water also has an agreement with Fairfax Water to purchase up to 50 MGD of treated water. Loudoun's new intake, treatment plant, and quarry are all represented in PRRISM using the following assumptions:

- Trap Rock will produce all of the water necessary to meet Loudoun's daily demand, up to an assumed maximum production rate of 40 MGD by the year 2040, and up to the amount allowed by its other constraints. Water for any unmet demand will be purchased from Fairfax Water.
- Quarry A will have a total capacity of 1.38 BG by the year 2018 according to Luck Stone's most recent mining plans. Assuming that dead storage accounts for 10 percent of this total and that several years will be required to convert the quarry to a raw water storage facility, it's assumed that the usable storage capacity of Quarry A is 1.24 BG beginning in the year 2022 (information provided by Dale Hammes, oral communication, June 26, 2016).
- Loudoun Water's withdrawals cannot exceed 40 MGD and are otherwise consistent with the requirements contained in its VWP permit (VWP Permit No. 10-2020 Part 1, I.2).

In the current study, two scenarios are considered for Quarry A: i) the base case scenario assumes that Potomac River withdrawals are restricted by Loudoun Water's current VWP permit, and ii) the alternative scenario assumes cooperative use of Quarry A, established via a formal agreement between Loudoun Water and the CO-OP suppliers.

Loudoun Water is not currently a signatory of the WSCA, which establishes the institutional framework, responsibilities, and operational guidelines for cooperative water supply operations in the WMA. The "cooperative use of Quarry A" alternative assumes that Loudoun Water enters into an agreement with the CO-OP suppliers and that its VWP permit is subsequently revised to allow it to operate in a manner that provides more benefits to both Loudoun and to the regional system. This possibility is anticipated in Loudoun's VWP permit, which states that "This permit may be reopened and modified" in the event that such an agreement is reached (VWP Permit No. 10-2020 Part 1, J.21).

2.6 Use of Beaverdam Reservoir for Low flow Augmentation

Loudoun Water purchased Beaverdam Reservoir, located on a small tributary to Goose Creek, from the City of Fairfax in 2014. It also purchased Goose Creek Reservoir, located on the Goose Creek main-stem approximately five miles upstream of the point at which the stream discharges into the Potomac River and downstream of a USGS stream gage, Station 01644000 (Goose Creek near Leesburg, Virginia). Beaverdam Reservoir has an estimated usable storage capacity of 1,240 MG and a six square mile drainage area. Goose Creek Reservoir has a storage capacity of 200 MG, but its capacity has been decreasing significantly over time due to the deposition of sediment. The two reservoirs have been operated as a system, with water pumped from Goose Creek Reservoir being used as a source of refill for Beaverdam Reservoir.

Loudoun Water has not yet developed plans for use of Beaverdam Reservoir, but one option it is considering is releasing water from Beaverdam during droughts to provide low flow augmentation for the Potomac River.

As a base case scenario for Beaverdam Reservoir, the current study assumes that it is used as a Loudoun County recreational facility, with no water supply withdrawals from the reservoir or from Goose Creek and no water supply releases made to Goose Creek. It's also assumed that the reservoir will rely on natural refill, with no refill provided by pumping from Goose Creek Reservoir.

As an alternative scenario, it's assumed that Loudoun will release water from Beaverdam Reservoir during droughts to augment Potomac River low flows, and in particular to help conserve storage in Little Seneca Reservoir. This scenario would require a new VWP permit and cooperative agreements and/or contracts between Loudoun Water and the CO-OP suppliers.

2.7 Improved Forecasts

As discussed in Section 1, many of the decisions made by CO-OP during droughts require forecasts of future river flows and of WMA water demand. Nine-day forecasts are needed to determine release rates from Jennings Randolph Reservoir and one-day forecasts are required to determine the need for releases from Little Seneca Reservoir and changes in Fairfax Waters operations. CO-OP's nine-day forecast of flow at Little Falls used during drought operations is based on an empirical equation derived from historical low flow data. CO-OP's one-day forecast is based on observed flows at upstream gages and a flow accumulation model which uses available estimates of lag times between these gages and Little Falls. More details on CO-OP's flow estimates are available in Ahmed *et al*. (2015).

Improved flow forecasts would enhance WMA system reliability by making more efficient use of stored water, since more accurate predictions of impending water needs would help avoid excess releases. CO-OP is currently evaluating the performance of its new Low flow Forecast System (LFFS), which automatically downloads real-time National Weather Service data and runs the Chesapeake Bay Program's Watershed Model to provide twice daily forecasts of Potomac basin stream flows. Continued development of the LFFS has the potential to provide better forecasts to inform CO-OP drought operations. Development of a decision support system that made use of real-time single forecasts and ensemble forecasts might provide even more operational benefits and improvements in system efficiency.

2.8 Use of JRR Water Quality Storage

Section 5019 of the Water Resources and Development Act of 2007 contains language instructing the Secretary of the Army to allow use of Jennings Randolph water quality storage for water supply purposes during droughts (USACE, 2014b). Specifically, this Act states that:

> "*The Secretary shall enter into an agreement with the Interstate Commission on the Potomac River Basin to provide temporary water supply and conservation storage at Federal facilities*

> *operated by the Corps of Engineers in the Potomac River basin for any period for which the Commission has determined that a drought warning or drought emergency exists."*

ICPRB has notified Corps staff at the Baltimore District Office of its intention to initiate discussions concerning the development of this agreement. The current study includes a very preliminary investigation of the potential benefits to the WMA system of such an agreement.

2.9 Reduction in Upstream Consumptive Use

Upstream water withdrawals from basin streams and aquifers reduce water availability at WMA intakes by decreasing river flow. A portion of the water withdrawn upstream is returned to the watershed, for example as discharge from wastewater treatment plants (WWTPs). But a portion is not returned due to processes which remove water, such as evaporation, transpiration by vegetation, incorporation into products, consumption by humans or livestock, lawn and agricultural irrigation, or diversion to another basin. The portion of water withdrawn that is removed and not available for downstream use is termed "consumptive use."

Estimates of current and future upstream consumptive use, at a monthly time scale, are available from ICPRB's 2015 water supply study (Ahmed, *et al.*, 2015). In the current study, the benefits of reducing upstream consumptive use are evaluated. An investigation of possible mechanisms for achieving such reductions is outside of the scope of this study. But these could include provision of seed money to upstream municipalities interested in developing storage in local quarries, a water markets approach to reducing agricultural use during droughts, as has been pioneered in Australia and California, or increased cooperation with state regulatory agencies on consumptive use restrictions during droughts.

2.10 More Water Use Restrictions

The WMA has a regional drought response plan, coordinated by the Metropolitan Washington Council of Governments (MWCOG), that was developed with input from the local cities and counties, water suppliers and distributors, ICPRB, and others (MWCOG, 2000). The plan defines drought stages for different levels of drought severity: Normal, Watch, Warning, and Emergency. For each drought stage the plan gives a trigger and a set of water use-related actions to be implemented. The two stages, Warning and Emergency, call for voluntary and mandatory water use restrictions, respectively. Previous versions of PRRISM simulated water use reductions associated with the declaration of water use restrictions, but used three rather than two levels of restrictions (Ahmed *et al.*, 2015).

For the current study, PRRISM was revised to simulate implementation of water use restrictions that more closely matches the existing regional plan. Voluntary restrictions are triggered in the model when combined water supply storage in Jennings Randolph Reservoir and Little Seneca Reservoir falls below 60 percent of capacity, similar to the regional plan's Warning stage. Mandatory restrictions, which are called for during the Emergency stage of the regional plan, are triggered when combined storage in these two upstream reservoirs falls below five percent of capacity. This study investigates the potential benefits of implementing a more stringent set of water use restrictions during droughts. This alternative would require that changes in the existing regional drought response plan be adopted by stakeholders. In this alternative, described in more detail in Section 3.5.10, three levels of water use restrictions are used, Voluntary, Mandatory, and Emergency, and the reservoir storage levels that trigger the restrictions are higher than those in other scenarios. In addition, the assumed reductions in water use during the Mandatory and Emergency stages are higher. Values for triggers and water use reductions are given in Table 3-5. This alternative may require increased enforcement capabilities at the local government and utility level and penalties associated with violations.

3 Modeling Future Operations of the WMA System

This section describes the modeling framework used to conduct the evaluation of water supply alternatives, in particular the simulation of the potential impacts of climate change and the simulation of daily water demands. It also describes the assumptions made concerning future use of the alternatives and future operational constraints. These assumptions are consistent with available information but are necessarily provisional, since details concerning the configuration and use of each potential alternative would be determined through future engineering and modeling studies.

The evaluation of water supply alternatives uses ICPRB's PRRISM model to simulate future water demand and availability for the WMA. The current version of PRRISM was developed using the object-oriented programming language ExtendSim™ Version 8 (Imagine That!, Inc.). PRRISM simulates daily system operations and the processes that govern water supply and demand in the system, including:

- natural 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 long-term average seasonal stream flows and withdrawals due to climate change.

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" daily Potomac River flows and reservoir inflows for input into PRRISM (Hagen *et al.*, 1998a; 1998b; 1998c; Hagen and Steiner, 1999), during the period, October 1, 1929, through December 31, 2013. PRRISM was used in the 2015 WMA water supply study (Ahmed *et al.*, 2015) to evaluate whether the current system could meet forecasted demands under hydrologic conditions which occurred in each year of this 84-year historical record, including the drought years of 1930 and 1966. It also was used to assess the vulnerability of the system to potential reductions in flow due to climate change. More details on PRRISM's representation of system supplies, operations, and constraints are available in ICPRB's 2015 water supply study.

For the current study, PRRISM was enhanced to allow it to simulate the potential impact of climate change on long-term average stream flows and water withdrawals, and the use of all alternatives described in Section 2, individually and in combination. A schematic diagram of PRRISM's representation of the WMA system along with the potential structural alternatives, as well as Beaverdam Reservoir, is shown in Figure 3-4. Key assumptions for each of the alternatives are given in Table 3-6 and Table 3-7.

3.1 Climate Change

A warming climate is expected to have a significant impact on water resources throughout the world. In our region, water availability is determined by flow in the Potomac River and flows into system reservoirs. Past ICPRB studies have shown a wide range of potential impacts of climate change on regional flows. Some climate projections indicate that precipitation will increase significantly in our region and lead to higher flows. Other projections indicate that flows will decrease, due to a combination of changing precipitation patterns and increases in evaporation from land and water surface and in transpiration by vegetation. In addition, higher temperatures and changes in precipitation patterns may result in higher than expected water demands due to increased summertime outdoor water use for landscaping and other purposes.

In this study, six scenarios are used to represent the range of potential impacts of climate change in the Potomac basin, three scenarios for 2040 and three for 2085. The scenarios were developed based on past CO-OP modeling results, and each consists of assumed changes in: i) long-term regional average seasonal stream flow (summer and non-summer month), ii) precipitation, and iii) temperature. The development of the scenarios is described in detail in Appendix A. As part of the scenario development process, two new sets of projected changes in climate, in the form of changes in mean monthly temperature and precipitation downscaled to the Potomac basin, were downloaded from the U.S. Geological Survey's Geo Data Portal. The new projections are derived from Climate Model Intercomparison Project Phase 5 (CMIP5) data sets, downscaled to user-selected regions by the USGS via statistical downscaling procedures. A total of 103 projections for the Potomac basin were obtained for the 10-year interval centered around 2040 ("2040 projections") and 101 projections for the 10-year interval center around 2085 ("2085 projections"), where in both cases the reference climate interval was 1989-1999. Results of past CO-OP studies were used to relate each projection to changes in long-term basin-wide seasonal average stream flow, as described below and in detail in Appendix A. The projected changes in climate also were related to changes in WMA daily demands, as discussed in the next section.

Changes in average annual temperature and precipitation for both sets of CMIP5 climate change projections are plotted in Figure 3-1. Changes in annual temperature, from the 1989-1999 reference period, range from 1.1° F to 5.7° F (degrees Fahrenheit) for the 2040 projections, with a median of 3.2° F, and 0.3° F to 12.7° F for the 2085 projections, with a median of 5.6° F. Changes in average basin precipitation range from -8 percent to +24 percent in 2040, with a median of +6 percent, and range from -8 percent to +31 percent in 2085, with a median of +11 percent.

A "climate response function" was used in the 2015 WMA water supply study to relate projected changes in Potomac basin climate to changes in stream flow. This function, developed using multiple regression analysis, describes the relationship between changes in average temperature and precipitation and changes in average summertime (June, July, August) basin-wide stream flow, as simulated by the Chesapeake Bay Program's Watershed Model. The climate response function was used to compute a projected change in summertime long-term average basin-wide stream flow for each climate change projection (see Appendix A). Results, ranked from lowest to highest change in stream flow, are plotted in Figure 3-2 for the 2040 projections and in Figure 3-3 for the 2085 projections. As depicted in Figure 3-2, in the 103 projections of climate in 2040, the estimated change in average summer (June, July, August) stream flow was greater than or equal to 2 percent in 50 percent of the projections, greater than or equal to -7 percent in 75 percent of the projections, and greater than or equal to -19 percent in 90 percent of the projections. Similarly, from Figure 3-3, in the 101 projections of climate in 2085, the estimated change in average summer flow was greater than or equal to 4 percent in 50 percent of the projections, greater than or equal to -12 percent in 75 percent of the projections, and greater than or equal to -23 percent in 90 percent of the projections.

These two sets of percent changes in flow are listed in Table 3-1, and are labeled CC50, CC75, and CC90 to indicate the percentage of climate change projections, 50 percent, 75 percent, and 90 percent, associated with flow changes exceeding these values.

The corresponding changes in non-summer month stream flow, precipitation, and temperature, also given in Table 3-1, were estimated using the methods described in Appendix A. For example, from Table 3-1, in 2085, changes in non-summer month stream flow, precipitation, and temperature associated with a four percent change in summer stream flow are three percent, 11.3 percent, and 5.6° F, respectively.

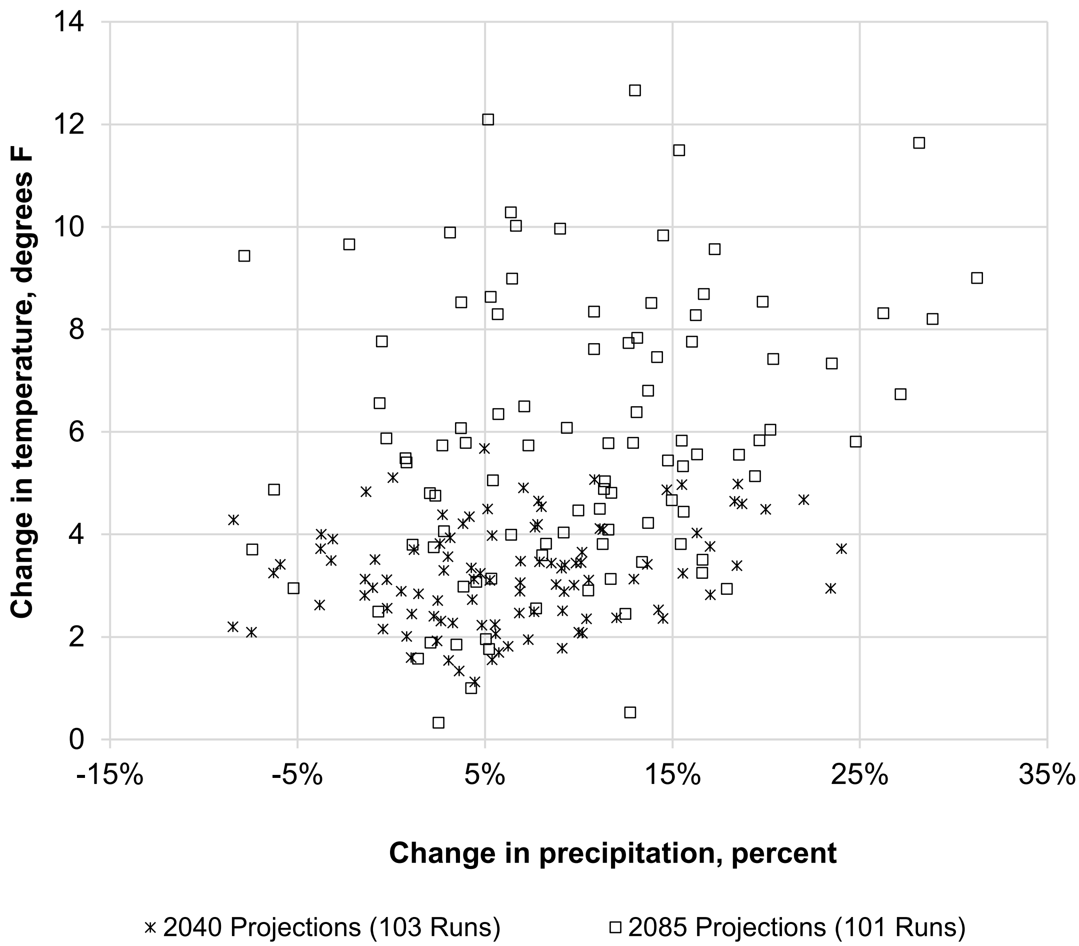


FIGURE 3-1: CHANGE IN AVERAGE ANNUAL TEMPERATURE AND PRECIPITATION OF THE CLIMATE CHANGE PROJECTIONS

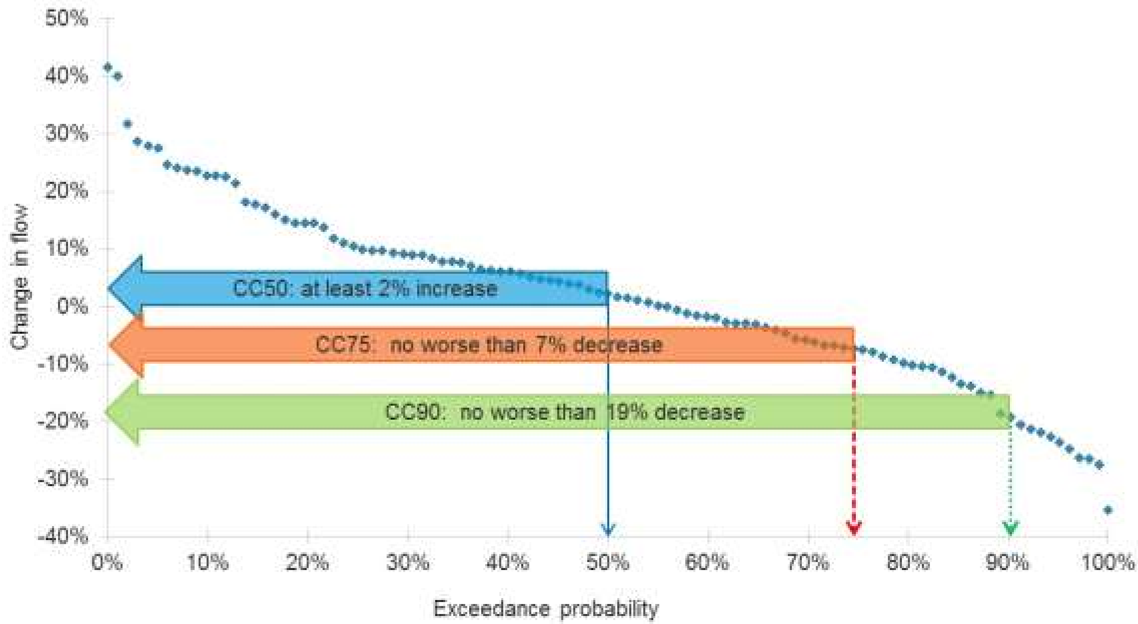


FIGURE 3-2: PROJECTED CHANGES IN AVERAGE 2040 SUMMER STREAM FLOW

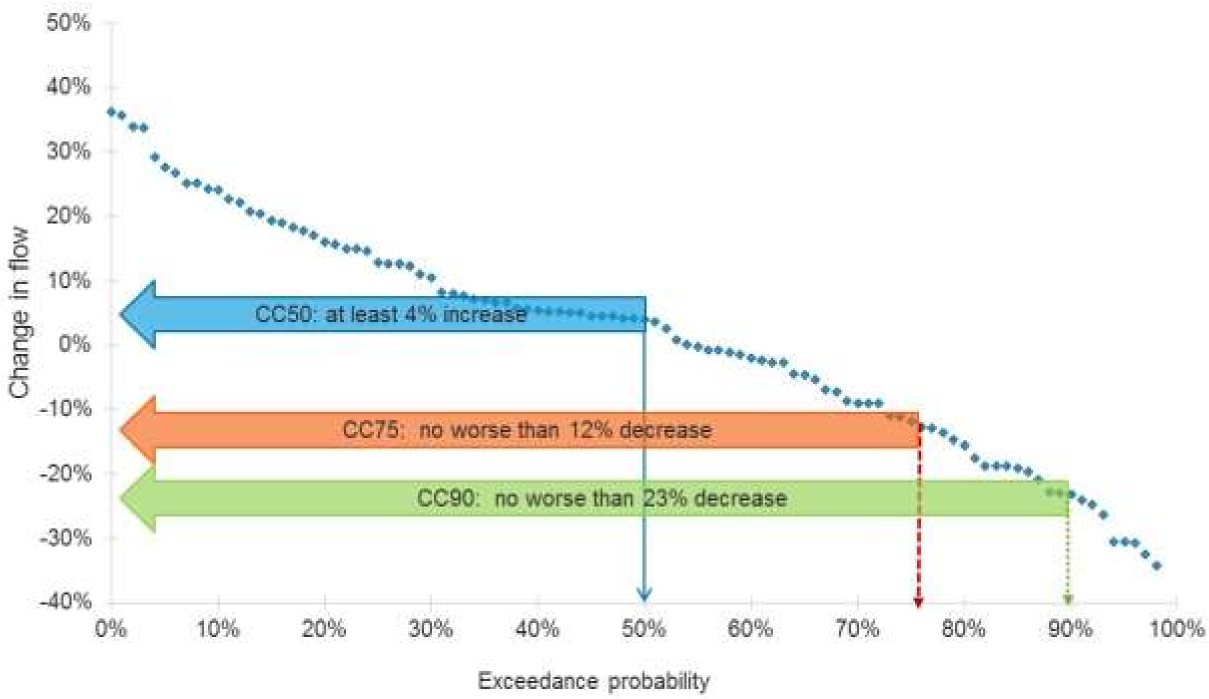


FIGURE 3-3: PROJECTED CHANGES IN AVERAGE 2085 SUMMER STREAM FLOW

TABLE 3-1: CLIMATE CHANGE SCENARIOS USED FOR EVALUATION OF ALTERNATIVES

Scenario year	2040			2085		
Climate change scenario	CC50	CC75	CC90	CC50	CC75	CC90
Change in long-term summer average basin-wide stream flow, percent	+2	-7	-19	+4	-12	-23
Change in long-term non-summer month average basin-wide stream flow, percent	+2	-6	-14	+3	-9	-17
Change in precipitation, percent	6.3	2.4	-2.9	11.3	5.4	1.4
Change in temperature, °	3.2	3.2	3.2	5.6	6.4	6.9

3.2 Simulation of Future Water Demand

The WMA water supply system often experiences rapid changes in river flow and in water demand, so simulation of operations at a daily time step, including daily demand patterns, is particularly important because reliability depends on how well operations can respond to these changes. PRRISM simulates the daily water withdrawal of each of the WMA suppliers, which is determined by their customers' water demand. Customer demand may be impacted by climate change, as discussed above, and estimates of this impact are also included in the simulated demands. The starting point for the model's daily demand values are the forecasts of average annual demand for the two scenario years considered in this study, 2040 and 2085, which are based on forecasts in the 2015 WMA water supply study (Ahmed *et al.*, 2015). Superimposed on the average annual demand is the variation that occurs depending on the month of the year and the daily variation caused by weather conditions (and also by day of the week), based on analyses of historical data. Finally, each day's demand contains a component that represents the observed short-term persistence, or memory, of daily demands and a component that represents the random, or unexplained, portion of each day's demand. Both the forecasts of average annual demands and the algorithms used to simulate the monthly and daily components of demand are discussed in detail in the 2015 WMA water supply study.

Future average annual water demand forecasts, without the impacts of climate change or water use restrictions, are given in Table 3-2. These forecasts are based on ICPRB's 2015 WMA water supply study, which gives forecasts for each of the WMA suppliers in five-year intervals from 2015 through 2040. The forecasts are made using a consistent set of assumptions for all WMA suppliers (see Ahmed *et al.*, 2015), and may differ from forecasts made by the individual suppliers. Total average annual water demand in the WMA in 2040 is estimated to be 545 MGD, a 12 percent increase from 486 MGD, the estimated demand in 2015. Over this same period of time, the population of the WMA is forecast to reach 5.7 million, a 23 percent increase over the current population of 4.6 million. Water demand is forecast to grow at a slower rate than population due to widespread adoption of new water saving fixtures and appliances (see Ahmed *et al.*, 2015 for the methodology and assumptions used in the simulation of future water demand through 2040). Table 3-2 also shows average July demands and "peak day" demands, which typically occur in the summer and early fall, as simulated by PRRISM. Daily demand on a hot summer day is generally greater than average annual demand. Average WMA demand in July is 18 percent higher than average annual demand, and annual peak day demand for the combined WMA system is 51 percent higher than average annual demand (a "peak day factor" of 1.51 for the combined system demands), based on 2009 through 2013 production data. Average annual demands for scenario year 2085 were obtained by using linear extrapolation to extend the available forecasts. Total average annual water demand in 2085 is estimated to be 665 MGD, a 37 percent increase from current levels. Estimates used in this study for upstream consumptive use are also given in Table 3-2. Average annual upstream consumptive use is 96 MGD in 2040 (Ahmed *et al.*, 2015) and 127.5 MGD in 2085, a 26 percent increase and a 68 percent increase, respectively, over the 2010 value of 76 MGD.

The sensitivity of customer demand to weather conditions is represented in PRRISM's daily demand model, and this allows the model to respond to changes in climate. For the climate change scenarios discussed above, each long-term average flow change is associated with an average temperature change and precipitation change (see Appendix A). These changes, given in Table 3-1, are applied to the daily historical temperature and precipitation time series. The resulting impact on simulated annual average and July average demands, obtained from PRRISM simulations, is shown in Table 3-3.

TABLE 3-2: FORECASTED ANNUAL WMA DEMANDS AND UPSTREAM CU, WITHOUT IMPACT OF CLIMATE CHANGE

	Forecasted Unrestricted Demands [1], MGD			Extrapolated Unrestricted - Demands, MGD		
Supplier	2040 average annual	2040 average July	2040 peak day	2085 average annual	2085 average July	2085 peak day
CO-OP suppliers						
Aqueduct	138.1	157.4	205	161.9	184.6	232
Fairfax Water (excludes water sold to Loudoun Water)	190.2	232.1	286	240.6	293.5	346
WSSC	179.3	200.8	250	201.5	225.7	274
Other WMA suppliers						
Loudoun Water	32.0	44.5	52	44.4	61.7	69
City of Rockville	5.7	6.3	8	7	7.8	9
WMA total	545	641	801	655	773	930
Upstream consumptive use	96	145	NA[2]	127.5	193	NA[2]

[1] From Ahmed, *et al.* (2015).

[2] NA = not applicable, since monthly averages are used to represent upstream consumptive use in PRRISM.

TABLE 3-3: IMPACT OF CLIMATE CHANGE ON WMA DEMANDS

	2040 Average Annual Demand, MGD	2040 Average July Demand, MGD	2085 Average Annual Demand, MGD	2085 Average July Demand, MGD
Based on forecasts in 2015 study	545	641	655	773
Including impact of climate change				
CC50	549	666	660	798
CC75	549	666	665	813
CC90	549	667	665	815

3.3 Use of Forecasts and Margins of Safety

As described in Section 2, 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.

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). For this study, an optional user-selected percent "improvement" in the nine-day flow forecast can also be simulated to investigate the sensitivity of system performance to forecast accuracy.

Releases from Little Seneca Reservoir and Fairfax Water load-shifts between Potomac River and Occoquan Reservoir withdrawals are based on one-day forecasts. 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 river flow. PRRISM's one-day forecast is similar to that currently used in CO-OP's drought operations spreadsheet 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). PRRISM also can simulate an optional user-selected percent improvement in the one-day forecast.

Only WSSC'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 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's Potomac intake to its Patuxent intake can increase flow and potentially prevent a Potomac River flow deficit, that is, prevent flow at Little Falls from falling below 100 MGD.

Forecasts also are used in PRRISM to simulate operations of the potential water supply alternatives. One-day forecasts are used in the simulation of releases from Loudoun Water's quarries B and C and from Beaverdam Reservoir, since it is assumed that it takes approximately one day for these releases to reach

Little Falls during low flow conditions. This assumption is provisional and may be changed in future studies if data indicate that travel times are closer to zero days or to two days. Similarly, Fairfax Water load-shifts that make use of Vulcan Quarry or the estuary RO facility are based on one-day forecasts.

Simulated use of 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 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 and Aqueduct to switch quickly from their Potomac withdrawals to Travilah.

Because of the reliance on forecasts, the following margins of safety (MOS) are added to PRRISM's release and load-shift decisions:

- <u>Releases from nine-day forecast resources</u>: i.e., combined Jennings Randolph/Savage releases
    - No margin of safety is added to the release because future deficits that develop downstream can be addressed by Little Seneca releases and other operational changes.
    - A Jennings-Little Seneca balancing buffer is added to or subtracted from the calculated release to keep the storage in these two reservoirs relatively equal, as a percent of capacity (see Section 3.4).
- <u>Releases from one-day forecast resources</u>: i.e., the combined Little Seneca release/quarries B & C release/Beaverdam release/Occoquan-Vulcan-RO plant load-shift in the absence of Travilah
    - For 2040, in the absence of Travilah, an MOS of 120 MGD (or 110 MGD if forecast improvements are simulated) is used if the Patuxent reservoirs are above the emergency storage threshold of 1.0 BG, and an additional 75 MGD MOS is included if Patuxent storage is below 1.0. BG.
    - For 2085, in the absence of Travilah, an MOS of 130 MGD is used if the Patuxent reservoirs are above the emergency storage threshold of 1.0 BG, and an additional 75 MGD MOS is included if Patuxent storage is below 1.0. BG.
    - If Travilah Quarry is part of the WMA system, then a MOS of -45 MGD is used in 2040 simulations and a MOS of -35 MGD is used in 2085 simulations.
- <u>Releases from current-day resources</u>: i.e., the Patuxent reservoirs and Travilah Quarry
    - A MOS of 40 MGD is used for the combined releases from the Patuxent reservoirs and Travilah Quarry.

No MOS for the Jennings Randolph/Savage release helps optimize system efficiency since any deficits that do occur in nine days can be addressed by Little Seneca releases and other downstream operational changes, as discussed above. The MOS of 120 MGD for the combined use of the one-day forecast resources helps ensure that Potomac River flow at Little Falls has little or no chance of falling below the 100 MGD minimum flow-by as long as storage is available in upstream reservoirs. It is based on past simulation results and is fairly consistent with the 100 MGD MOS actually used during CO-OP drought operations in the summer of 2002 (Kiang and Hagen, 2003). The MOS of 40 MGD used for releases from the current-day resources is included to account for potential errors that may result from PRRISM's use of a one-day time step and from approximations used in the current modeling effort.

3.4 Balancing Reservoir Storage

During drought operations, CO-OP aims to keep the percent of water supply storage balanced in Jennings Randolph and Little Seneca to enhance operational efficiency. Percent storage in the off-Potomac reservoirs, Occoquan and Patuxent, is also considered in operational decisions, but strict balancing is not desirable because storage in these reservoirs is used on a daily basis, not just during droughts. PRRISM contains an algorithm that simulates the balancing of storage in Jennings Randolph and Little Seneca. For the current study, new algorithms were added to help keep total Loudoun Water storage (Luck Stone quarries B and C, if present, and Beaverdam Reservoir, if available, but excluding Quarry A), and total Fairfax Water resources (Occoquan and Vulcan, if present) in balance with Little Seneca.

Water supply storage in Jennings Randolph and Little Seneca, as a percent of capacity, is kept in balance in PRRISM by means of an addition, $JRR_{addition}$ (which can be positive or negative), to the Jennings water supply release:

$$JRR_{addition} = JRR\_LSen_{factor} * \left(\frac{JRR_{stor}}{JRR_{cap}} - \frac{LSen_{stor}}{LSen_{cap}}\right) \qquad \text{(EQ 1)}$$

where

JRR_{stor}	= *beginning of the day water supply storage in JRR, MG*
JRR_{cap}	= *water supply storage capacity of JRR, MG*
$LSen_{stor}$	= *beginning of the day water supply storage in Little Seneca, MG*
$LSen_{cap}$	= *water supply storage capacity of Little Seneca, MG*
JRR_LSen_{factor}	= *user-selected balancing factor for JRR and Little Seneca percent storage*

In all simulations conducted for this study JRR_LSen_{factor} was set equal to 1000.

Algorithms were added in this study to balance total Loudoun Water and total Fairfax Water storage with storage in Little Seneca Reservoir. All of these resources are used to meet a need for flow augmentation predicted by one-day flow and demand forecasts. On a day when flow augmentation is needed, the total need is met by combined releases from these resources. Storage balancing of the one-day resources is accomplished by adjusting the fraction of the need met by Loudoun Water resources, LW_{frac}, and Fairfax Water resources, FW_{frac}, as follows:

$$LW_{frac} = LW_{frac0} + \alpha_{LW} * \left(\frac{LW_{stor}}{LW_{cap}} - \frac{LSen_{stor}}{LSen_{cap}}\right) + \beta * \left(\frac{LW_{stor}}{LW_{cap}} - \frac{FW_{stor}}{FW_{cap}}\right) \qquad \text{(EQ 2)}$$

$$FW_{frac} = FW_{frac0} + \alpha_{FW} * \left(\frac{FW_{stor}}{FW_{cap}} - \frac{LSen_{stor}}{LSen_{cap}}\right) + \beta * \left(\frac{FW_{stor}}{FW_{cap}} - \frac{LW_{stor}}{LW_{cap}}\right) \qquad \text{(EQ 3)}$$

where

FW_{stor}	= *beginning of the day Fairfax Water total storage, MG*
FW_{cap}	= *water supply Fairfax Water total storage capacity, MG*
LW_{stor}	= *beginning of the day Fairfax Water total storage, MG*
LW_{cap}	= *water supply Fairfax Water total storage capacity, MG*

and where LW_{frac0} is the ratio of Loudoun Water total storage capacity to total one-day storage capacity (combined capacity of Loudoun Water resources, excluding Quarry A, Fairfax Water resources, and Little Seneca Reservoir), FW_{frac0} is the ratio of Fairfax Water total storage capacity to total one-day storage capacity, and where α_{LW} , α_{FW} , and β are all user-selected parameters. Constraints are imposed on the calculations of LW_{frac} and FW_{frac} to make sure these values are between 0 and 1, and to exclude the effects of resources that are not in place in a given simulation.

The values used in this study for the multiplicative factors used in the balancing equations, JRR_LSen_{factor}, α_{LW}, α_{FW}, and β are given in Appendix B.

3.5 PRRISM Simulation of Alternatives

This section describes the assumptions used by PRRISM to simulate each of the alternatives. These assumptions are preliminary, based on available information and on input from the study's Technical Advisory Committee, composed of CO-OP supplier, Loudoun Water, and ICPRB staff members. Upon implementation of any of the alternatives, information on operational constraints will be updated and operating protocols will be developed cooperatively by the CO-OP suppliers. The information in the paragraphs below is summarized in Table 3-6 and Table 3-7.

3.5.1 Luck Stone Quarries B and C

In PRRISM, the Luck Stone quarries B and C are simulated as a single resource, used in two different ways: 1) to directly meet Loudoun Water demands with withdrawals treated at the Trap Rock plant and 2) to make releases to the Potomac River to augment flows, helping ensure that downstream needs are met. The quarries are assumed to be filled with water withdrawn from the river and delivered via Loudoun Water's raw water transmission pipe. The following assumptions are made about Loudoun Water's future system:

- The usable combined storage capacity of the Luck Stone quarries is 2.5 BG beginning in 2035 and 6.5 BG beginning in 2060.
- Capacity loss due to the deposition of sediment is assumed to be 0.1% per year.
- Loudoun Water's maximum production rate at its Trap Rock WTP will be 40 MGD beginning in 2035 and 80 MGD beginning in 2060.
- Trap Rock will produce all of the water necessary to meet Loudoun Water's daily demand, up to its assumed maximum production rate and up to the amount allowed by its other constraints. Water for any unmet demand, up to an additional 50 MGD, will be purchased from Fairfax Water.
- Beginning in 2060, the capacity of Loudoun Water's Potomac River intake and raw water transmission pipe will be expanded to 80 MGD.
- It is assumed that until 2060, the maximum rate at which the Luck Stone quarries can release water for the purpose of augmentation of low flows in the Potomac River is 80 MGD. After 2060, if the combined capacity increases to 6.5 BG then the maximum rate becomes 160 MGD.
- The assumed travel time of a release from the quarries to Little Falls is one day, so releases, similar to those from Little Seneca Reservoir, are determined based on one-day forecasts.
- It's assumed that percent storage in the Luck Stone quarries will be kept in balance with percent storage in Little Seneca Reservoir.

3.5.2 Travilah Quarry

For the purposes of this study, it is assumed that Travilah Quarry will become available for use in 2040. The assumed usable capacity is 8.5 BG. This was determined by the study's Technical Advisory Committee to be an appropriate conservative value. It is the expected capacity in 2025 and beyond that would be available between the elevations 150 to 350 feet and thus accessible via gravity flow and single stage pumping (Black & Veatch, 2015; Cary Hirner, private communication, January 12, 2016).

Based on results of preliminary analyses, the travel time of a release through underground conduits from Travilah to both the WSSC and Dalecarlia water treatment plants is less than half of a day. In addition, because of the proximity of WSSC and Aqueduct Potomac River intakes to Little Falls, the time lag between reductions in WSSC and Aqueduct Potomac withdrawals and impact on flow at Little Falls ranges from immediate to less than a half day. Thus, Travilah Quarry is a particularly valuable regional alternative because of its ability to quickly increase flow at Little Falls, similar to the Patuxent reservoirs.

Operational assumptions used in PRRISM to simulate use of Travilah Quarry during droughts are summarized below.

- Like WSSC's Patuxent reservoirs, the need for use of water stored in Travilah Quarry is determined based on the current day's flow at Little Falls and estimates of current day demands. The impact of the resulting reductions in WSSC and Aqueduct withdrawals on flow at Little Falls is assumed to be immediate.
- Consistent with Black & Veatch (2015), it's assumed that Travilah can provide up to 200 MGD of WSSC's raw water needs and 200 MGD of Aqueduct's raw water needs.
- The quarry is refilled with water pumped from the Potomac River at a constant rate of 60 MGD. Refill is allowed when flow in the river at Little Falls exceeds the current day's need, that is, the current day demands plus the 100 MGD flow-by at Little Falls, plus a 75 MGD buffer which allows for potential load-shifting to allow refill of WSSC's Patuxent reservoirs.
- It is assumed that use of Travilah is minimized during the first phase of a drought because it is a dual purpose facility which could potentially be needed after a spill event. During the first phase of a drought, it is assumed that both Aqueduct and WSSC make Potomac withdrawals. The current day's potential Potomac River flow deficit is met by a WSSC load shift to the Patuxent reservoirs, and only the portion of the deficit that cannot be met by the Patuxent, due to operational constraints, is met by Travilah. Later in the drought, if and when total usable storage in the Patuxent reservoirs falls below a reserve storage level of 4.0 BG, the entire current day's deficit is met by Travilah. In this case, WSSC Patuxent plant production is assumed to be constrained by values in Table 1-1 and by the rule curves implemented in PRRISM, to the range of 34 to 41 MGD.
- As discussed in Section 3.3, if Travilah is in use as a raw water storage facility, the margin of safety for the combined release from the one-day forecast resources is reduced.
- To compute each day's water supply need from Travilah and/or the Patuxent, a margin of safety of 40 MGD is included in the calculation of the current day deficit to account for potential errors that are outside of the scope of the current modeling effort.

3.5.3 Vulcan Quarry

Many of the assumptions used to simulate the capacity and operations of Vulcan Quarry were taken from the study conducted for Fairfax Water by Malcolm Pirnie (2012). The usable capacity of the quarry is assumed to be 1.7 BG in 2035 when the Northern Reservoir becomes available ("Vulcan Phase 1"). It's assumed that additional storage volume, resulting in a usable capacity of 17.0 BG, becomes available in 2085. The actual capacity in 2085 will depend on mining operations and may also be influenced by cost considerations. A sensitivity test is conducted to compare benefits to the system of 14 BG and 17 BG capacities (see Section 4.3.3). The capacity of the quarry will diminish over time due to the accumulation of settled solids. The annual rate of capacity loss was estimated as a function of annual Griffith WTP production based on observed loss rates at another Fairfax Water solids disposal facility, taking into account recent changes in the Griffith plant coagulant loads (Malcolm Pirnie, 2012). The resulting value, 0.242 MG/year per MGD of Griffith production, was used by Malcolm Pirnie, along with estimates of future annual Griffith production, to obtain Vulcan capacity loss rates and cumulative losses as a function of year (Malcolm Pirnie, Table 2-2). These cumulative losses range from 107 MG by 2040 and 1168 MG by 2085. They are reproduced in Table 3-4, and were used in the current study to calculate the usable capacity of Vulcan in any given year.

Table 3-4: Estimates of Vulcan Quarry Capacity Loss by Year [1]

Year	Assumed Griffith WTP annual production, MGD	Vulcan Quarry storage depletion rate, MG/year	Vulcan Quarry cumulative storage depletion, MG
2035	87.6	21.2	0
2040	89.6	21.7	107
2050	94.0	22.7	329
2060	96.9	23.4	560
2070	99.8	24.1	798
2080	102.8	24.8	1043
2085	104.4	25.2	1168

[1] From Malcolm Pirnie (2012).

Vulcan Refill

As discussed in Section 2, refill of Vulcan Quarry from 2035 to 2085 (Vulcan Phase 1) will be provided by the solids waste stream from the Griffith WTP treatment process. This is assumed to provide a daily refill volume equal to five percent of raw water input to the Griffith plant.

Beginning in 2085, the capacity of Vulcan will significantly expand to include the southern, or main, portion of the quarry ("Vulcan Phase 2"). Refill for this larger capacity reservoir will come from two sources:

- The Griffith WTP solids discharge stream, and
- Water from the Occoquan Reservoir, primarily via gravity flow, at a rate of 100 MGD, when storage in Occoquan Reservoir is greater than 80 percent of capacity.

At some point after 2085, refill will be provided from the two sources listed above and also from water pumped on a seasonal basis from the Occoquan Estuary ("Vulcan Phase 3"). Pumping will be restricted to the months of January through May (when freshwater conditions typically occur in the estuary downstream of Occoquan Reservoir). The pump rate is assumed to be 72.5 MGD when storage in Vulcan Quarry is less than 75 percent of capacity (Malcolm Pirnie, 2012).

Vulcan Withdrawals

From 2035 to 2085, the simulation of Vulcan Quarry operations in PRRISM assumes that the quarry will be operated in a manner that keeps it full during non-drought years, or if it is not full, then allows it to refill. During drought years, storage is used in a manner that will tend to draw the reservoir completely down over the period from June 1 through December 31. Though not included in the current study's simulations, withdrawals may also be influenced by water quality. In more detail, the decision rules for simulated daily withdrawals are as follows:

- During non-drought conditions
  - If Vulcan is full, each day's withdrawal will be equal to the day's inflow,
  - If Vulcan is not full, no withdrawal will be made to allow for refill;

- During drought conditions, indicated by storage in Little Seneca Reservoir falling below 95 percent
  - During January through May, each day's withdrawal will be equal to the day's inflow,
  - During June through December, daily withdrawal will equal the sum of the day's inflow and a fraction of available storage, where the fraction of available storage is equal to the available storage divided by the number of days remaining in the calendar year.

Beginning in 2085, withdrawals for Griffith WTP production will be split between Occoquan Reservoir and Vulcan Quarry in a manner that tends to balance percent storage in the two reservoirs. Using the operating rules in the Malcolm Pirnie study (2012):

- If percent usable storage in Occoquan Reservoir is greater than 80 percent of capacity or is greater than percent usable storage in Vulcan Quarry, then all water for Griffith will be withdrawn from Occoquan Reservoir;
- Otherwise, 51 percent of the required withdrawal will be made from Occoquan Reservoir and 49 percent will be made from Vulcan Quarry.

Other Fairfax Water System Changes

Vulcan Quarry provides a regional benefit by allowing Fairfax Water to reduce its Potomac River withdrawals during low flow periods. In order to realize this benefit, Fairfax Water will need to enhance its system to allow it to treat the larger volumes of water available because of Vulcan. It will also need to enhance its capacity to transfer this water to its Potomac, or Western, service area, which normally largely depends on water from the Potomac River. ICPRB conducted sensitivity tests prior to the alternatives analysis to estimate the magnitude of the required enhancements, and results are discussed in Section 4.3.3. Based on these results, the following changes were made to PRRISM to simulate Fairfax Water's system for scenarios in which Vulcan Quarry is present:

- Beginning in 2035
  - The maximum capacity of the Griffith WTP is increased to 160 MGD (from the present maximum of 120 MGD)
  - The maximum rate of transfer of treated water from the Eastern to the Western service area is increased to 50 MGD (from the present maximum of 35 MGD)
  - The maximum daily change in the rate of transfer of treated water from the Eastern to the Western service area is increased to 40 MGD (from the present value of 10 MGD)
- Beginning in 2085
  - The maximum capacity of the Griffith WTP is increased to 240 MGD
  - The maximum rate of transfer of treated water from the Eastern to the Western service area is increased to 100 MGD
  - The maximum daily change in the rate of transfer of treated water from the Eastern to the Western service area is increased to 50 MGD

3.5.4 Reverse Osmosis Water Treatment Plant

The RO plant is viewed as an option that could be implemented relatively quickly if it were determined that there was a need, since the plant could be situated on a site already owned by Fairfax Water. In this study it is assumed that the RO plant alternative could be available as a resource as early as 2035.

In PRRISM simulations the facility is operated at a constant rate of 50 MGD during droughts, with operations triggered, following Malcolm Pirnie (2012), when combined water supply storage in Little Seneca and Jennings Randolph reservoirs is less than 60 percent of combined capacity.

Similar to Vulcan Quarry, the RO facility will provide more of a regional benefit if Fairfax Water enhances its ability to send treated water to its Western service area. Based on ICPRB's sensitivity analyses (discussed in more detail in Section 4.3.4), PRRISM results on the benefits of the RO facility assume the following:

- The maximum rate of transfer of treated water from the Eastern to the Western service area is increased to 65 MGD
- The maximum daily change in the rate of transfer of treated water from the Eastern to the Western service area is increased to 50 MGD

3.5.5 Cooperative Use of Quarry A

In PRRISM's simulation of cooperative use of Quarry A, it is assumed that restrictions on Loudoun's Potomac River withdrawals are relaxed, and in particular, that there are no restrictions on Loudoun's withdrawals related to Jennings Randolph water supply releases. It's also assumed that Loudoun helps conserve storage in Little Seneca Reservoir by completely relying on Quarry A on days in which a water supply release from Little Seneca is occurring or when a Potomac River withdrawal by Loudoun would reduce Potomac River flow to an extent that would require a release from Little Seneca.

3.5.6 Use of Beaverdam Reservoir for Low flow Augmentation

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. The following assumptions are used in PRRISM to simulate this alternative:

- Water is pumped from Goose Creek Reservoir at a fixed rate of 15 MGD to refill Beaverdam Reservoir when flow in Goose Creek is greater than 139 MGD (215 cfs);
- Goose Creek Reservoir is modeled as a run-of-the-river reservoir;
- The maximum release rate from Beaverdam is 40 MGD;
- Beaverdam's usable capacity in 2005 was 1290 MG;
- Capacity loss of Beaverdam Reservoir due to the deposition of sediment is assumed to be 1.3 MG per year; and
- It's assumed in PRRISM that percent storage in Beaverdam will be kept in balance with percent storage in other WMA system resources.

3.5.7 Improved Forecasts

To simulate improvements in flow forecasts, PRRISM's nine-day and one-day forecasts were both replaced with linear combinations of the original forecasts and actual historical flow. The percentage of actual flow is a user-selected value, and the percent of forecasted flow equals 100 minus the percentage of actual flow. Thus, if the percentage of actual flow was set equal to 100, it would represent a perfect forecast. If the percentage of current day flow was set equal to zero, it would represent no improvement in the forecast.

Under the improved forecasts alternative, the accuracies of both the nine-day and the one-day forecast are assumed to improve by 10 percent. Under some combinations of alternatives, additional improvements are assumed (see Table 4-7 and Table 4-8).

3.5.8 Use of JRR Water Quality Storage

This study conducted a very preliminary investigation of the potential benefits of using Jennings Randolph water quality storage for water supply purposes during droughts. The following assumptions were used in PRRISM to simulate this alternative:

- 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 a specified trigger;
- The trigger for the transfer is water supply storage at 2.6 BG, which is approximately 20% of its capacity when conservation storage is full; and
- The transfer does not take place if water quality storage is below 5.0 BG.

Because of time constraints it was not possible to test a range of triggers and transfer values and determine their effects on system performance. Other values and other means of using water quality storage during droughts, including changes in the USACE's water accounting procedures, should be explored in future studies.

3.5.9 Reduction in Upstream Consumptive Use

Upstream consumptive use is simulated in PRRISM as a reduction in Potomac River flow which varies by month and is dependent on scenario year. Values for upstream consumptive use are based on estimates given by Ahmed *et al*. (2015) for monthly consumptive use in 2010 and for annual growth rates. PRRISM is configured to simulate user-specified changes in annual average consumptive use.

For the reduction in upstream consumptive use alternative, simulations were conducted using a 10% reduction in upstream consumptive use for the 2040 scenario year. Upstream consumptive use in 2040 is estimated to average 96 MGD annually and 145 MGD in the month of July. Therefore, a 10% reduction in the annual average, 9.6 MGD, was used in the model runs. The resulting 10% reduction in July is 14.5 MGD.

3.5.10 More Water Use Restrictions

This alternative assumes that a set of more stringent drought-related water use restrictions is adopted by the region. The triggers and assumed water use reductions are given in Table 3-5. This table also gives the "baseline" values of triggers and water use reductions which are assumed for all simulations that do not include the "more stringent restrictions alternative".

In the more stringent restrictions alternative, it's assumed that Voluntary restrictions occur in an earlier stage of a drought – when combined water supply storage in Jennings Randolph Reservoir and Little Seneca Reservoir falls below 80 percent of capacity. Also, the assumed summertime water use reductions during Emergency restrictions are higher than assumed in previous ICPRB studies. Water use reductions of 22% were found to be achievable by Virginia municipalities with good communication and public outreach components of their drought response plans (Halich and Stephenson, 2009).

TABLE 3-5: ALTERNATIVE WATER USE REDUCTIONS

Water use restriction scenario	PRRISM Restriction Type	Combined JRR-Seneca storage trigger	Assumed summer use reduction	Assumed non-summer month use reduction
Baseline – used for all other alternatives	Voluntary	60%	5%	3%
	Mandatory/Emergency	5%	15%	5%
More stringent restrictions alternative	Voluntary	80%	5%	3%
	Mandatory	40%	15%	10%
	Emergency	5%	22%	10%

Table 3-6: Key Assumptions for Structural Alternatives

No.	Alternative/year available		Assumptions in PRRISM
1	Luck Stone Quarries B and C		Luck Stone quarries B and C can be used for Potomac River low flow augmentation
1a	Luck 1	2035	Luck Stone Quarry B is available for low flow augmentation: • 2.5 BG starting usable storage capacity in Quarry B • 2.5 MG/year sedimentation rate for Quarry B • Refill via the 40 MGD pipe from Potomac intake • 80 MGD max release to Goose Creek for low flow augmentation
1b	Luck 2	2060	Luck Stone quarries B and C are available for low flow augmentation: • 4.0 BG starting usable storage capacity in Quarry C • 4.0 MG/year sedimentation rate for Quarry C • Refill of quarries B and C via an 80 MGD pipe from Potomac intake • 160 MGD max combined release to Goose Creek from quarries B and C
2	Travilah Quarry	2040	Travilah Quarry is available as a direct supply of raw water for Aqueduct and WSSC: • 8.5 BG starting usable storage capacity • 8.5 MG/year sedimentation rate (0.1% annual capacity loss) • Releases from Travilah begin when Patuxent storage falls below 4.0 BG • 200 MGD maximum can be supplied to WSSC's Potomac WTP • 200 MGD maximum can be supplied to Aqueduct's Dalecarlia & McMillan WTPs • Refill rate of 60 MGD (Refill when excess flow in Potomac River ≥ 135 MGD)
3	Vulcan Quarry		Vulcan Quarry stores raw water that is treated by Fairfax Water's Griffith WTP
3a	Vulcan 1	2035	Vulcan Phase 1 – Northern Reservoir is available: • 1.7 BG starting usable storage capacity • Refill from Griffith backwash (5% of plant production) • Sedimentation rate from Malcolm Pirnie (2012) based on Griffith production • Fairfax Water East to West finished water transfer capacity upgraded to 50 MGD and max daily transfer change upgraded to 40 MGD • Griffith WTP max production rate/daily change is 160 MGD/40 MGD

3b	Vulcan 2	2085	Vulcan Phase 2 – both Northern and Main reservoirs are available:
			• Main Reservoir adds 17.6 BG starting usable storage capacity
			• Sedimentation rate based on Griffith production
			• Refill from
			  ○ Griffith backwash (5% of plant production)
			  ○ Occoquan Reservoir at rate of 100 MGD max if Occoquan is > 80% full
			• Fairfax Water East to West finished water transfer rate/daily change is 100/50 MGD
			• Griffith WTP max production rate/daily change is 240 MGD/40 MGD max daily change

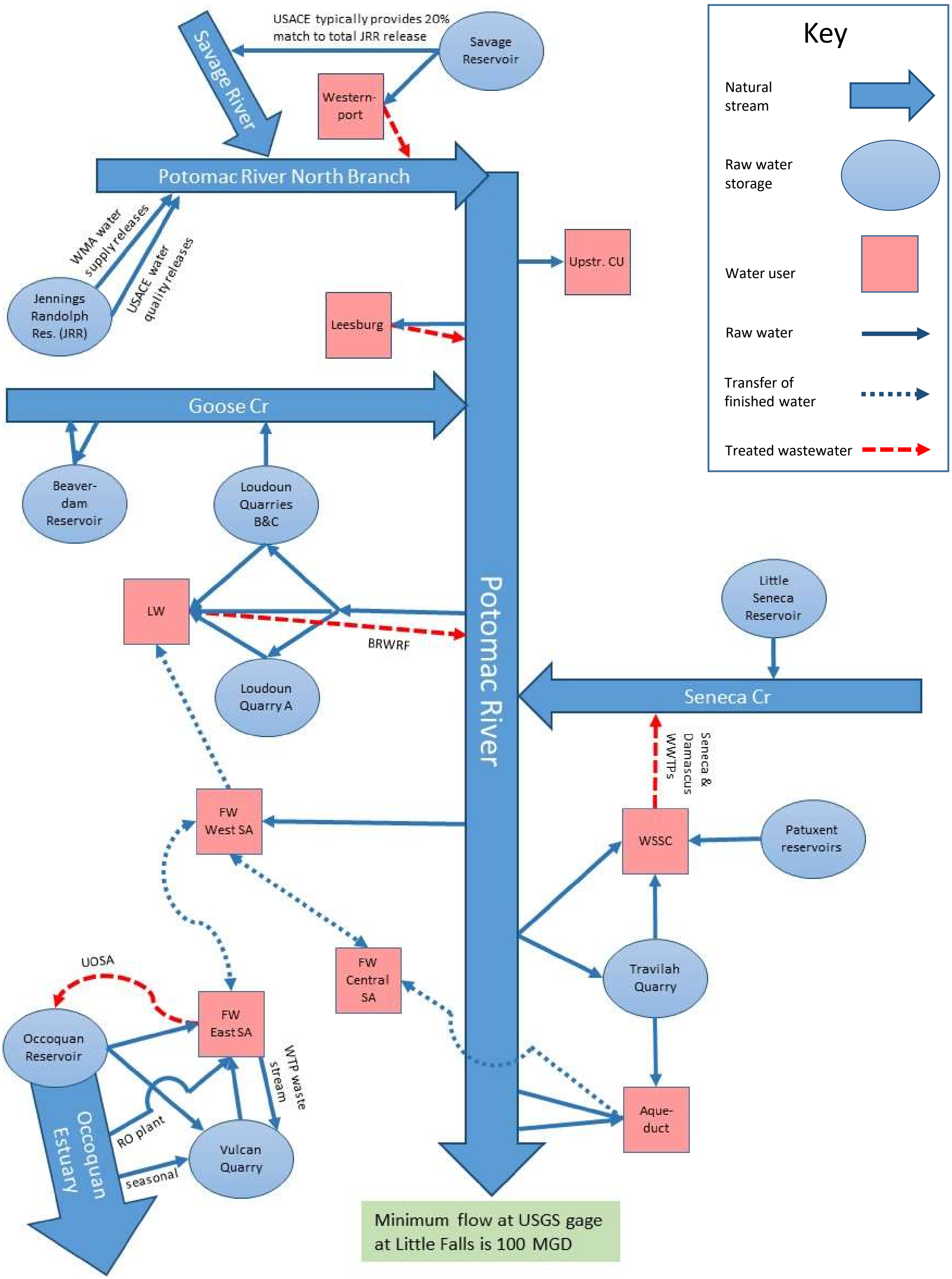
3c	Vulcan 3	2085	Vulcan Phase 3 – identical to Vulcan 2 except that another refill source is added: • Additional refill from seasonal pumping (January – May) from the Occoquan Estuary at rate of 72.5 MGD when Vulcan storage < 75% of capacity
4	RO Plant	2035	RO WTP uses the Occoquan Estuary as its raw water supply: • 50 MGD fixed production rate • Operated when combined water supply storage in Jennings Randolph and Little Seneca falls below 60% of capacity • Fairfax Water East to West finished water transfer rate/daily change is 65/50 MGD

TABLE 3-7: KEY ASSUMPTIONS FOR OPERATIONAL ALTERNATIVES

No.	**Alternative/year available**		**Assumptions in PRRISM**
5	Quarry A Coop	2025	Quarry A used cooperatively during drought operations: • 1.24 BG starting usable storage capacity • Loudoun Water's Potomac River withdrawals not constrained by presence of JRR water supply releases • Loudoun Water reduces Potomac River withdrawals on days when Seneca Reservoir water supply releases are made

6	Beaverdam	2025	Beaverdam Reservoir is used for Potomac River low flow augmentation:
			• Usable capacity of 1.29 BG in 2005
			• Assumed sedimentation rate of 1.3 MG/year
			• Refill from
			  o natural inflow
			  o from 15 MGD pumping from Goose Creek when flow in Goose > 215 cfs
			• Maximum water supply release is 40 MGD

7	FC Improve-ments	2025	Improvements are achieved in the accuracy of forecasts of Potomac River flow at Little Falls: • 10% improvement in the 9-day forecast • 10% improvement in the 1-day forecast by 2040, or greater for some alternatives • 35% improvement in the 1-day forecast by 2085, or greater for some alternatives
8	JRR WQ Transfer	2025	A lump transfer of 2.0 BG is made from JRR water quality storage to water supply storage whenever water supply storage falls below 2.6 BG, with the constraint that water quality storage does not fall below 5.0 BG as a result of the transfer.
9	Reduce upstream CU	TBD	Upstream consumptive use is assumed to decrease by 10%: • A reduction of 9.6 MGD in the 2040 annual average • A reduction of 12.8 MGD in the 2085 annual average
10	Increase Restrictions	TBD	The following more stringent water use restrictions are imposed during droughts: • When combined JRR-Seneca storage < 80%, Voluntary (5%/3% summer/other reductions) • When combined JRR-Seneca storage < 40%, Mandatory (15%/10% summer/other reductions) • When combined JRR-Seneca storage < 5%, Emergency (22%/10% summer/other reductions)


USACE typically provides 20% match to total JRR release
Savage Reservoir
Savage River
Western-port
Potomac River North Branch
WMA water supply releases
USACE water quality releases
Jennings Randolph Res. (JRR)
Upstr. CU
Leesburg
Goose Cr
Beaver-dam Reservoir
Loudoun Quarries B&C
LW
BRWRF
Loudoun Quarry A
Potomac River
Little Seneca Reservoir
Seneca Cr
Seneca & Damascus WWTPs
FW West SA
WSSC
Patuxent reservoirs
Travilah Quarry
FW Central SA
UOSA
Occoquan Reservoir
FW East SA
WTP waste stream
RO plant
Vulcan Quarry
seasonal
Occoquan Estuary
Aque-duct
Minimum flow at USGS gage at Little Falls is 100 MGD
Key
Natural stream
Raw water storage
Water user
Raw water
Transfer of finished water
Treated wastewater

4 Results

In this section of the report, results on the benefits of the individual alternatives described in Sections 2 and 3, and of selected combinations of alternatives, are presented. The alternatives are evaluated in terms of their ability to help the WMA system meet summertime demands and on their ability to increase the system's reserve storage on the worst day of a severe drought. The evaluations are conducted for two future scenario years, 2040 and 2085, and for a range of future climate conditions, represented by three climate change scenarios. Improvements are measured by comparing PRRISM simulation results for the "baseline" system with results for the alternative(s) added to the baseline system.

4.1 Scenarios

Two scenario years are considered, 2040 and 2085. Results for 2040 provide information to aid the water suppliers in fulfilling their responsibilities under the WSCA: To begin selecting and implementing measures to address the need for additional resources identified in the 2015 water supply study (Ahmed *et al.*, 2015). Results for 2085 provide information for long-term planning purposes.

The future effects of climate change on water supply are uncertain in our region, so evaluations of alternatives were conducted for the three different climate change scenarios described in Section 3.1: CC50, CC75, and CC90. Under all scenarios, water demands are assumed to rise due to higher temperatures, but the impact on stream flows range from slightly positive in the mild scenario (CC50) to moderately negative in the most severe scenario (CC90).

4.1.1 Scenario Years

In PRRISM, the scenario year determines average annual WMA demand, upstream consumptive use, and reservoir capacity loss due to sedimentation. The first scenario year, 2040, represents a relatively near-term planning horizon and provides information to the WMA suppliers to aid them in development of a strategy to address the need for new resources. It allows 20-plus years for implementation of the alternatives that they select. This is a reasonable amount of time because, especially in the case of structural measures, implementation may be a lengthy process requiring permitting, identification of funding sources, negotiation of agreements and/or contracts, and design and construction.

Results for the second scenario year, 2085, should be considered highly preliminary because of the uncertainty of the assumptions required to simulate conditions 70 years in the future. The 2085 scenario was included to aid in long-term planning conducted in an "adaptive management" framework. That is, current results indicate which options need to be "kept on the table" to ensure a reliable water supply in the distant future, but following an adaptive management approach, a program should be in place to monitor the forecasts used in the analysis, e.g. for WMA demands, upstream consumptive use, and trends in regional stream flows, and to update the evaluation as new data and information become available. Such a framework is already largely in place in the WMA because of the WSCA, which requires that demand and availability forecasts be conducted every five years, and because of the existence of ICPRB's CO-OP Section, which provides ongoing planning assistance to the WMA suppliers including periodic assessments of the impact of climate change.

4.1.2 Baseline Scenarios

Baseline scenarios were defined for each of the two scenario years. The 2040 baseline scenario represents the WMA system if none of the structural or operational alternatives listed in Section 2 is implemented. The 2085 baseline scenario represents a hypothetical WMA system in which the alternatives currently planned for, under development, or under discussion for 2040 or earlier have been implemented. In the definitions of baseline scenarios given below, the current system is defined as: Jennings Randolph water supply storage (taking into account matching releases from Savage Reservoir), Little Seneca Reservoir, Occoquan Reservoir, and the Patuxent Reservoirs, with system constraints given in Table 1-1.

- 2040 baseline scenario:
  - Current system,
  - Quarry A operated in accordance with VWP Permit No. 10-2020.
- 2085 baseline scenario:
  - Current system,
  - Luck 1 (2.5 BG),
  - Vulcan 1 (1.7 BG),
  - Cooperative use of Quarry A during droughts,
  - Use of Beaverdam Reservoir for low flow augmentation,
  - Improvement in one-day and nine-day flow forecasts of 35% and 10%, respectively,
  - Use of JRR water quality storage during droughts.

4.1.3 Climate Change Scenarios

Climate change will likely affect both water supplies and water demand. To represent these impacts, percent changes are applied to the following sets of PRRISM inputs: natural Potomac River flows (that is, flows in which the impacts of dams and withdrawals have been removed), reservoir inflows, and WMA demands. The alternatives were evaluated for each of the two scenario years under three separate climate change scenarios, CC50, CC75, and CC90, discussed in Section 3.1. Each climate change scenario assumes constant regional changes in average seasonal stream flows, precipitation, and temperature, as given in Table 3-1. For each climate change scenario, the impact on flows is simulated by applying a single constant percent change to all of the daily flow time series that represent natural Potomac River flows and inflows to the WMA system reservoirs: Jennings Randolph, Savage, Little Seneca, Occoquan, and the Patuxent. These percent changes are given in Table 3-1. The impact on WMA demands is estimated by applying single constant regional changes in temperature and in precipitation, also from Table 3-1, to the daily time series for temperature and precipitation, which are used by PRRISM to compute variations in daily demands due to recent weather conditions.

4.2 Evaluation Metrics

Two evaluation metrics, described below, are used to compare the relative benefits the alternatives: 1) worst day shared storage, and 2) system safe summer yield.

4.2.1 Worst Day Shared Storage

Worst day shared storage (WDSS) is defined as the minimum of daily combined JRR water supply storage and Little Seneca Reservoir storage that occurs over the course of the simulation period. This metric is important because PRRISM simulations indicate that when combined JRR water supply and Little Seneca storage becomes exhausted, Potomac River flow deficits have occurred or are likely to occur. A Potomac River deficit occurs, by definition, on any day in which flow in the river at Little Falls is below the environmental flow-by of 100 MGD. Combined JRR water supply and Little Seneca storage is also of importance because the cost of this storage is shared by the three CO-OP suppliers, and releases from these two reservoirs to augment Potomac River flow directly benefit all three suppliers and are subject to few constraints. This metric is used in the MWCOG drought response plan and in PRRISM simulations to determine whether voluntary water use restrictions are called for. It is also used in PRRISM simulations to determine when emergency restrictions are triggered.

4.2.2 System Safe Summer Yield

System safe summer yield (SSSY) is an extension of the classic water supply planning concept of safe yield. Safe yield is a measure of the maximum amount of water that can be extracted on a sustainable basis from an individual water source. SSSY, introduced in this study, is a measure of the total demand that the WMA system can provide, on average, in the month of July. This system safe yield metric is reported as average July demand to provide a measure of the value of an individual system resource at a critical time of year, when demands are typically close to their highest levels. The SSSY values may be useful in cost-share discussions, since the cost-share formula for future resources in the WSCA is based on growth in July demands.

WMA demand can be characterized by its annual average, which is the quantity that water supply planning studies typically endeavor to forecast. It is also characterized by variations around this average, largely due to outdoor water use: a monthly variation, with July and August typically being the months of highest demand, and a daily variation, which is partially dependent on recent temperatures and rainfall and is partially "unexplained" or random. PRRISM's daily demand model simulates all of these characteristics, as described in detail by Ahmed *et al*. (2015). Annual average demand is a user input, monthly variations are based on average variations in past data, and the response of daily demands to recent weather conditions is simulated using a regression model based on daily values of precipitation and temperature. Finally, the unexplained portion of daily demand is simulated using a time series of random numbers with an appropriate statistical distribution. Figure 4-1 shows actual total WMA demand in 2010, along with five example simulations of 2085 demand from PRRISM. The graph also shows actual annual average demand in 2010, and this study's estimate of the annual average and July average demand in 2085.

A single PRRISM simulation for a future scenario year consists of results for each of a sample of 84 years of potential future conditions, where the 84-year historical record is used to simulate the weather-dependent variations in daily demand, subject to user-selected changes in climate as well as past variations in natural Potomac River flow and reservoir inflows. PRRISM output provides statistics calculated from this sample of 84 years. One of the years in this sample, based partially on 1930 historic data (the WMA's "drought of record"), represents conditions in a prolonged severe drought. A second year in the sample, partially based on 1966 historic data, represents conditions in a short but severe drought. Any two different PRRISM simulations, each consisting of 84 years, are different because of the random component of the daily demand model. Most results reported in this study are calculated from output from a set of 100 PRRISM simulations, or "runs," providing a sample of 8400 years.

SSSY, reported as the average of July demand, is determined by trial and error in PRRISM simulations by increasing the average annual demand and finding the maximum demand level for which the system is reliable. PRRISM provides a variety of output metrics to characterize and evaluate the reliability, vulnerability, and resilience of the WMA water supply system, as described in detail by Ahmed *et al*. (2015). This study defines system reliability based on the value of the following two metrics:

- Percentage of years with no Potomac River flow deficits: the percentage of years in the simulation period in which flow in the river at Little Falls is above 100 MGD (the Little Falls flow-by) on every day of the year.
- Percentage of 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 five percent of the combined capacity.

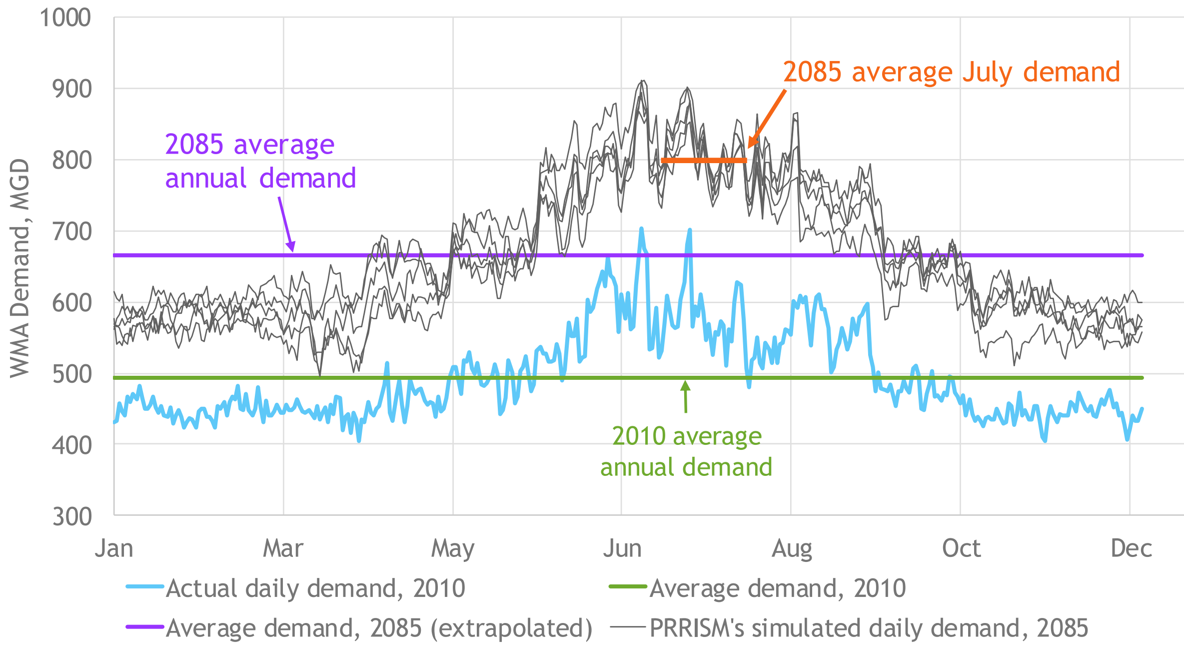


FIGURE 4-1: DAILY WMA DEMAND

In the determination of SSSY, the criteria for system reliability are the following (output is provided for each 84-year simulation period, then averaged over the set of simulations):

- Percent years with no Potomac River flow deficit >= 99.88, and
- Percent years with emergency water use restrictions <= 0.06.

To put these criteria in context, if percent years with emergency water use restrictions <= 0.06, then for a single PRRISM simulation based on the 84-year period of record, assuming that emergency water use restrictions occurred only in the year representing a prolonged severe drought, the probability that emergency water use restrictions would occur sometime during that year would be <= 84 x 0.06/100, that is, <= 5 percent.

4.3 Results for Individual Scenarios

Simulations were conducted for both the 2040 and 2085 scenario years to compare individual alternatives under the median (CC50) climate change scenario. The individual operational alternatives were not evaluated for 2085 because their individual abilities to improve system performance in this scenario year were very limited. But, combined operational alternatives 5 through 8 are included in the 2085 baseline scenario, as discussed above. Assumptions used for the individual alternatives are summarized in Table 3-6 and Table 3-7. Detailed PRRISM output for the individual alternatives is available in Appendix C.

The WDSS and SSSY values for the individual alternatives are reported in Table 4-1 for 2040 and in Table 4-2 for 2085. Results were obtained from sets of 100 runs, unless otherwise noted. As discussed above, the SSSY is a measure of the value of an alternative in terms of its ability to help the system meet summertime demands and WDSS is a measure of the amount of reserve shared storage in the system on the worst day of the worst drought. In the case of the WDSS, both the mean value from the set of runs and the 5th percentile value are given. The 5th percentile value of WDSS, plotted in Figure 4-2, is an indication of the risk of shared storage falling below a given level. For example, if the 5th percentile of WDSS is equal to 0.8 BG, which is the storage level that triggers emergency water use restrictions, then there is a 5 percent probability that WDSS would drop to this level or below during a severe drought. Two other "worst day" storage metrics appear in Table 4-1: the minimum daily system storage (combined storage in JRR water supply, Little Seneca, Occoquan, and Patuxent) over the simulation period and the minimum daily combined system plus alternative(s) storage over the simulation period. In both cases, the table gives the mean of the values for the sets of runs.

Results on the performance of the individual alternatives are discussed below. Also discussed are any additional sensitivity tests or observations and insights gained from a detailed examination of the simulation time series output.

Table 4-1: 2040 Results for Individual Alternatives

2040 Alternatives		SSSY for CC50, MGD	Worst day storage for 2040 forecasted demand under CC50			
			5th %tile of WDSS, BG	Mean of WDSS, BG	Mean of worst day combined system storage, BG	Mean of worst day combined system + alternative(s) storage, BG
2040 Baseline		661[1]	0.8	2.5	6.1	6.8
Individual Structural Alternatives						
1a	Luck 1	701[1]	3.8	4.7	8.2	9.6
2	Travilah Quarry	841	9.6	10.3	14.8	23.0
3a	Vulcan 1	686[1]	2.9	3.9	7.6	8.3
4	RO Plant	741	5.1	5.7	11.7	12.7
Individual Operational Alternatives						
5	Quarry A cooperative	671[1]	1.7	3.2	6.4	7.6
6	Beaverdam	686[1]	2.8	3.8	7.2	8.1
7	Improvement in stream flow forecasts (10%/10%)	676	2.4	4.2	7.6	8.3
8	Use of JRR WQ storage	691	2.7	3.3	7.2	8.0
9	Reduction in upstream CU	676	2.0	3.6	7.6	8.5
10	More stringent water use restrictions	691	2.9	4.1	8.9	9.7
5-10	All operational alternatives combined (FC improvement = 10%/10%, MOS = 110 MGD)	791	5.8	6.8	10.3	12.1

[1] 400 run sets.

TABLE 4-2: 2085 RESULTS FOR INDIVIDUAL ALTERNATIVES

2085 Alternatives		SSSY for CC50, MGD	Worst day storage for 2085 forecasted demand under CC50			
			5th %tile of WDSS, BG	Mean of WDSS, BG	Mean of worst day combined system storage, BG	Mean of worst day combined system + alternative(s) storage, BG
2085 baseline		713	0.0	0.0	1.4	2.1
Individual Structural Alternatives						
1b	Luck 2	728	0.0	0.5	2.4	3.4
2	Travilah Quarry	883	5.5	6.4	8.6	15.1
3b	Vulcan 2	788	1.0	2.3	5.9	7.6
4	RO Plant	748	1.1	2.5	7.5	9.2

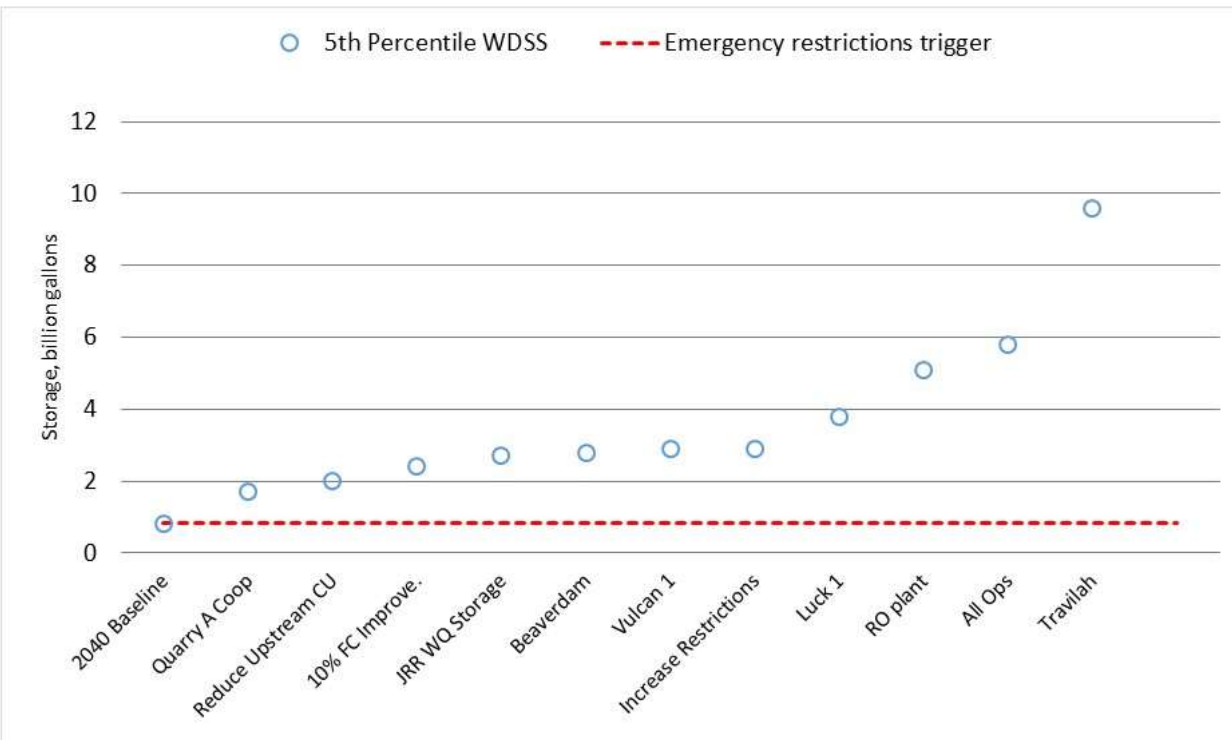


FIGURE 4-2: 2040 5TH PERCENTILE WDSS VALUES FOR INDIVIDUAL ALTERNATIVES UNDER THE CC50 CLIMATE CHANGE SCENARIO

4.3.1 Luck Stone Quarries B and C

In PRRISM simulations, the Luck Stone quarries are used in tandem with Little Seneca and Occoquan reservoirs. When the one-day forecast indicates that flow in the river without augmentation would not be adequate to meet water supply and environmental needs, water is released from Little Seneca and the Luck Stone quarries and a portion of Fairfax Water withdrawals are shifted from the Potomac to the Occoquan. The Luck Stone quarries are also assumed to be a direct source of raw water supply for Loudoun Water.

Modeling results for the individual alternatives in 2040 under the median (CC50) climate change scenario (Table 4-1) indicate that the Luck 1 alternative, that is, the addition of the 2.5 BG Quarry B to the 2040 baseline system, would provide substantial benefits. SSSY would increase by 40 MGD to 701 MGD, which is comfortably above the system's forecasted summer demand of 666 MGD. Also, the 5th percentile WDSS increases by 3.0 MG to 3.8 MGD. By 2085, again under the median climate change scenario, simulation results (Table 4-2) indicate that the Luck 2 alternative, that is, the addition of the 4.0 BG Quarry C to the 2085 baseline system, increases the SSSY to 728 MGD. This is not sufficient to bring SSSY up high enough to meet the forecasted summer demand of 798 MGD. The 5th percentile WDSS remains at 0.0 BG.

Use of the Luck Stone quarries for water supply purposes is still at the conceptual planning stage. The operational constraints assumed in PRRISM simulations, discussed in Section 3.5.1, are based on preliminary estimates. Sensitivity tests were conducted for one of these constraints, the maximum release rate. In 2040 simulations, this maximum is assumed to be 80 MGD, based on input from Loudoun Water. PRRISM sensitivity runs for the 2040 forecasted demands under the CC50 climate change scenario indicated that doubling this value, to 160 MGD, provided no significant benefits. This result is consistent with observations made in an examination of PRRISM daily time series, which showed that during droughts release requests from Quarry B were usually well below 80 MGD. In 2085 simulations, however, release requests from the Luck Stone quarries were often above 80 MGD, and raising the maximum release rate to 160 MGD did provide significant benefits. Therefore, a maximum release rate of 160 MGD was used in 2085 simulations in cases where Quarry C was assumed to be present, as indicated in Table 3-6.

A minimum release rate during droughts was used for the Luck Stone quarries in order to help alleviate the problem of Potomac River flow deficits, one of the system reliability criteria. These deficits are more likely to occur as demands rise or as natural river flow falls during the more severe climate change scenarios. The minimum release rates were set at 8 MGD for Luck 1 and 10 MGD for Luck 2 (see Appendix B). The trigger for the minimum release was combined JRR water supply and Little Seneca storage below 60% of capacity.

4.3.2 Travilah Quarry

Travilah Quarry would provide tremendous benefits to the system in times of drought. In PRRISM simulations, Travilah is assumed to be used in place of the Patuxent reservoirs to eliminate current day Potomac River flow deficits in the latter stages of a drought, that is, when Patuxent storage falls below a threshold value of 4 BG. (In the earlier stages of a drought, all Travilah storage is reserved for use in a potential spill emergency.) When Travilah storage is available, the one-day MOS can be reduced considerably from its usual value of 120 MGD in 2040 and 130 MGD in 2085, as discussed below.

Under the 2040 median climate change scenario, CC50, the addition of Travilah to the 2040 baseline system increases the SSSY by 180 MGD and increases the 5th percentile WDSS by 8.8 BG (Table 4-1). These results were obtained by using a one-day margin of safety of -45 MGD, that is, by subtracting 45 from any estimated one-day flow deficit at Little Falls used to compute required releases from Little Seneca and other one-day resources. In 2085 under the median climate change scenario, using a margin of safety of -35 MGD, Travilah again provides the largest increases in SSSY and worst day storage values of any of the other structural alternatives (Table 4-2). SSSY increases by 170 MGD over the baseline, to 883 MGD, and the 5th percentile WDSS increases to 5.5 BG.

The margins of safety used to simulate use of Travilah were obtained through trial and error. They were found to provide significant increases in SSSY values for a wide range of scenarios while allowing some water to remain in Travilah for potential use in case of a spill emergency. For example, in the 2040 median climate change scenario simulations, average worst day storage in Travilah is 6.95 BG (Table C-2). However, considerably less water remains in Travilah on the worst day of a severe drought for the more severe 2040 climate change scenarios (3.49 for CC75 and 2.45 for CC90) and for all 2085 scenarios (2.80, 1.66, and 0.85 for CC50, CC75, and CC90, respectively). The appropriate amount of reserve storage, given Travilah's potential use as a backup water supply in case of spills or other pollution events in the Potomac River, is a topic for future discussion if Travilah is acquired as a regional water supply resource.

4.3.3 Vulcan Quarry

The addition of Vulcan Quarry to Fairfax Water's system, along with the increases in Griffith treatment capacity and accompanying infrastructure improvements listed in Table 3-6, enhances Fairfax Water's ability to reduce its Potomac River withdrawals during low flow periods. In 2040 under the CC50 climate change scenario, the addition of Vulcan 1, that is, the addition of Vulcan Phase 1 and accompanying infrastructure upgrades, including an increase in Griffith capacity to 160 MGD, benefits the system by increasing the SSSY by 25 MGD over the baseline value, to 686 MGD, and increasing the 5th percentile of the WDSS to 2.9 MG (Table 4-1). By 2085, the Vulcan 2 alternative, that is, the addition of the much larger volume of storage in Vulcan Phase 2, along with the upgrade of Griffith capacity to 240 MGD and additional infrastructure upgrades, increases the SSSY by 75 MGD over the 2085 baseline, to 788 MGD.

A "minimum release rate" was used for Vulcan quarry in order to help alleviate the problem of Potomac River flow deficits, similar to that used in the case of the Luck Stone quarries. This was implemented by increasing the Griffith plant minimum production rate, which is ordinarily 45 MGD based on physical constraints. For Vulcan 1, minimum Griffith plant production was set at 50 MGD, a 5 MGD increase, and for Vulcan 2 and 3, minimum Griffith plant production was set at 95 MGD, a 50 MGD increase (see Appendix B). These minimum release rates were triggered when combined water supply storage in Jennings Randolph and Little Seneca reservoirs was below 60% of capacity.

Model runs were conducted to test the sensitivity of Vulcan benefits to changes in assumptions about accompanying infrastructure upgrades, that is, upgrades in Griffith capacity and finished water transfer capabilities. Results for 2040 appear in Table 4-3. The SSSY and worst day storage values in the first line of this table are repeated from Table 4-1 and are from simulations using the set of 2040 upgrades which are assumed in this study and given in Table 3-6. The following four lines of values are from sensitivity tests. The first of the tests assumes that 1.7 BG of storage in Vulcan is in place but no accompanying infrastructure upgrades are made. The second test assumes that Fairfax Water's ability to transfer water produced by the Griffith plant to its Western service area is enhanced with the East to West transfer capacity increased from 35 to 50 MGD. It also assumes that the maximum daily change in East to West transfer increased from 10 to 40 MGD and that the Griffith plant production capacity remains at 120 MGD. The third test assumes that the Griffith plant capacity is increased to 160 MGD, but no upgrades are made in East to West transfer capabilities. The fourth test assumes that the Griffith plant capacity is increased to 160 MGD, the East to West transfer capacity is increased to 80 MGD, and the maximum daily change in East to West transfer is increased to 80 MGD.

From the results in Table 4-3, the benefits in SSSY provided by Vulcan Phase 1 are very much dependent on the assumed infrastructure upgrades. In sensitivity test 1, with no upgrades, SSSY remains at 661 MGD, which is the same as the 2040 baseline SSSY value in Table 4-1, indicating that the presence of Vulcan Phase 1 provides no increase in SSSY if no changes to infrastructure occur. In sensitivity test 2, with an upgrade in the ability to transfer treated water, the SSSY increases by 5 MGD, to 666 MGD. In sensitivity test 3, which assumes an increase in Griffith treatment capacity, SSSY is 676 MGD, an increase of 15 MGD over its baseline value. Finally, sensitivity test 4 indicates that there is little benefit in further increases in the maximum East to West transfer rate.

Tests were also conducted to explore the sensitivity of benefits to the ultimate capacity of Vulcan and to refill options. In 2085 Fairfax Water plans to increase its storage capacity significantly with the addition of up to 17 BG in Vulcan Quarry, but this volume may depend on mining conditions and cost considerations. Refill will be provided by Griffith plant backwash and from the Occoquan Reservoir (Vulcan 2). There is also an option to add an additional source of refill: seasonal pumping from the Occoquan Estuary (Vulcan 3). Time constraints for this study prevented a full investigation of system sensitivity to the size of Vulcan in 2085 and to refill from the Occoquan Estuary; the benefits to the system depend on climate scenario and on system configuration, that is, on what other alternatives have been implemented. Table 4-4 contains some limited sensitivity test results for 2085, comparing SSSY and certain other model output under the CC50 scenario for a future system that includes 2085 baseline alternatives, Travilah, and Luck 2. These results indicate that there is little sensitivity to these factors. However, sensitivity may be greater for other scenarios and combinations of alternatives.

TABLE 4-3: 2040 SENSITIVITY OF VULCAN BENEFITS TO INFRASTRUCTURE UPGRADES

Assumed 2040: Vulcan storage capacity (BG)/Griffith production capacity (MGD)/E to W transfer capacity (MGD)/max daily E to W transfer change (MGD)			Worst day storage for 2040 forecasted demand under CC50			
		SSSY for CC50, MGD	5th %tile of WDSS, BG	Mean of WDSS, BG	Mean of worst day combined system storage, BG	Mean of worst day combined system + alternative(s) storage, BG
Vulcan Phase 1, with Fairfax Water system constraints from Table 3-6						
	1.7/160/50/40	686	2.9	3.9	7.6	8.3
Sensitivity tests						
1	1.7/120/35/10	661	1.1	2.6	7.9	12.2
2	1.7/120/50/40	666	0.9	2.7	7.9	12.1
3	1.7/160/35/10	676	2.1	3.5	8.1	12.3
4	1.7/160/80/80	686	3.0	4.2	8.2	12.4

Table 4-4: 2085 Sensitivity to Vulcan Phase 3 Refill Option

Assumed for 2085: Vulcan storage capacity (BG)/Vulcan estuarine refill? (yes or no)		Worst day storage for 2085 forecasted demand under CC50				
	SSSY for CC50, MGD	**5th %tile of WDSS, BG**	**Mean of WDSS, BG**	**Mean of worst day combined system storage, BG**	**Mean of worst day combined system + alternative(s) storage, BG**	**Mean of worst day Vulcan storage, BG**
17 BG/no	843	3.2	3.8	6.7	10.8	1.5
17 BG/yes	853	3.9	3.7	6.6	10.6	4.6
14 BG/no	843	3.0	3.6	6.2	9.9	1.1
14 BG/yes	848	3.0	3.5	6.2	9.9	3.4

4.3.4 Reverse Osmosis Water Treatment Plant

PRRISM simulations indicate that a 50 MGD reverse osmosis plant which used the Occoquan Estuary as a raw water source would be an extremely effective, albeit costly, water supply alternative. According to 2040 simulation results under the median climate change scenario (Table 4-1), the addition of the RO plant would increase the SSSY by 80 MGD, to 741 MGD and increase the 5th percentile WDSS by 4.3 MG, to 5.1 MGD. By 2085 under the median climate change scenario, the RO plant increases the SSSY to 748 MGD and the 5th percentile WDSS to 1.1 BG (Table 4-2).

Similar to the Vulcan Quarry alternative, the ability of the RO plant to provide regional benefits depends on accompanying infrastructure upgrades. Table 4-5 gives results showing the sensitivity of RO plant benefits to various levels of enhancement of Fairfax Water's East to West finished water transfer capability. The benefit to SSSY is diminished by 25 MGD without the assumed infrastructure upgrades.

Table 4-5: 2040 Sensitivity of RO Plant Benefits to Infrastructure Upgrades

RO Plant Assumed: Griffith capacity/E to W transfer capacity/E to W max transfer change (MGD)		**Worst day storage for 2040 forecasted demand under CC50**			
	SSSY for CC50, MGD	5th %tile of WDSS, BG	Mean of WDSS, BG	Mean of worst day combined system storage, BG	Mean of worst day combined system + alternative(s) storage, BG
Values assumed in this study (see Table 3-6)					
120/65/50	748	1.1	2.5	7.5	9.2
Sensitivity test					
120/35/10	723	4.2	5.2	11.5	16.1

4.3.5 Cooperative Use of Quarry A

Loudoun Water's Quarry A is assumed to be in use as a raw water storage facility in baseline simulations, with operations conducted in accordance with Loudoun Water's VWP Permit No. 10-2020. Under the cooperative use alternative, it's assumed that Loudoun Water's use of the quarry and Potomac River withdrawals are conducted in a somewhat different manner that is intended to be more beneficial to both the CO-OP suppliers and to Loudoun Water, as described in Section 3. Results for the cooperative use of

Quarry A alternative indicate that this would indeed be the case. For the CO-OP system in 2040, the average and 5th percentile values of WDSS increase by 0.7 and 0.9 BG over the baseline case, and the other two worst day storage metrics also increase (Table 4-1). The SSSY increases by 10 MGD under this alternative over the 2040 baseline value.

This alternative operations scenario also provides benefits to Loudoun Water. Worst day storage in Quarry A averages 0.33 BG in baseline simulations, but this increases to 0.63 BG under the cooperative use of Quarry A alternative (Tables C-0 and C-5 in Appendix C).

4.3.6 Use of Beaverdam Reservoir for Low Flow Augmentation

Under this alternative, it is assumed that Loudoun Water's Beaverdam Reservoir becomes part of the cooperative system and is used in tandem with Little Seneca and Occoquan reservoirs during droughts to increase Potomac River flow when a need is indicated by one-day flow and demand forecasts. This use of Beaverdam is very similar to the simulated use of Luck Stone quarries B and C.

In 2040, the addition of Beaverdam to the system increases SSSY by 25 MGD over the baseline value, to 686 MGD, and increases WDSS by 2.0 BG, to 2.8 BG. This is very similar to results for Vulcan Quarry Phase 1, which is slightly larger than Beaverdam but whose benefits are to some extent limited by finished water transfer capabilities. Increases in SSSY and WDSS from Beaverdam are roughy half of the increases provided by Luck Stone Quarry B, which is consistent with the fact that Beaverdam Reservoir has approximately half the storage capacity of Quarry B.

4.3.7 Improved Forecasts

As described in Section 3.5.7, PRRISM can simulate improvements in nine-day stream flow forecasts, which are needed to calculate Jennings Randolph water supply release rates. It can do the same for the one-day flow forecasts, which are needed to determine the need for Little Seneca releases and other operational changes. Under the improved forecast alternative, the improvement in the nine-day forecast is assumed to be fairly modest, just 10%. This limited improvement is due to the forecast being quite dependent on National Weather Service nine-day precipitation forecasts, which are currently limited in accuracy. Depending on the scenario year and simulated alternatives, improvements in the one-day forecast of 10%, 35%, and 50% are considered in this study. These levels of improvements may be achievable through upgrades in the models used to simulate watershed processes and flow routing.

Simulations were conducted to compare improvements in both the one-day and nine-day forecasts by 10% with other operational alternatives under the 2040 CC50 climate change scenario. For these model runs, the one-day forecast margin of safety was set to 110 MGD, approximately a 10% reduction, to take advantage of the greater forecast accuracy. Results, given in Table 4-1, indicate that the benefits of this level of forecast improvements are on par with most of the other operational alternatives, with the SSSY improving by 15 MGD, to 676 MGD, and the 5^{th} percentile of the WDSS improving by 1.6 BG, to 2.4 BG.

Greater improvements in the one-day forecasts of 35% and 50% are considered in certain scenarios discussed below because modeling results indicate that these levels of improvement would allow the system to make better use of added storage in the future. Though added storage is effective in influencing one of the criteria for system reliability used to determine SSSY values – the likelihood that WDSS will drop to emergency levels – it is not as effective in reducing the chance of a Potomac River flow deficit, the other criteria. Potomac flow deficits are the result of one-day forecast errors that the system is unable to rectify by a shift of withdrawals from WSSC's Potomac intake to the Patuxent intake, or by shifts of WSSC and Aqueduct withdrawals to Travilah, if that resource is available. In the absence of Travilah, deficits will tend to increase in the future because WSSC's ability to make sufficient shifts in withdrawals to the Patuxent are constrained by capacity limitations. The presence of Travilah Quarry is an effective remedy for deficits because, as discussed in Section 3.5.2, Travilah is assumed to have the same capability as the Patuxent reservoirs of being able to respond quickly to prevent an impending deficit. In the absence of Travilah, improvements in flow forecasts would be particularly important. This is discussed in more detail in Section 4.4.3, below.

4.3.8 Use of JRR Water Quality Storage

A preliminary investigation was conducted of the potential benefits of using JRR water quality storage during droughts. It was assumed that a lump volume of 2 BG is transferred from the reservoir's water quality storage account to the water supply storage account when water supply storage falls below 2.6 BG, with the constraint that water quality storage not fall below 5.0 BG as a result of the transfer. This is only one of many possible approaches to using JRR water quality storage during droughts.

The benefits of this alternative to the WMA system are evident from Table 4-1, showing results for the 2040 CC50 climate change scenario. This alternative provides a 30 MGD increase in SSSY over the baseline case and an increase in average and 5th percentile WDSS, to 3.3 and 2.7, over the baseline case values of 2.5 and 0.8.

Of interest for this alternative is the impact on reservoir refill and on worst day water quality storage. PRRISM output shows that just as in the baseline case, under this alternative JRR refills to at least 90 percent of its capacity by June 1 of every year in the simulation. Worst day JRR water quality storage remains essentially unchanged from the baseline scenario, at 2.84 BG over the simulation period, and 5.26 BG and 3.49 BG for 1930 and 1966, respectively (see Tables C-0 and C-8 in Appendix C).

It was beyond the scope of this project to explore the many possible options for use of JRR water quality storage during droughts, but based on these preliminary results, a more detailed investigation is warranted. Other options for use of this storage include an increase in the release rate from water quality storage during a water supply release, which in PRRISM is assumed to be 100 cfs.

4.3.9 Reduction in Upstream Consumptive Use

Simulations were conducted to evaluate the benefits under the 2040 CC50 climate change scenario of a 10% reduction in upstream consumptive use. This reduction corresponds to an annual average reduction of 9.6 MGD and a July reduction of 14.5 MGD, as discussed in Section 3.5.9. This change was found to increase SSSY by 15 MGD, to 676 MGD, which is consistent with the expected increase in July river flows of about 15 MGD. The increase in the 5th percentile WDSS is 1.2 BG, to 2.0 BG.

4.3.10 More Water Use Restrictions

Use of more stringent water use restrictions during droughts increases reservoir storage by reducing water demands to lower levels and at an earlier stage of a drought. It is the most effective of the operational alternatives in terms of increasing worst day storage values, as is evident from Table 4-1. For example, the 5th percentile of the WDSS increases 2.1 BG over the baseline value, to 2.9 BG.

Results in Table 4-1 also indicate that the more stringent restrictions alternative is effective in increasing the 2040 SSSY. However, the reported SSSY values do not include the effects of restrictions, so this result is somewhat misleading. To examine these effects, daily time series of system demand with more stringent restrictions were compared to demands with baseline restrictions (from Table 3-5) for the drought years based on 1930 and 1966 hydrology. For both of these droughts, PRRISM did not simulate the occurrence of voluntary restrictions until very late July or early August. Therefore, average July demands were not significantly different with or without restrictions. However, restrictions did reduce average August system demands significantly, by 19 MGD (3%) and by 5 MGD (1%) for 1930 and 1966, respectively, in the case of baseline restrictions, and by 31 MGD (4%) and by 32 MGD (5%) for 1930 and 1966, respectively, in the case of more stringent restrictions. Restrictions also reduced longer term averages of system demand. Under baseline restrictions, average demand was decreased by 16 MGD (3%) and 9 MGD (1%) for July through December of 1930 and for July through September of 1966, respectively. Under more stringent restrictions, average demand was decreased by 45 MGD (7%) and 26 MGD (4%) for July through December of 1930 and for July through September of 1966, respectively.

4.3.11 All Operational Alternatives Combined

Simulations results for 2040 are also provided in Table 4-1 for the combination of all operational alternatives, 5 through 10. SSSY and WDSS values for this combination is higher than those for all of the structural alternatives, with the exception of Travilah. However, as discussed in Section 4.3.10, the reported SSSY values do not include the effects of restrictions, so this result is not directly comparable to the other values in the table.

4.4 A Roadmap for the Future

The previous section provides insights on the relative abilities of the individual alternatives to help the WMA system meet growing regional demands. But these results are from simulations conducted under this study's median climate change scenario, which projects that the basin will experience a slight increase in average stream flow in future years. If the effects of future climate change are more severe, causing average flow to fall significantly, then more than one alternative may be required to ensure a reliable water supply.

In this section, strategies for a phased implementation of combinations of alternatives are evaluated in terms of their ability to meet the WMA's needs, under a range of potential climate conditions in the scenario years, 2040 and 2085. These strategies were developed based on preliminary modeling results for a larger number of combinations. The strategies also take into consideration the need to protect the region from shortfalls in the years leading up to 2040 and the need for steps toward broader regional cooperation in order to ensure system reliability in the long-term.

For 2040, three combinations of alternatives are considered, depending on the availability of Travilah Quarry and on the region's success in developing cooperative agreements. The availability of Travilah is a key consideration because according to study results, the addition to the WMA system of this resource alone would provide the region with a reliable supply in 2040 and beyond. On the other hand, in the absence of Travilah, most of the other alternatives would need to be present by 2040 for the system to withstand a significant decline in stream flows due to climate change. Likewise, the region's success in developing cooperative agreements with Loudoun Water determines whether or not several of the alternatives are viable options: cooperative use of Quarry A, use of Beaverdam Reservoir for low flow augmentation, and use of the Luck Stone quarries.

4.4.1 Strategies for 2040

Three strategies for phased implementation by 2040 are listed in Table 4-6, with evaluation results appearing in Table 4-7 and Figure 4-3. All three assume the presence of Vulcan Quarry Phase 1, since it provides clear benefits and agreements for this storage facility have already been completed. All the options also include some improvement in stream flow forecast accuracy, since work on this is already underway, and since modeling results have pointed to the effectiveness of improved forecasts in reducing the likelihood of Potomac River deficits in future years (see Section 4.4.3). Results on the ability of the three strategies to meet summer demands under the three 2040 climate scenarios appear in Table 4-7 and Figure 4-3. Results for two individual alternatives, Travilah and the RO plant, are also provided.

TABLE 4-6: PROPOSED STRATEGIES FOR PHASED IMPLEMENTATION OF ALTERNATIVES

2040 Strategy	Implementation Steps	Target Year	Combined Alternatives
A	Step A-1: operational alternatives 5-8	2025	Agreement for cooperative use of Quarry A
			Agreement for use of Beaverdam Reservoir for low flow augmentation
			Achievement of 10% improvements in 1-day and 9-day flow forecasts
			Agreement for use of JRR water quality storage for water supply purposes
	Step A-2	2035	Step A-1 + Vulcan Quarry Phase 1 (Vulcan 1)
	Step A-3	2040	Step A-2 + Luck Stone Quarry B (Luck 1)
			Achievement of 35% improvement in 1-day flow forecast
B	Step B-1	2025	Same as Step A-1 above
	Step B-2	2035	Same as Step A-2 above
	Step B-3	2040	Step B-2 + Travilah Quarry
C	Step C-1	2035	Vulcan Phase 1 with no Griffith plant upgrade + achievement of 10% improvements in 1-day and 9-day flow forecasts
	Step C-2	2040	Step C-1 + RO plant

Strategy A is the phased implementation of operational alternatives five through eight, along with Vulcan 1 and Luck 1. This is this study's recommended strategy for 2040 if the region chooses not to pursue acquisition of Travilah Quarry in the near term or if that facility proves to be unavailable. The first step, the implementation of the four operational alternatives, may be achievable within a relatively short time frame, since discussions and/or work on all of these is already underway. Study results in Table 4-7 indicate that after Step A-1 is implemented, the WMA could meet 2040 forecasted summertime demands during a severe drought even if average summer stream flows fell by 7%, as projected under the CC75 climate scenario, though the system would fall short if flows fell by 19%, as under the CC90 scenario. Step A-1 would also help pave the way for Step A-3, since it includes bringing Loudoun Water resources into the cooperative system and also includes a modest improvement in flow forecasts. Step A-2, Vulcan Quarry Phase I, is planned by Fairfax Water to be available in 2035, and provides some marginal increases in SSSY values. But its benefits are somewhat limited by an increased chance of Potomac River deficits due to a decreasing ability of Patuxent reservoir load shifts to mitigate one-day forecast errors as demands rise or flows fall. This issue is discussed in more detail in Section 4.4.3. Step A-3 is the addition of Luck Stone Quarry B and further improvement in the accuracy of the one-day flow forecast, to 35 percent. After completion of Step A-3, the SSSY value for the CC90 scenario in Table 4-7, 636 MGD, is much closer to the forecasted July demand of 666 MGD, though still 30 MGD short. However, future improvements in operational policies or updates of modeling assumptions may succeed in increasing this value.

In Strategy B, it is assumed that Travilah Quarry is available as a regional storage facility by 2040. This is the study's recommended strategy if acquisition of Travilah Quarry is feasible in the relatively near term. Travilah would serve as a dual purpose reservoir, providing a supply of raw water for both WSSC and Aqueduct in times of drought and also in case of a contaminant release into the Potomac River. The first step, B-1, identical to Step A-1, is the implementation of operational alternatives five through eight. Step B-1 is desirable, first, because it would enhance the system at little expense while work proceeded on acquisition of Travilah and construction of the necessary accompanying infrastructure. Second, including these operational alternatives would help conserve storage in Travilah during droughts and increase the supply available in case of a contaminant event. Finally, implementing the alternatives in Step B-1 would help prepare the region for steps which might be necessary in the decades following 2040. Step B-2, identical to Step A-2, is Fairfax Water's planned addition of Vulcan Phase 1 to its system, which would also help maintain reserve storage in Travilah. Finally, Step B-3 is the addition of Travilah Quarry as a raw water storage facility and construction of the raw water conduits between WSSC's Potomac River intake and treatment plant, Travilah, and Aqueduct's Great Falls intake. Results in Table 4-7 show that once Strategy B is fully implemented, the SSSY values are well above the forecasted July demand of 666 MGD for all three of the climate scenarios. Thus, Strategy B would provide the region with a reliable supply for a wide range of future climate conditions, with room for further growth in demand in the decades beyond 2040.

Strategy C is construction of a 50 MGD RO plant on the Occoquan Estuary and associated infrastructure upgrades listed in Table 3-6. Strategy C also includes operational alternative seven (10% improvement in stream flow forecasts) and Fairfax Water's planned addition of Vulcan Phase 1, though without any increase in Griffith production. This will likely be viewed as the least desirable of the strategies because of the high construction and energy costs associated with reverse osmosis treatment facilities. It is included as an option for the region in case the acquisition of Travilah Quarry by 2040 proves to be infeasible and in case development of regional agreements related to Loudoun Water resources will not completed by 2040. Results in Table 4-7 show that Strategy C is the least effective of the three in terms of helping the region meet summertime demands, with SSSY values of 766, 716, and 566 MGD for the CC50, CC75, and CC90 climate change scenarios, respectively. These values indicate that under Strategy C, the WMA could meet 2040 forecasted summertime demands during a severe drought under both the CC50 and the CC75 climate scenarios, but not under the CC90 scenario.

TABLE 4-7: 2040 RESULTS FOR RANGE OF FUTURE CLIMATE CONDITIONS

		SSSY for CC50	SSSY for CC75	SSSY for CC90
Projected WMA 2040 July Demand [1]		666	666	667
2040 Baseline		661	616	541
2040 Strategy A: phased implementation, assuming absence of Travilah Quarry				
	Step A-1 – by 2025: Operational alternatives 5 thru 8 (fc[*] improvement = 10%/10%, MOS=110)	736	696	566
	Step A-2 – by 2035: Step A-1 + Vulcan Phase 1 (with Griffith max = 160 MGD and min = 50 MGD)	741	706	566
	Step A-3 – by 2040: Step A-2 + Luck Stone Quarry B + additional improvement in 1-day forecast to 35%	776	726	636
2040 Strategy B: Travilah Quarry				
	Step B-1 – by 2025: Operational alternatives 5 thru 8 (FC improvement = 10%, MOS=110)	736	696	566
	Step B-2 – by 2035: Step B-1 + Vulcan Phase 1 (with Griffith max = 160 MGD and min = 50 MGD)	741	706	566
	Step B-3 – by 2040: Step B-2 + Travilah Quarry (with MOS= -45)	911	861	786
2040 Strategy C: RO Plant				
	Occoquan RO + Vulcan Phase 1 (with Griffith max = 120 MGD) + 35% 1-day fc improvement	766	716	566
Other Results				
	Travilah Quarry only (with MOS= -45)	841	791	721
	Occoquan RO plant only (120/40/65/50)	741	686	566

[1] From Table 3-3.

[*]fc = forecast

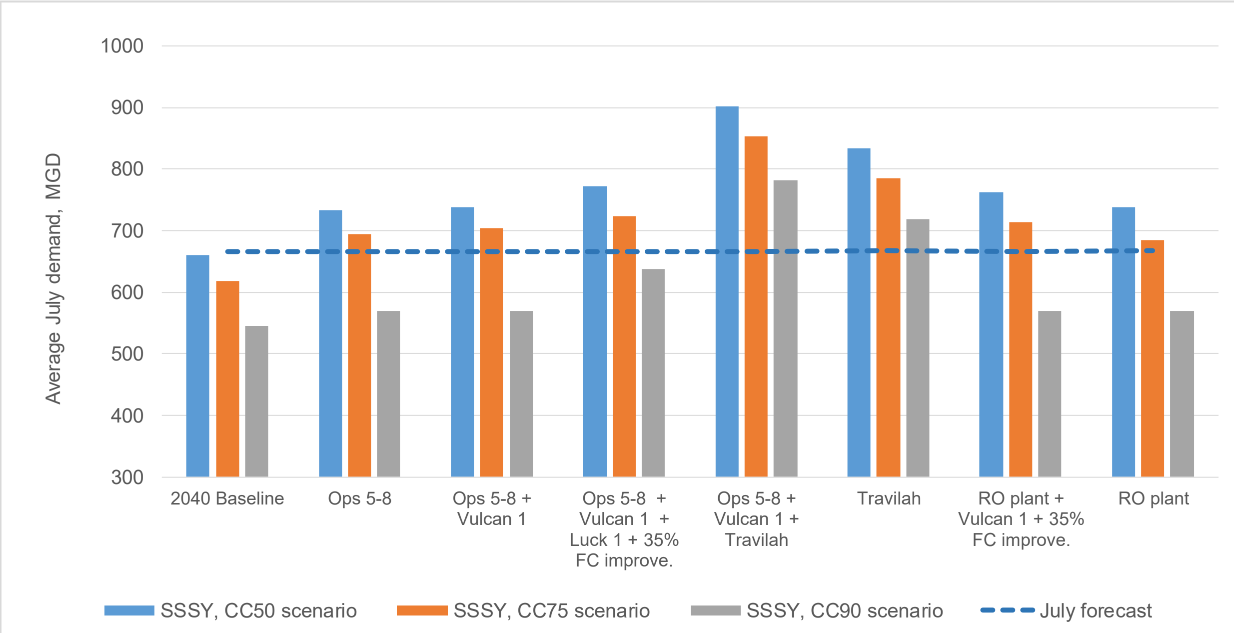


FIGURE 4-3: 2040 RESULTS - SSSY VALUES FOR THE THREE CLIMATE CHANGE SCENARIOS

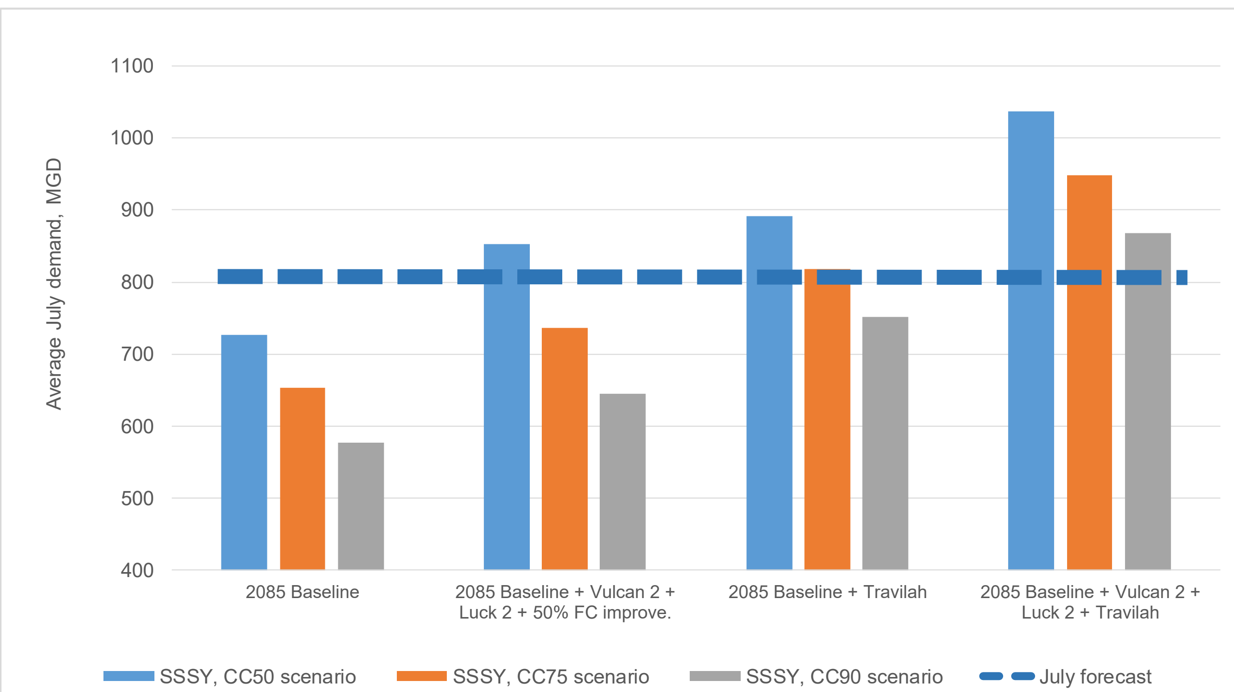


FIGURE 4-4: 2085 RESULTS - SSSY VALUES FOR THE THREE CLIMATE CHANGE SCENARIOS

4.4.2 Strategies for 2085

Our ability to forecast water needs and water availability almost 70 years in the future is limited. Results presented in this section provide only a first look at how well proposed alternatives can ensure a reliable water supply in 2085, and need to be verified and refined in subsequent studies as projections of water demand and of the impact of climate change on basin stream flows improve.

Between the years 2040 and 2085, projected WMA demands increase by 110 to 116 MGD, depending on the climate change scenario (Table 3-3), and average July demands increase by 132 to 148 MGD. At the same time, river flows can be expected to decrease due to rising upstream consumptive use, which is projected to increase by 32 MGD annually and 48 MGD in July. If forecasted growth in water use does occur, study results indicate that a variety of alternatives in combination need to be in place in 2085 to meet regional needs under the range of changes in stream flow considered for 2085 (+ 4%, -12%, and -23% for the CC50, CC75, and CC90 scenarios, respectively).

PRRISM simulations were conducted to assess the ability of selected combinations of alternatives to meet summertime demands in 2085. SSSY values for three for implementation strategies under the three 2085 climate scenarios are compared with projected July demand in Table 4-8 and Figure 4-4. In each case it's assumed that the listed alternatives are added to a system in which the 2085 baseline combination of alternatives is already present. Also shown are the SSSY values for the 2085 baseline combination of alternatives, which consists of the operational alternatives five through eight, Vulcan 1, and Luck 1. The baseline set of alternatives fails to meet projected July demands under all three climate scenarios.

In the first case, results indicate that Strategy A, that is, the addition to the system of 17 BG in Vulcan Quarry (Vulcan 2) and 4 BG in Luck Stone Quarry C (Luck 2), along with an assumed improvement in the one-day flow forecast of 50% over current accuracy, would provide substantial benefits. The SSSY would increase by 130 MGD, to 843 MGD for the CC50 climate change scenario, comfortably above the forecasted July demand. SSSY values for CC75 and CC90 would also increase, to 718 MGD and 623 MGD, respectively, but these increases would not allow the system to meet projected July demands.

The second 2085 strategy in Table 4-8 is the addition to the 2085 baseline system of Travilah Quarry. Travilah was shown to provide large increases in SSSY in 2040, well above forecasted demands. By 2085, even in combination with the resources of the 2085 baseline system, Travilah falls slightly short of meeting projected July demands under the CC75 climate scenario, and falls well short under the CC90 scenario.

The third 2085 strategy in Table 4-8 is the addition of all proposed 2085 quarry alternatives to the WMA system: Vulcan 2, Luck 2, and Travilah. SSSY values increase to 1033, 938, and 858 MGD, respectively, for the CC50, CC75, and CC90 climate scenarios, all well above the corresponding projections of July demands.

TABLE 4-8: 2085 RESULTS FOR A RANGE OF FUTURE CLIMATE CONDITIONS

		SSSY for CC50	SSSY for CC75	SSSY for CC90
Projected WMA 2085 July Demand [1]		798	813	815
2085 Baseline: operational alternatives 5-8 + Vulcan 1 + Luck 1, with 35 percent 1-day forecast improvement		713	633	553
2085 Strategies				
A	Baseline + Vulcan 2 + Luck 2 + 50% 1-day forecast improvement	843	718	623
B	Baseline + Travilah	883	803	733
C	Baseline + Vulcan 2 + Luck 2 + Travilah	1033	938	858

[1] From Table 3-3.

4.4.3 Importance of Improving Stream Flow Forecasts

One of the goals of WMA water supply operations is preventing Potomac River flow deficits, that is, maintaining daily flow in the Potomac River at Little Falls above the 100 MGD environmental flow-by. Flow deficits can result if system storage is seriously depleted and insufficient to help meet demands on low flow days. But they can also occur even if reservoirs are full, as a result of inaccurate one-day flow and demand forecasts during a low flow period.

Because WSSC operational changes have a relatively immediate impact on flow at Little Falls, a WSSC load-shift, that is, a shift of withdrawals from WSSC's Potomac intake to the Patuxent intake, can elevate river flow and potentially avoid a flow deficit caused by an error in the previous day's one-day forecast. However, the Patuxent's ability to alleviate deficits is limited since the maximum WSSC load-shift is planned to be approximately 75 MGD by 2040 (the difference between the Patuxent plant's minimum and future maximum production rate). Study simulations indicated that in future years, as demands rise and as flows may fall, the likelihood of Potomac flow deficits increases. This limits gains in SSSY provided by the addition of new storage to the system.

In this study, three strategies were identified which reduce the likelihood of Potomac River flow deficits and lead to increased SSSY values. The first is the addition to the system of Travilah Quarry. In PRRISM simulations, Travilah plays a role in system operations similar to that of the Patuxent reservoirs. That is, it's assumed that shifts in withdrawals by WSSC and Aqueduct from the Potomac River to Travilah storage have an immediate impact on flow at Little Falls. Because these combined load-shifts can be quite large, up to 400 MGD, the presence of Travilah eliminates the occurrence of flow deficits when system storage is adequate.

The second strategy is the use of minimum releases from system reservoirs (see Appendix B). In the case of the Luck Stone quarries, an 8 MGD minimum release from Quarry B in 2040, and a 10 MGD minimum combined release from quarries B and C in 2085 were found to increase SSSY values when these alternatives were in place. In the case of Vulcan, for Vulcan 1, minimum Griffith plant production was set at 50 MGD, a 5 MGD increase, and for Vulcan 2 and 3, minimum Griffith plant production was set at 95 MGD, a 50 MGD increase. These minimum release rates were triggered when combined water supply storage in Jennings Randolph and Little Seneca reservoirs was below 60% of capacity. Minimum releases reduced the occurrence of Potomac River flow deficits on days in which the one-day forecast erroneously indicated no need for water supply releases.

The third strategy is improvement in one-day flow forecasts, since these are the primary source of the release errors which may lead to flow deficits at Little Falls. Current one-day flow forecasts used by CO-OP during drought operations, and simulated by PRRISM, rely solely on Little Falls and upstream gage data. CO-OP's new Low Flow Forecast System, which makes use of real-time meteorological data and flow simulations from the Chesapeake Bay Program's watershed model, should be able to improve forecasts because it includes the effects of local precipitation. Current forecasts also use constant rather than variable lag times to predict the travel of flows from upstream to downstream locations. Incorporation of better flow routing methods which reflect the flow-dependence of travel times will also reduce errors.

This study's operational alternative No. 7, improved forecasts, assumes that both the nine-day and the one-day forecasts improve by 10% over current accuracy. However, the proposed 2040 Strategy A assumes that more resources are devoted to development of flow forecast tools and that a 35% improvement in the one-day forecast is achieved by 2040 (Step A-3). This is important in order to realize the benefits of Strategy A's additional storage, from Vulcan 1 and Luck 1. Table 4-9 compares SSSY values for Strategy A, which assumes a 35% improvement in one-day forecasts, with the same set of alternatives but with a 10% and a 50% forecast improvement. SSSY values rise under each climate change scenario as one-day forecasts improve. The largest gain, 85 MGD, occurs under the CC90 climate change scenario, as the forecast improvement rises to 35%.

TABLE 4-9: EFFECT OF 1-DAY FORECAST IMPROVEMENTS ON STRATEGY A BENEFITS

Strategy A: Operational alternatives 5-8 + Vulcan 1 + Luck 1	**SSSY for CC50**	**SSSY for CC75**	**SSSY for CC90**
With 10% improvement in 1-day flow forecast	756	721	551
With 35% improvement in 1-day flow forecast	776	726	636
With 50% improvement in 1-day flow forecast	791	731	656

Similarly, greater one-day forecast improvements are assumed for all 2085 alternatives scenarios. A 35% improvement is part of the 2085 baseline system. A 50% improvement is assumed for the 2085 Strategy A in Table 4-8, again to help realize the benefits of the additional storage from Vulcan 2 and Luck 2 in the absence of Travilah.

5 Cost Estimates

Available cost information for each alternative is summarized in this section. Since the estimates were developed for various intended purposes, and are reported here as estimated for their original purposes (i.e. utility-specific studies/reports), the costs include different components and are not directly comparable between alternatives. In order to be directly comparable, application of a standardized methodology of cost estimation is required. A future step in the process of determining a strategy to ensure water supply reliability for the WMA will be the development of complete and comparable cost estimates for selected alternatives.

According to the Association for the Advancement of Cost Engineering (AACE, 2005), cost estimation is conducted at various stages during project planning. The uncertainty associated with cost estimates decreases over time as project definition (planning, design, and engineering) are completed (Figure 5-1). The long-term structural alternatives being evaluated in this study have preliminary levels of project definition at this time. As such, the estimated costs may be off by +/-50 percent or more (AACE 2005). Information contained in this section should, therefore, be used for informational purposes and is provided only to give the reader a general sense of cost associated with each alternative.

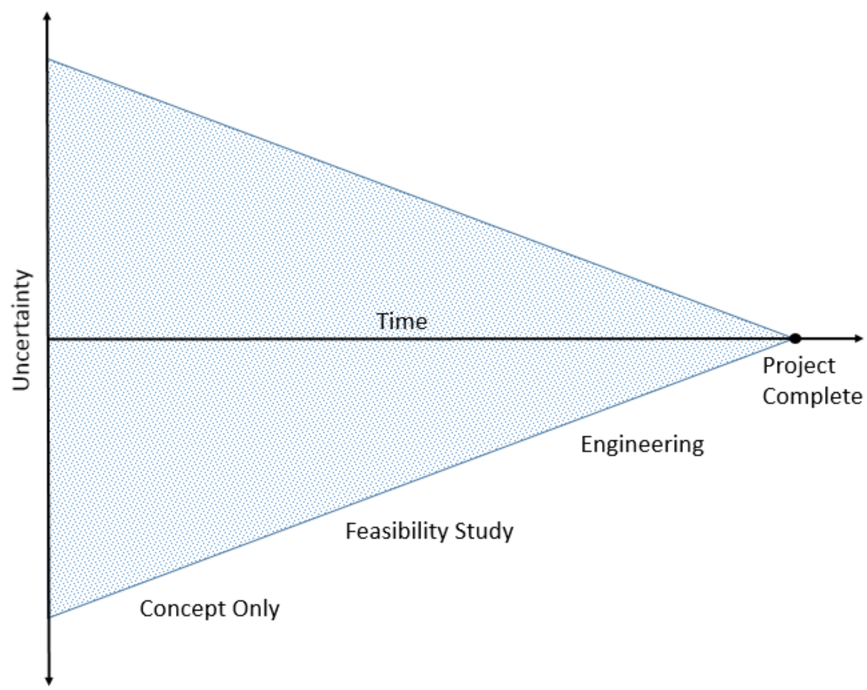


FIGURE 5-1: CONE OF UNCERTAINTY FOR COST ESTIMATES

5.1 Structural Alternatives

Details of the cost estimation methods and components can be found in the literature cited in this section. Complete descriptions of each alternative can be found in Sections **2** and **3**.

5.1.1 Luck Stone Quarries B and C

Loudoun Water and Luck Stone have formally agreed to add Quarries B and C to the long-term plans of their partnership, which began with Loudoun Water's acquisition of raw water storage capacity in Quarry A, already included in Loudoun Water's VWP withdrawal permit. To date, there have been no regional studies to develop planning level cost estimates regarding Quarries B and C, which would be based on engineering plans to augment surface water flow in times of need in the Potomac River.

5.1.2 Travilah Quarry

Several quarry and water transfer configurations were evaluated by Black & Veatch as part of the Travilah Quarry studies (Black & Veatch, 2014; Black & Veatch, 2015). The most likely configuration based on cost and community and environmental impacts are i) one tunnel and one pump station for quarry fill and withdrawal and ii) a conveyance tunnel to Great Falls along the Potomac River for transport to Washington Aqueduct. Construction costs of these configurations, including a 30% contingency, are $150 million and $80 million, respectively. Probable annual operations and maintenance costs, including a 30% contingency, are $1.5 million and $117,000, respectively.

The Net Present Value for quarry fill and withdrawal and transport to Aqueduct, which includes capital and operation and maintenance costs, are $450,000 per MGD and $410,000 per MGD, respectively (Black & Veatch, 2015). Other quarry and water transfer configurations have Net Present Values ranging up to $772,500 per MGD for quarry fill and withdrawal, and $725,000 per MGD for transport to Aqueduct. Net Present Value assumes a 100-year planning horizon, constant probable operation and maintenance costs over the planning horizon, and a constant 4.5% discount rate over the planning horizon.

Although the cost of land acquisition was not included in the Black & Veatch study, the costs associated with acquisition of the land and associated mineral rights are expected to be a significant additional expense.

5.1.3 Vulcan Quarry

Cost estimates for construction and operation of Vulcan Quarry were provided in the 2010 demand study (Ahmed *et al.*, 2010). At that time, construction costs were estimated to be $1.44 to $2.5 million per MGD. Revisions to those estimates were developed in 2012 (Malcolm Pirnie, 2012) based on updated engineering plans. According to that study, the Main Quarry is estimated to cost $130 million without estuary pumping and $155 million with estuary pumping (in 2011 dollars) or $3 million per MGD and $2.6 million per MGD of safe yield, respectively. Estuary pumping has a lower unit construction cost per MGD due to the relatively low construction cost associated with the increased safe yield. Relocation of pipelines or electrical facilities needed to proceed with the mining plan are not included in these estimates as Vulcan is expected to cover those costs (Malcolm Pirnie, 2012). Construction costs for the Northern Reservoir are estimated to be $40 million or $4.3 million per MGD of safe yield for water supply uses only (Malcolm Pirnie, 2012).

5.1.4 Occoquan Estuary RO Plant

CDM (2004) estimated the construction cost of the estuary treatment facility at approximately $4.6 million per MGD of safe yield. In that study, the facility was estimated to increase regional safe yield by 39 MGD for the 50 MGD treatment capacity. Malcolm Pirnie (2012) provided planning level costs for the RO estuary treatment facility to reflect changes in pipeline alignments, facility locations, and required treatment basins and buildings. Based on this study, the planning-level construction cost estimate increased $25 million (2011 price levels) as compared with the 2004 study.

5.2 Operational Alternatives

5.2.1 Cooperative Use of Quarry A

The incremental change in cost associated with operating Quarry A cooperatively is assumed to be negligible.

5.2.2 Use of Beaverdam Reservoir for Low flow Augmentation

Cooperative use of the Beaverdam Reservoir is not expected to be associated with any incremental changes in Loudoun Water's operations costs. No information on the potential contractual costs for incorporation of the reservoir into the CO-OP system are available at this time.

5.2.3 Improved Forecasts

CO-OP has been engaged in an ongoing effort to improve stream flow forecasts since 2013, through the its real-time Low Flow Forecast System (LFFS). Development of a Decision Support System (DSS) would speed progress and increase the benefits of the LFFS and of forecast products that are becoming available from the National Weather Service. A preliminary estimate for a DSS for CO-OP water supply planning and operations is $2 million, partially based on the cost of a somewhat comparable system, the New York City Operations Support Tool, which addressed both water quantity and water quality issues and cost an estimated $8 million (NYC DEP, 2014).

5.2.4 Use of JRR Quality Storage

The legislative language described in Section 2.8 to allow use of Jennings Randolph water quality storage for water supply purposes during droughts includes the following:

> *"The agreement* [entered into between ICPRB and the Corps of Engineers] *shall provide that the cost for water supply and conservation storage…shall not exceed the incremental operating costs associated with providing the storage."*

The transfer of Jennings Randolph water quality storage to water supply storage during times of drought potentially could be accomplished via a revision in water accounting procedures, which would not have associated operational costs. Such a revision, however, would require ongoing conversation with the Corps and other stakeholders and would likely be implemented via a revision of the Jennings Randolph Water Control Plan. Because of the large number of stakeholders with an interest in Jennings Randolph water quality storage, implementation of this alternative would be aided by a shared vision planning process. A preliminary estimate for the cost of contractor support for such a process, including modeling support to facilitate discussion of stream temperature issues, is $100,000 to $250,000 (information provided by Dan Sheer and Megan Rivera of HydroLogics, Inc., private communication, March 2, 2017).

5.2.5 Reduction in Upstream Consumptive Use

The cost associated with reducing upstream consumptive use depends on the mechanisms used to achieve the reduction. As discussed in Section 2.9, reductions may be achieved through various approaches including provision of seed money to upstream municipalities interested in developing storage in local quarries, a water markets approach to reducing agricultural use during droughts, or increased cooperation with state water supply agencies on consumptive use restrictions during droughts. Further discussion on this alternative is needed before preliminary costs can be assigned.

5.2.6 More Water Use Restrictions

The cost of implementing more stringent water use restrictions may take multiple forms including reduced revenue for the water utility as well as societal and/or environmental costs to the consumer (e.g. Grafton and Ward, 2008; Dandy, 1992). Discussions with participating utilities indicate that the revenue lost due to water use restrictions would be an insignificant portion of the overall budget (personal communication, Technical Advisory Committee, October 27, 2016). The potential consumer costs were not quantified as part of this effort.

6 Conclusions

The WMA is fortunate to have water supplies that are more than ample in typical years and to have a suite of alternatives to choose from for providing a reliable supply in the future, even if rising temperatures and changing precipitation patterns cause stream flows to fall and water demands to rise. The three major WMA suppliers participate in a cooperative system of water supply management and conduct forecasts of future system demand and supply every five years. The most recent of these indicated that the current system needs to be augmented by 2040 to reduce the region's vulnerability in the event of severe drought (Ahmed *et al.*, 2015). The current study considers ten water supply alternatives for such a system augmentation. The alternatives have been evaluated on their abilities, both individually and in combination, to increase system reliability in the face of growing WMA demands, decreasing river flows due to upstream consumptive use, and the potential impacts of climate change. The evaluations are conducted for two scenario years, 2040 and 2085.

According to projections of future climate in the Potomac basin, temperatures will rise but precipitation may rise or may fall. Both temperature and precipitation have an impact on stream flows, and the various climate projections lead to a wide range of potential changes in water availability in the basin, introducing tremendous uncertainty into water supply planning. ICPRB watershed modeling results, which make use of global climate model output downscaled to the Potomac basin by the USGS's National Research Program, project changes in long-term average summer basin-wide stream flows ranging from -35 percent to +42 percent, with a median of +2 percent, over the period between 1995 and 2040, and ranging from -54 percent to +36 percent, with a median of +4 percent, between 1995 and 2085. To take into account this uncertainty, three future climate scenarios, informed by past modeling results, were developed for each of the two scenarios years.

The impact of a changing climate on water demand is also taken into account in study evaluations. Water demands both in the WMA and in upstream areas are expected to grow in coming years because of rising population, though this growth has been and will continue to be mitigated because of the region's adoption of water saving technologies, a factor which is incorporated into ICPRB's WMA demand forecasts. In the three 2040 climate scenarios, average regional temperature increases by 3.2° F and change in precipitation ranges from -2.9 to 6.3 percent. As a result, projected summer WMA demands rise to 666-667 MGD (July average), a four percent increase over the 641 MGD forecast in ICPRB's 2015 water supply study, which did not consider the impact of climate change, and a 14% increase over the current value of 583 MGD. In the three 2085 climate scenarios, average regional temperature increases by 5.6 to 6.9° F and increase in precipitation ranges from 1.4 to 11.3 percent. Projected summer demands rise to 798-815 MGD (July average), a three to five percent increase over the 773 MGD estimate based on in ICPRB's 2015 water supply study, and a 37 to 40 percent increase over the current value of 583 MGD.

The future climate scenarios pose varying degrees of challenge to WMA system reliability, from moderate to severe. In 2040 under the CC50 scenario, stream flows actually increase slightly, though the current WMA water supply system would not be able to reliably meet regional needs in a severe drought due to increased demands. The addition to the current system of any single one of the alternatives, however, would be sufficient to ensure that needs could be reliably met, according to the SSSY values in Table 4-7. For the most severe scenario, CC90, under which summer flows fall by 19 percent, Travilah is the only individual alternative able to meet regional needs. In general, study results indicate that combinations of alternatives will need to be in place to ensure reliability under the full range of climate change scenarios. The exception is the case of Travilah Quarry, which is such an effective alternative that it alone is a sufficient measure for 2040 under all scenarios. By 2085, study results indicate that most of the ten alternatives would need to be in place to reliably meet projected needs during a severe drought. However, as noted in Section 4.1.1, assumptions and results for the 2085 scenario year should be considered highly preliminary and are meant to be taken into consideration under an adaptive management approach to long-term planning.

Two recommended strategies are provided in this study for phased implementation of combinations of alternatives over the medium-term planning horizon of 2040. The first of these, Strategy A, is recommended if the region chooses not to pursue acquisition of Travilah Quarry or if that facility proves to be unavailable in the near term. As a first step, it calls for work to begin on implementation of operational alternatives 5-8: agreements to allow cooperative use of Loudoun Water's Quarry A and Beaverdam Reservoir during droughts, improvements stream flow forecasts, and use of JRR water quality storage for water supply purposes during droughts. Completion of these four measures by 2025 would be cost effective and provide a measure of protection against the potential impact of climate change during the years leading up to 2040. The second step of Strategy A is implementation of Vulcan Quarry Phase 1 (Vulcan 1) by 2035, which is already planned by Fairfax Water. As a final step, Strategy A calls for implementation of Luck Stone Quarry B (Luck 1), along with further improvements in stream flow forecasts, by 2040.

Just Step 1 of Strategy A, that is, the implementation of operational alternatives 5-8, is sufficient for system reliability under two of the 2040 climate change scenarios, CC50 and CC75. However, even after Vulcan Phase 1 and Luck Stone Quarry B are in place, Strategy A, as currently simulated by ICPRB's planning model, falls somewhat short of reliably meeting 2040 demands. Nonetheless, Strategy A is arguably a reasonable combination of alternatives for the region. A future evaluation may conclude that Strategy A will be effective in meeting 2040 demands if it is determined that demands are growing at a slower rate than forecasted, if a new generation of global climate models or use of long-term trend data for model verification have shrunk the range of uncertainty for changes in basin stream flow, if better than anticipated increases in the accuracy of stream flow forecasts are achieved, or if better policies for operation of the specific alternatives in Strategy A can be developed.

The second of the recommended combinations of alternatives, Strategy B, involves acquisition of Travilah Quarry and construction of infrastructure to carry raw water to and from the quarry and WSSC's water treatment facility on the Potomac River and to Aqueduct's Dalecarlia treatment plant. As a part of this recommendation, implementation of operational alternatives 5-8 and of Vulcan Quarry Phase 1 are included as first steps. These initial steps would provide protection against the potential impact of climate change in the years prior to completion of the Travilah project, and would help increase regional cooperation and pave the way for measures needed in the decades after 2040.

Implementation of Strategy B would provide the region with a reliable water supply under a wide range of potential climate conditions, including the most severe scenario considered in this study, CC90. Strategy B could also be viewed as a "no regrets" option, because Travilah Quarry would serve another important function for the region: providing an alternative water supply for both Aqueduct and WSSC in case of an emergency event which contaminated the Potomac River.

Results for the second scenario year, 2085, indicate that most of the ten alternatives need to be in place, that is: operational alternatives 5-8, Vulcan 2 (the addition of the Main Reservoir with 17 BG), Luck 2 (including the addition Quarry C with 4 BG), and Travilah Quarry. This combination of alternatives, designated as 2085 Strategy C in Table 4-8, was found in PRRISM simulations to be able to provide a reliable supply even under the most severe climate change scenario, CC90. Of course, these results should be considered highly preliminary, but are meant to aid in long-term planning conducted in an "adaptive management" framework under the assumption that CO-OP will continue to monitor the forecasts used in the analysis, e.g. for WMA demands, upstream consumptive use, and trends in regional stream flows, and will update the evaluation as new data and information become available.

Study results highlight the future vulnerability of the WMA system to Potomac River flow deficits, that is, to river flow falling below the 100 MGD minimum at Little Falls due to inherent inaccuracies in the one-day flow forecasts used to calculate Little Seneca Reservoir releases and other operational changes. The poor performance of some of the structural alternatives under the CC90 climate change scenario was often due to an unacceptable likelihood of flow deficits. As currently operated, the WMA system can usually prevent these deficits by shifting WSSC withdrawals to the Patuxent reservoirs. But in future years, as potential deficits increase, this strategy will become less effective due to limited capacity at the Patuxent treatment plant. An increased capacity at the Patuxent plant is probably not a reasonable option because it would likely not be supported by the yield of the Patuxent watershed. Other options that were shown to be effective in study simulations are:

a) Use of Travilah Quarry, which would serve a function similar to the Patuxent reservoirs,
b) Additional improvements in one-day flow forecasts, and
c) Increases in minimum releases from reservoirs during droughts.

If acquisition of Travilah Quarry is not pursued in the near term, then resources need to be devoted to b) and c). The option, b), could be achieved by devoting more resources to CO-OP's on-going effort to improve the one-day forecast through development of its Low Flow Forecast System. The option, c), was explored in a preliminary manner over the course of this study, but more research is warranted to better understand how to balance use of constant minimum releases and use of variable releases based on flow forecasts.

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APPENDICES

A. DEVELOPMENT OF CLIMATE CHANGE SCENARIOS
B. PRRISM INPUT PARAMETERS
C. PRRISM OUTPUT FOR INDIVIDUAL ALTERNATIVES

A. DEVELOPMENT OF CLIMATE CHANGE SCENARIOS

A.1. Introduction

This appendix describes the development of the climate change scenarios which appear in Table 3-1 of the main report, three scenarios, denoted as CC50, CC75, and CC90, for each of the two scenario years, 2040 and 2085. Each scenario consists of

1. an assumed percent change in long-term average regional stream flow in the summer months (June, July, August),
2. an assumed percent change in long-term average regional stream flow in the other months of the year (January-May and September-December),
3. an assumed percent change in long-term average regional precipitation, and
4. an assumed change in long-term average regional temperature, in degrees Fahrenheit (ºF).

The scenario values were informed by i) a climate response function which relates changes in average regional precipitation and temperature to percent change in long-term average regional summer stream flow, based on ICPRB watershed modeling results (Ahmed *et al.*, 2013; 2015), and ii) new sets of projected changes in monthly precipitation and temperature, derived from General Circulation Model (GCM) output, downscaled to the Potomac basin and available from the U.S. Geological Survey (USGS), GeoData Portal. Details are given below.

A.2. Climate Projections

ICPRB's recent climate change work has relied on global climate projections promoted by the World Climate Research Programme (WCRP) through the Climate Model Intercomparison Project (CMIP). Sets of CMIP projections, released every five to seven years, have been the standard for multi-model climate research including the Intergovernmental Panel on Climate Change (IPCC) Assessment Reports. The IPCC's Fourth Assessment Report (AR4) used the CMIP3 projections (IPCC, 2007), which are the most prevalently cited climate projections. The IPCC's Fifth Assessment Report (AR5) used a combination of the CMIP5 projections, which are the newest available projections, as well as the older CMIP3 projections (IPCC, 2013).

For the current study, 226 pairs of CMIP5 precipitation and temperature projections were obtained, derived from 35 GCMs listed in Table A-1, with up to four scenarios per model (multiple model runs of the same scenario were averaged). The data were obtained from the USGS Geo Data Portal (http://cida.usgs.gov/gdp/). In the previous assessments reported in Ahmed *et al.* (2013 and 2015) only 18 climate projections derived from six global climate models and three carbon emission scenarios from CMIP3 were used. These 18 projections were specially constructed by the USGS National Research Program in Denver, Colorado, as part of a separate project to assess the impact of climate change in the Chesapeake Bay region (Lauren Hay, personal communication, March 13, 2012).

A.2.a. CMIP3 versus CMIP5

While the CMIP3 model archive has been more thoroughly examined by the research community, the CMIP5 has had greater participation from modelling groups (Collins *et al.*, 2013; Flato *et al.*, 2013). This record participation in the CMIP5 project resulted in a larger number of models and experiments performed compared to CMIP3. Some of the advancements made to the CMIP5 models include higher spatial resolution, better representation of processes, and inclusion of more processes such as those needed to better simulate the carbon cycle of the earth (Collin *et al.*, 2013; Flato *et al.*, 2013).

Other than changes in the models themselves, differences in CMIP3 and CMIP5 projections have been attributed to how their respective scenarios approach the climate change question and a new baseline period (Collins *et al.*, 2013). CMIP5 uses four Representative Concentration Pathways (RCP), whereas CMIP3 uses three scenarios from the Intergovernmental Panel on Climate Change's (IPCC) Special Report on Emissions Scenarios (SRES). Unlike the SRES scenarios, the RCP scenarios specify concentrations and corresponding emissions, but are not directly based on fixed socio-economic storylines (Collins *et al.*, 2013; Cubasch *et al.*, 2013). This change from SRES to RCP scenarios allows planners to experiment with and optimize future socio-economic changes for possible mitigation and adaptation measures. However, RCP scenarios are not necessarily more capable of representing future developments than the SRES scenarios (Cubasch *et al.*, 2013). In addition, the baseline period used to compute anomalies has advanced 6 years, from 1980–1999 to 1986–2005.

The four RCP scenarios cover a larger range of possible future greenhouse gas concentrations, resulting in a wider range of climate outcomes compared to the three SRES scenarios (Cubasch *et al.*, 2013). Due to consideration of a broader range of emission scenarios, CMIP5 features a larger spread of temperature projections (Brekke *et al.*, 2013). That said, the IPCC reports that for large-scale analyses the differences between CMIP3 and CMIP5 are small, both in magnitude and in spatial distributions (Sun *et al.* 2015). When comparing CMIP3 and CMIP5 for the United States it has been reported that: average and maximum temperatures may increase for the moderate to high emissions scenarios; precipitation changes are split by a transitions zone with wetter conditions across the north and drier conditions in the southwest in the winter and spring. Regional patterns of projected precipitation changes, however, do vary some between CMIP3 and CMIP5, reflecting both differences in scenarios and the fact that precipitation projections tend to vary more widely among different climate models.

Table A-1: List of GCMs[1] from which the CMIP5 projections were derived

Modeling Center (or Group)	Institute ID	Model Name
Commonwealth Scientific and Industrial Research Organization (CSIRO) and Bureau of Meteorology (BOM), Australia	CSIRO-BOM	ACCESS1.0 ACCESS1.3
Beijing Climate Center, China Meteorological Administration	BCC	BCC-CSM1.1 BCC-CSM1.1(m)
College of Global Change and Earth System Science, Beijing Normal University	GCESS	BNU-ESM
Canadian Centre for Climate Modelling and Analysis	CCCMA	CanESM2
National Center for Atmospheric Research	NCAR	CCSM4
Community Earth System Model Contributors	NSF-DOE-NCAR	CESM1(BGC) CESM1(CAM5)
Centro Euro-Mediterraneo per I Cambiamenti Climatici	CMCC	CMCC-CM
Centre National de Recherches Météorologiques / Centre Européen de Recherche et Formation Avancée en Calcul Scientifique	CNRM-CERFACS	CNRM-CM5
Commonwealth Scientific and Industrial Research Organization in collaboration with Queensland Climate Change Centre of Excellence	CSIRO-QCCCE	CSIRO-Mk3.6.0
EC-EARTH consortium	EC-EARTH	EC-EARTH
LASG, Institute of Atmospheric Physics, Chinese Academy of Sciences and CESS,Tsinghua University	LASG-CESS	FGOALS-g2
LASG, Institute of Atmospheric Physics, Chinese Academy of Sciences	LASG-IAP	FGOALS-s2
The First Institute of Oceanography, SOA, China	FIO	FIO-ESM
NOAA Geophysical Fluid Dynamics Laboratory	NOAA GFDL	GFDL-CM3 GFDL-ESM2G GFDL-ESM2M
NASA Goddard Institute for Space Studies	NASA GISS	GISS-E2-H-CC GISS-E2-R GISS-E2-R-CC
National Institute of Meteorological Research/Korea Meteorological Administration	NIMR/KMA	HadGEM2-AO
Met Office Hadley Centre (additional HadGEM2-ES realizations contributed by Instituto Nacional de Pesquisas Espaciais)	MOHC (additional realizations by NPE)	HadCM3 HadGEM2-CC HadGEM2-ES
Institute for Numerical Mathematics	INM	INM-CM4
Institut Pierre-Simon Laplace	IPSL	IPSL-CM5A-LR IPSL-CM5A-MR IPSL-CM5B-LR
	MIROC	MIROC-ESM

Modeling Center (or Group)	Institute ID	Model Name
Japan Agency for Marine-Earth Science and Technology, Atmosphere and Ocean Research Institute (The University of Tokyo), and National Institute for Environmental Studies		MIROC-ESM-CHEM
Atmosphere and Ocean Research Institute (The University of Tokyo), National Institute for Environmental Studies, and Japan Agency for Marine-Earth Science and Technology	MIROC	MIROC4h MIROC5
Max-Planck-Institut für Meteorologie (Max Planck Institute for Meteorology)	MPI-M	MPI-ESM-LR

[1]Output from yellow highlighted models is available for unrestricted use. Output from the others may only be used for non-commercial research and educational purposes. [See complete "Terms of Use": http://cmip-pcmdi.llnl.gov/cmip5/terms.html]

A.2.b. Projected Changes in Temperature & Precipitation

The change factors for temperature and precipitation were calculated from bias corrected spatially downscaled monthly CMIP5 climate projections from the USGS Geo Data Portal (cida/usgs/gov). These projections were downloaded as area weighted mean values from a gridded dataset based on a vector polygon feature of the Upper Potomac River basin, which is located upstream of the USGS stream gage (Station ID 01646500) on the Potomac River at Little Falls dam near Washington, D.C. The area weighting algorithm was provided by the USGS Data Portal website (https://cida.usgs.gov/gdp/client/#!catalog/gdp/dataset/54dd5e4be4b08de9379b38ff/process). A reference period of 1988-1999 was selected for calculating the precipitation and temperature changes in order to be consistent with Ahmed *et al.* (2015).

Figure A-1 is a plot of changes in average annual temperature and precipitation for the 103 CMIP5 climate scenarios used in this study for the 2035-2045 period. For comparison, changes in temperature and precipitation for 18 CMIP3 climate scenarios from Part 2 of the 2010 demand study are also shown. The range of temperature changes in the current study is 1.07 to 5.72 degrees Fahrenheit, which compares to 0 to 4.14 degrees Fahrenheit in Ahmed et al. (2015). The precipitation range for the current study is -8 percent to 24 percent, which compares to -9 percent to 9 percent in Ahmed et al. (2015).

Table A-2 summarizes all model mean changes in temperature and precipitation changes and likely ranges for the different RCP scenarios.

TABLE A-2: PROJECTED CHANGE IN TEMPERATURE AND PRECIPITATION FOR THE 2035-2045 AND 2080-2090 PERIODS RELATIVE TO THE REFERENCE PERIOD OF 1988-1999

		2035-2045		2080-2090	
	Scenario	Mean	Range (Likely[c])	Mean	Range (Likely[c])
Temperature Change (°F)[a]	RCP2.6	2.9	1.1 to 5.0 (2.5 to 3.4)	2.9	0.3 to 5.8 (2.2 to 3.5)
	RCP4.5	3.2	1.6 to 5.1 (2.9 to 3.6)	4.9	2.0 to 7.8 (4.4 to 5.4)
	RCP6.0	2.7	1.3 to 4.6 (2.2 to 3.2)	5.8	3.1 to 8.5 (4.9 to 6.6)
	RCP8.5	3.7	1.8 to 5.7 (3.4 to 4.0)	8.8	5.8 to 12.7 (8.2 to 9.5)
Precipitation Change (%)[b]	RCP2.6	6	-8 to 20 (2 to 9)	7	-7 to 17 (4 to 10)
	RCP4.5	7	-6 to 23 (4 to 9)	9	-6 to 25 (7 to 12)
	RCP6.0	7	-7 to 24 (3 to 11)	11	1 to 27 (7 to 14)
	RCP8.5	6	-8 to 18 (4 to 9)	13	-8 to 31 (9 to 16)

[a] Temperature changes are reported as the difference between the climate scenario projection and the reference period value in degrees Fahrenheit.

[b] Precipitation changes are reported as a percent difference: the difference between the climate scenario projection and the reference period, divided by the reference period, and multiplied by 100.

[c] Based on CMIP5 ensemble where the likely range is the 5 to 95 percent confidence interval.

Figure A-2 shows how projected changes in temperature and precipitation shift over time for the current study, where the respective 2085-2095 temperature and precipitation ranges are now equal 0.27 to 12.70 degrees Fahrenheit and -8 percent to 30 percent. In Figure A-3, boxplots compare CMIP3 and CMIP5 average projections for summer months (June, July, August). In Figure A-4, CMIP5 summer projections for the periods, 2035-2045 and 2080-2090 are compared. These plots shows that as time progresses, projected temperatures and precipitation increase. Of the 2080-2090 projections, 90 become hotter with 47 of them exceeding the 2035-2045 maximum temperature change in degrees Fahrenheit of 5.72. Additionally, 73 scenarios become wetter with five of them exceeding the 2035-2045 maximum percent change of 24.

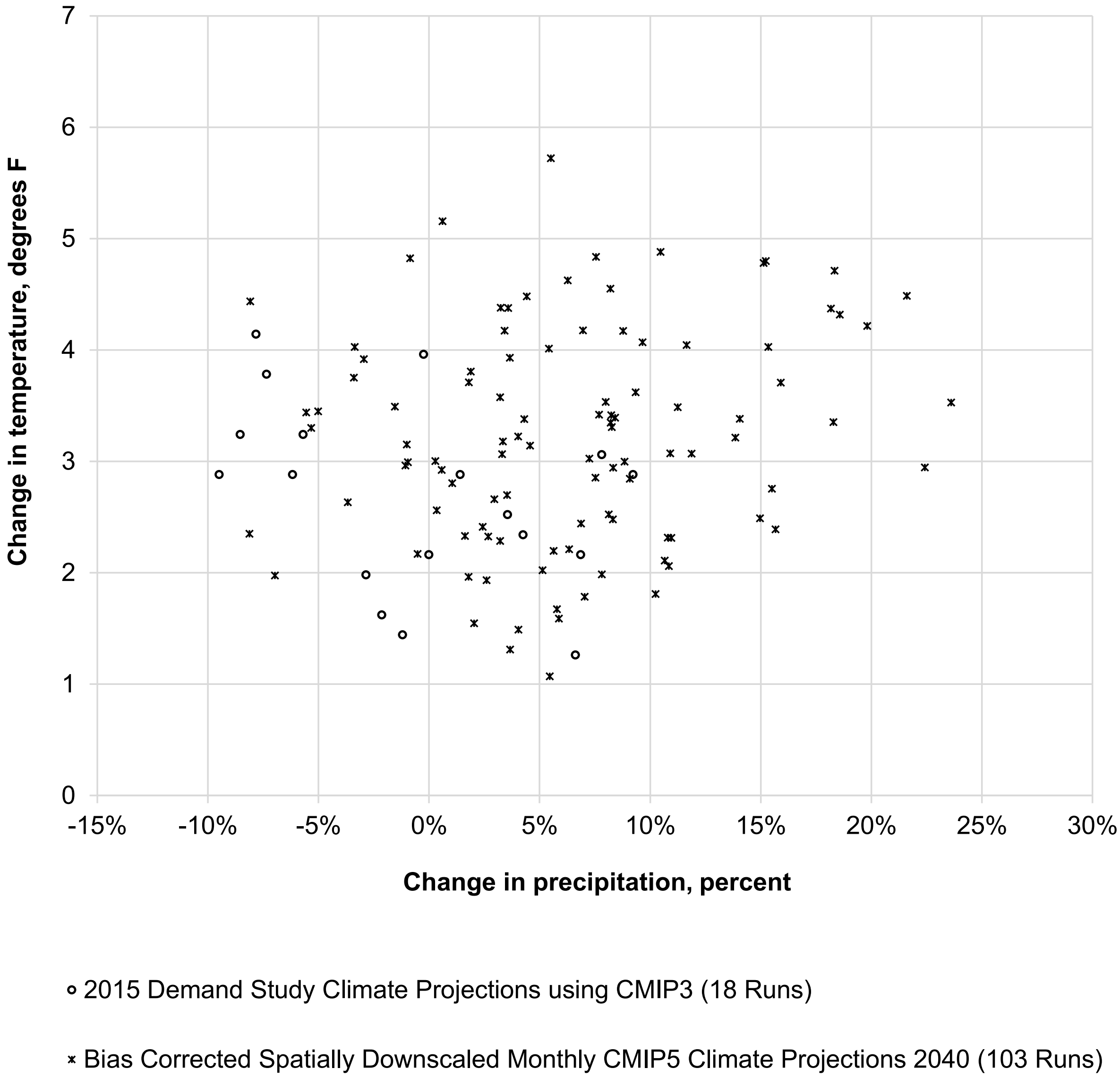

FIGURE A-1: COMPARISON OF 2040 CMIP3 VERSUS CMIP5 PROJECTIONS FOR CHANGES IN AVERAGE ANNUAL PRECIPITATION AND TEMPERATURE

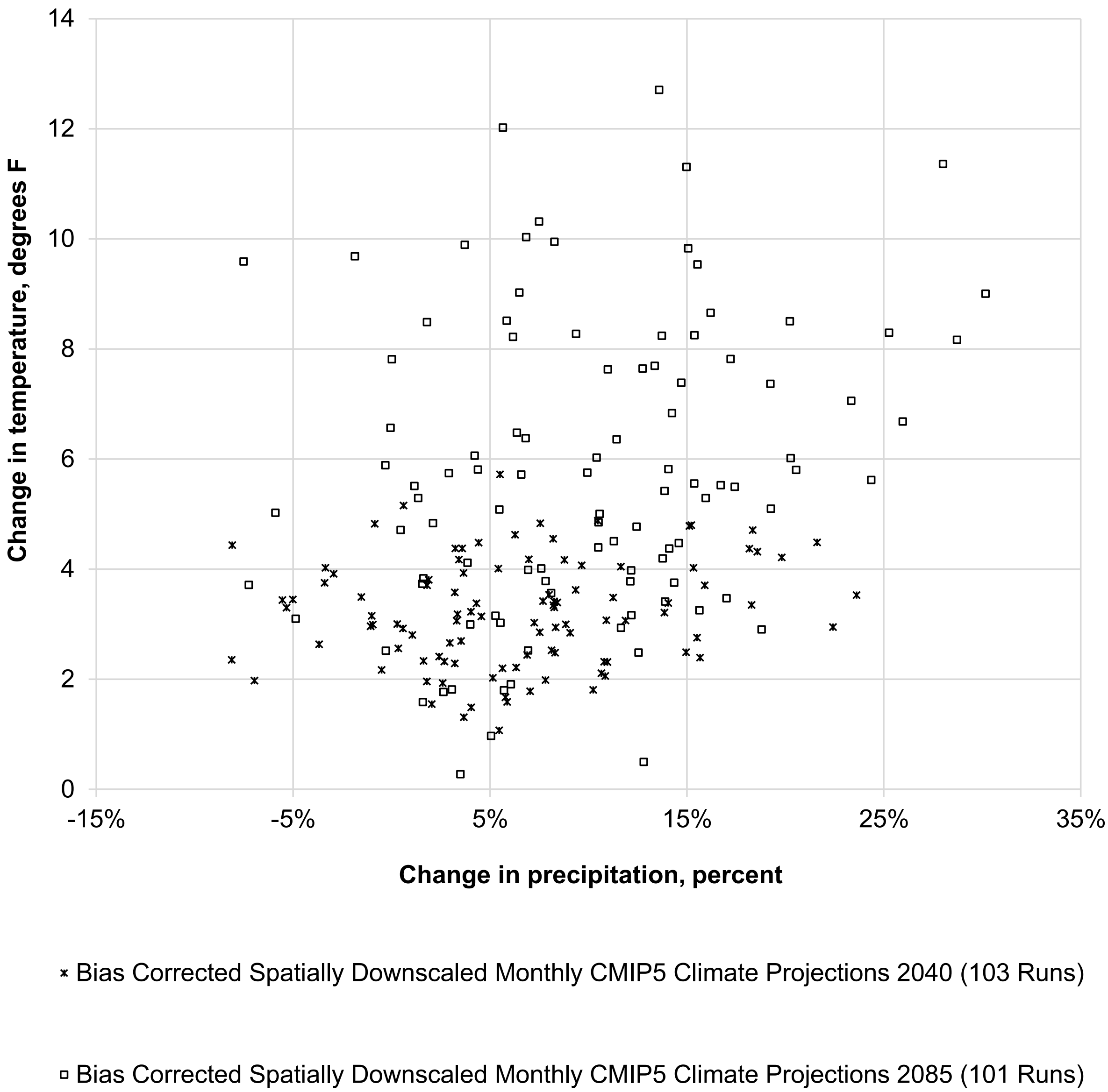

FIGURE A-2: COMPARISON OF 2040 AND 2085 CMIP5 PROJECTIONS FOR CHANGES IN AVERAGE ANNUAL PRECIPITATION AND TEMPERATURE

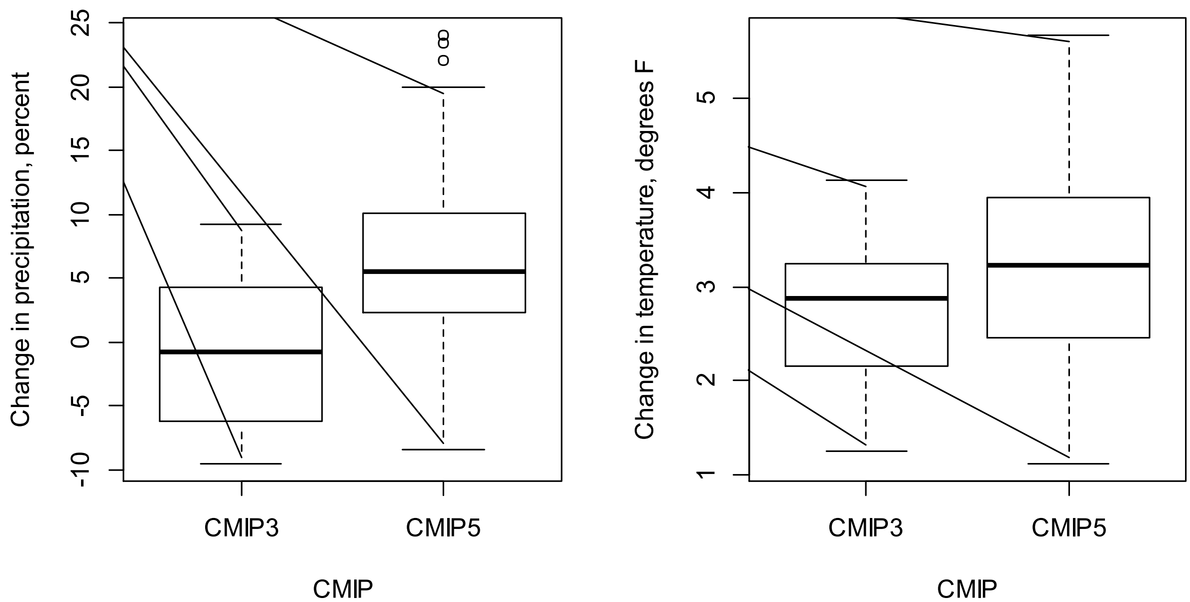

FIGURE A-3: COMPARISON OF 2035-2045 CMIP3 AND CMIP5 SUMMER PROJECTIONS

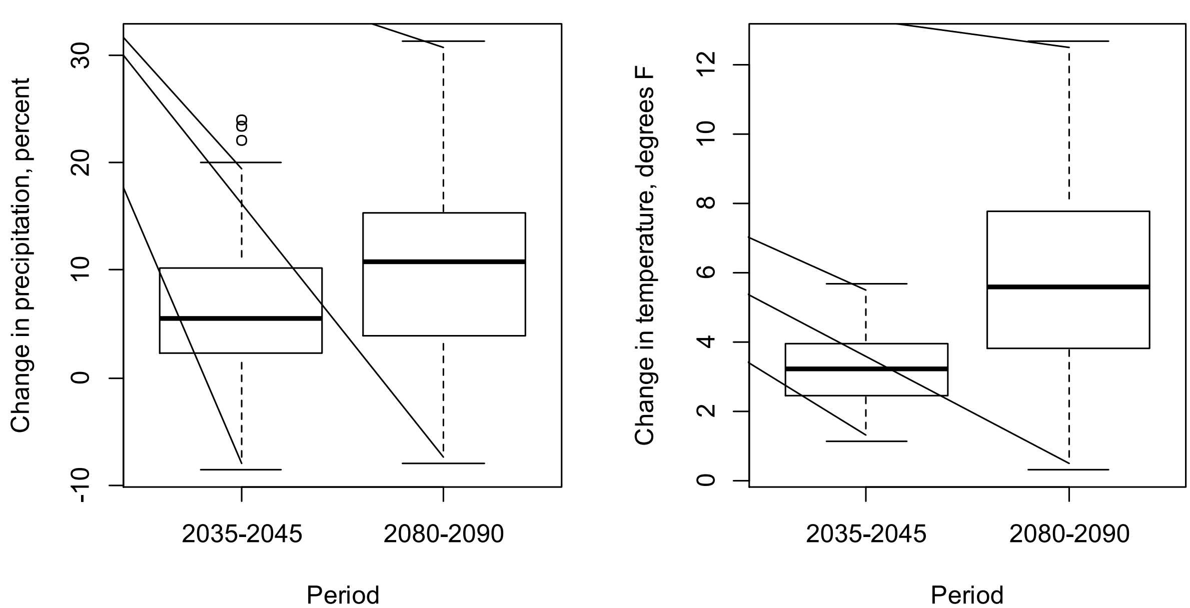

FIGURE A-4: COMPARISON OF CMIPS 2035-2045 AND 2080-2090 SUMMER PROJECTIONS

A.3. Stream Flow Projections

Both this study and the 2015 water supply study applied a pair of climate response functions to changes in mean annual precipitation and temperature to estimate a change in average basin stream flow. The climate response functions, described in Section 7.5 of Ahmed *et al.* (2015), estimate future percent changes in long-term average seasonal flow for the Potomac Basin from temperature and precipitation change factors. They were derived from CMIP3 data and Chesapeake Bay Program Watershed Model (Phase 5.2) simulation results for daily flows. For the current study, the decision was made to limit the assessment to the CMIP5 climate change projections and not to expand on the CMIP3 projections of the previous assessment because multiple studies have been done on the Potomac River basin using CMIP3 (WRF, 2013; Stagge, 2012; Stagge and Moglen, 2013; Ahmed *et al.,* 2013; 2015).

For the current study, the new CMIP5 change factors were used with the climate response function to obtain sets of changes in seasonal stream flow for the 2035-2045 and 2080-2090 periods relative to the reference period of 1988-1999. Projections were obtained for percent change in average summer flow (June, July, August) and average other month flow (January-May and September-October). The summer and other month flow changes for the 103 climate change projections for 2035-2045 and the 101 projections for 2080-2090 are plotted in Figure A-5 as functions of exceedance probability, that is, of the probability that a given flow change is exceeded in the calculated set of flow changes. Table A-3 lists changes for selected exceedance probabilities.

Table A-4 and Figure A-6 show statistics on streamflow changes by RCP.

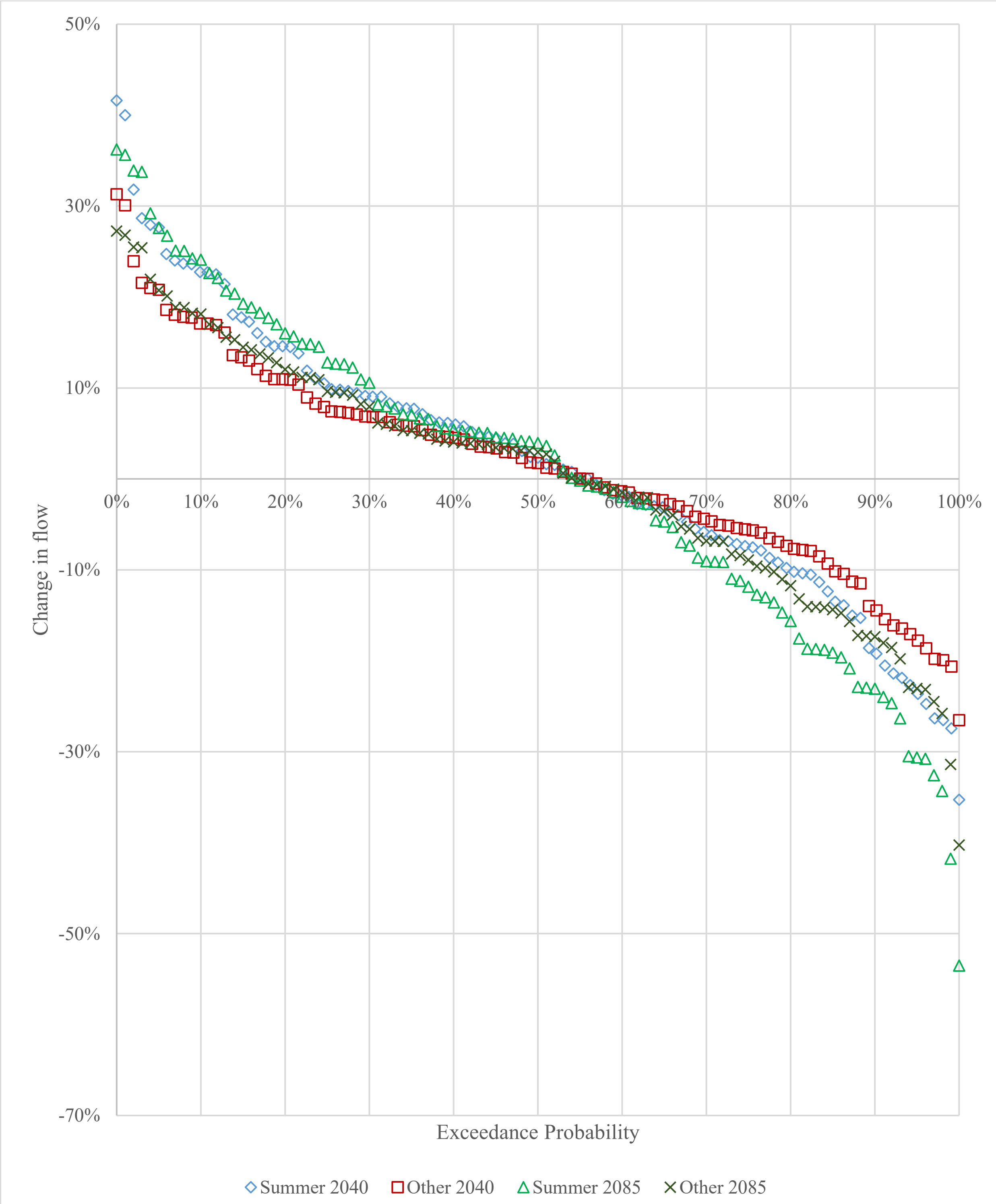

FIGURE A-5: SUMMER AND OTHER MONTH AVERAGE FLOW CHANGE FOR ALL CLIMATE PROJECTIONS

Table A-3: Changes in Summer and Other Month Streamflow by Exceedance Probability

	2035-2045		2080-2090	
Probability that change in flow exceeds value	Change in Summer Streamflow	Change Other Month Streamflow	Change in Summer Streamflow	Change in Other Month Streamflow
<1%	42%	31%	36%	27%
1%	40%	30%	36%	27%
2%	32%	24%	34%	26%
5%	28%	21%	28%	21%
10%	23%	17%	24%	18%
15%	18%	13%	19%	14%
20%	15%	11%	16%	12%
25%	11%	8%	13%	10%
50%	2%	2%	4%	3%
75%	-7%	-6%	-12%	-9%
80%	-10%	-8%	-16%	-12%
85%	-13%	-10%	-19%	-14%
90%	-19%	-14%	-23%	-17%
95%	-24%	-18%	-31%	-23%
98%	-27%	-20%	-34%	-26%
99%	-27%	-21%	-42%	-31%
>99%	-35%	-27%	-54%	-40%

Table A-4: Mean and Range of Projected Change in Long-Term Average Basin-Wide Streamflow by RCP

		2035-2045		2080-2090	
	Scenario	Mean	Range (Likely[a])	Mean	Range (Likely[a])
Summer Change (%)	RCP2.6	2	-27 to 28 (-5 to 8)	4	-31 to 27 (-2 to 11)
	RCP4.5	2	-27 to 42 (-3 to 7)	3	-33 to 34 (-4 to 9)
	RCP6.0	6	-25 to 40 (-4 to 15)	2	-19 to 36 (-6 to 9)
	RCP8.5	0	-35 to 29 (-6 to 6)	-5	-54 to 36 (-13 to 4)
Other Change (%)	RCP2.6	1	-21 to 21 (-4 to 6)	3	-23 to 20 (-1 to 8)
	RCP4.5	2	-20 to 31 (-2 to 6)	2	-24 to 25 (-3 to 6)
	RCP6.0	4	-19 to 30 (-3 to 11)	2	-13 to 25 (-4 to 7)
	RCP8.5	0	-27 to 22 (-4 to 5)	-3	-40 to 25 (-9 to 3)

[a] Based on CMIP5 ensemble where the likely range is the 5 to 95 percent confidence interval.

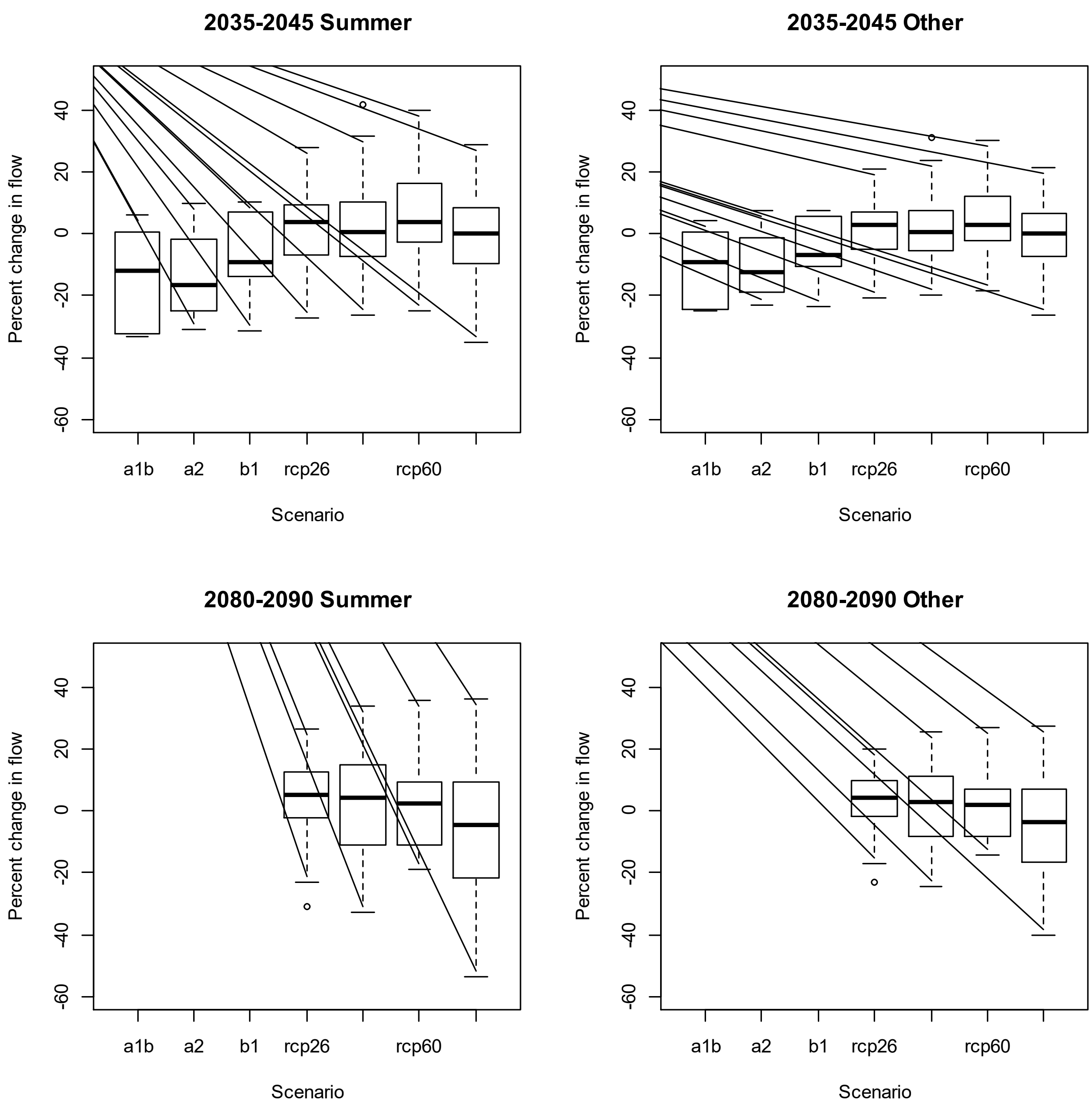

FIGURE A-6: PROJECTED CHANGE IN AVERAGE BASIN-WIDE STREAMFLOW FOR SREF A1B, A2, AND B1, AND RCP 2.6, 4.5, 6.0, AND 8.5

A.4. Climate Scenarios

The climate change scenarios for the study consist of six sets of changes in long-term average seasonal flow, precipitation, and temperature, given in Table A-5. The flow changes were selected based on the changes computed from the CMIP5 climate projections for the 2035-2045 and the 2080-2090 time periods, based on the 1988-1999 reference period, and on their exceedance probabilities. Projected summer flow changes with exceedance probabilities of 50, 75, and 90 percent, which are denoted CC50, CC75, and CC90, are used in the scenarios. In the study, the scenario changes given in Table A-5 are applied to appropriate simulation model daily inputs for each year in historic record, 1929-2013.

TABLE A-5: CLIMATE CHANGE SCENARIOS

Scenario year	2040			2085		
Climate change scenario	CC50	CC75	CC90	CC50	CC75	CC90
Change in long-term summer average basin-wide stream flow, percent	+2	-7	-19	+4	-12	-23
Change in long-term other month average basin-wide stream flow, percent	+2	-6	-14	+3	-9	-17
Change in precipitation, percent	6.3	2.4	-2.9	11.3	5.4	1.4
Change in temperature, degrees F	3.2	3.2	3.2	5.6	6.4	6.9

The changes in precipitation and temperature in Table A-5 were obtained from simple linear regression equations, derived from the data sets, which predict changes in precipitation and temperature from x = change in summer flow:

$$\Delta precip_{2040} = 0.0546 + 0.4419\ x$$

$$\Delta temp_{2040} = 3.2368 - 0.1026\ x$$

$$\Delta precip_{2085} = 0.0982 + 0.3675\ x$$

$$\Delta temp_{2085} = 5.8251 - 4.5175\ x$$

All regression coefficients in the equations above were found to be significant with the exception of the β_1 coefficient for $\Delta temp_{2040}$ (-0.1026). Plots of change in precipitation and change in temperature versus change in summer flow, along with the regression lines, are shown in Figure A-7 and Figure A-8.

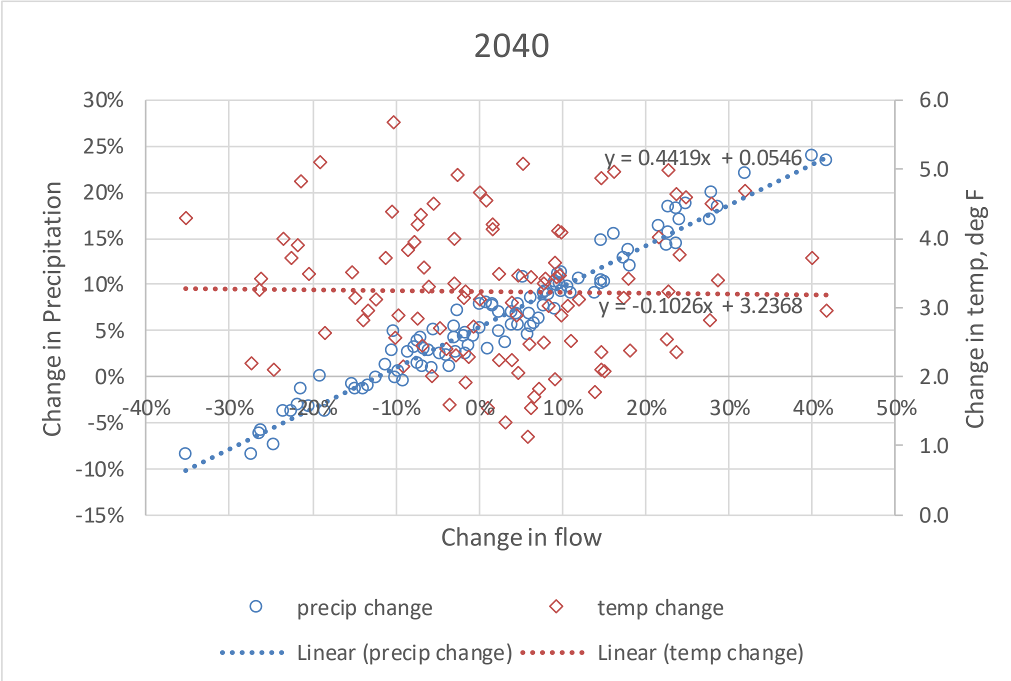

FIGURE A-7: 2040 CMIP5 CHANGE IN PRECIPITATION AND TEMPERATURE VERSUS CHANGE IN SUMMER FLOW

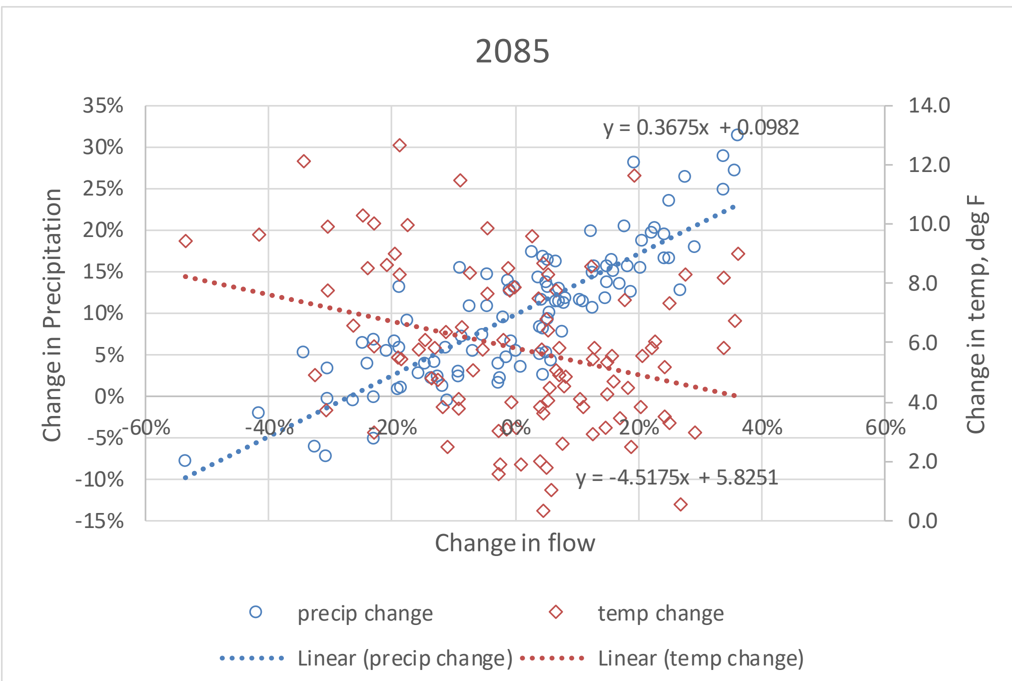

FIGURE A-8: 2085 CMIP5 CHANGE IN PRECIPITATION AND TEMPERATURE VERSUS CHANGE IN SUMMER FLOW

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B. PRRISM INPUT PARAMETERS

Table B-1: PRRISM Input Parameters

Parameter	**2040**	**2085**
1-day MOS, MGD	120/110 with FC improv/-45 with Travilah	130 except -35 with Travilah
1-day additional MOS if Patuxent storage < 1000 MG, MGD	75	75
1-day/9-day forecast improvement, percent	0/0 - 2040 Baseline 10/10 - alternative 7 35/10 – 2040 Strategy A-3	35/10 – 2085 Baseline 50/10 – 2085 Strategy A
JR-Seneca balancing factor, MGD (JRR_LSen_{factor})	1000	1000
FW-Sen balancing coefficient (α_{FW})	4	4
LW-Sen balancing coefficient (α_{LW})	2	4
FW-LW balancing coefficient (β)	0	2
Luck Stone quarries max release, MGD	80	160
Luck Stone quarries min release in drought (assuming no Travilah), MGD	8	8 (Luck 1) 10 (Luck 2)
Vulcan min release in drought (added to Griffith min production, assuming no Travilah), MGD	5	5 (Vulcan 1) 50 (Vulcan 2 & 3)
DEQ permit max withdrawal, MGD	40	80
JR WQ storage protected, MG	5000	5000

C. PRRISM OUTPUT FOR INDIVIDUAL ALTERNATIVES

TABLE C-0: 2040 BASELINE

Historical period for simulation of variability:	**1930-2013**	**1930**	**1966**
Reliability, Vulnerability, Resiliency			
Percentage with no Potomac deficits	99.99%	0.00%	0.00%
Maximum number of days in a row of Potomac deficits	-	-	-
Number of days in which Potomac deficits must be allocated	0	0	-
Maximum amount of deficit allocated in a single day, MGD	(0.0)	(0)	-
Total amount of deficit allocated, full simulation period, MG	(0.0)	(0)	-
Number of Patuxent water supply shortfalls over simulation period	9	-	-
Number of Occoquan water supply shortfalls over simulation period	0	-	-
Number of days in which Patuxent plant production is less than 30 MGD	3,948	185	357
Percentage of years with restrictions (Percentage of days for 1930 and 1966)			
Voluntary restrictions	4.66%	37.94%	28.16%
Emergency restrictions	0.08%	0.77%	0.01%
Minimum reservoir storage, BG			
Little Seneca Reservoir	0.56	0.58	0.96
ffffffffffffffffffffffffffJennings Randolph water supply account	1.88	2.29	2.35
Jennings Randolph water quality account	2.84	5.26	3.49
Patuxent reservoirs	0.00	1.71	1.64
Occoquan Reservoir	1.15	1.15	2.44
Savage Reservoir	0.60	0.62	0.65
Loudoun Water Quarry A	0.33	0.33	0.97
Loudoun Water/Luck Stone Quarries B-C	0.00	0.00	0.00
Vulcan Quarry	0.00	0.00	0.00
Travilah Quarry	0.00	0.00	0.00
Beaverdam Reservoir	0.00	0.00	0.00
Little Seneca Reservoir and Jennings Randolph water supply account, combined	2.49	2.87	3.31
Patuxent, Occoquan, Little Seneca, and Jennings Randolph water supply, combined	6.08	6.09	9.25
Loudoun Water Quarry A and B-C, Vulcan, Travilah, Beaverdam, Patuxent, Occoquan, Little Seneca reservoirs and Jennings Randolph water supply, combined	6.81	6.82	10.26
Miscellaneous			
Number of simulation years	84	1	1
WMA average annual unrestricted demand without climate change, MGD	545		
WMA average July unrestricted demand without climate change, MGD	642		
WMA average annual unrestricted demand, MGD	549		
WMA average July unrestricted demand, MGD	666		
Minimum average flow			
Minimum average natural flow late summer, MGD	609	661	609
Minimum average natural flow fall, MGD	528	528	3,604
Minimum average late summer flow downstream of intakes, MGD	288	369	288
Minimum average fall flow downstream of intakes, MGD	242	242	3,259
System mass balance, MGD	0	0	0
Number of years where reservoirs refill to 90 percent full by June 1 (percent)			
Little Seneca Reservoir	83 (98)	1	1
Jennings Randolph water supply account	84 (100)	1	1
Jennings Randolph water quality account	84 (100)	1	1
Patuxent Reservoir	70 (83)	1	0
Occoquan Reservoir	84 (100)	1	1
Savage Reservoir	82 (98)	1	1

TABLE C-1: 2040 LUCK 1

Historical period for simulation of variability:	1930-2013	1930	1966
Reliability, Vulnerability, Resiliency			
Percentage with no Potomac deficits	99.98%	0.00%	0.00%
Maximum number of days in a row of Potomac deficits	-	-	-
Number of days in which Potomac deficits must be allocated	0	-	-
Maximum amount of deficit allocated in a single day, MGD	(0.0)	-	-
Total amount of deficit allocated, full simulation period, MG	(0.0)	-	-
Number of Patuxent water supply shortfalls over simulation period	9	-	-
Number of Occoquan water supply shortfalls over simulation period	0	-	-
Number of days in which Patuxent plant production is less than 30 MGD	3,962	185	355
Percentage of years with restrictions (Percentage of days for 1930 and 1966)			
Voluntary restrictions	3.61%	37.08%	17.32%
Emergency restrictions	0.00%	0.00%	0.00%
Minimum reservoir storage, BG			
Little Seneca Reservoir	1.01	1.03	1.36
Jennings Randolph water supply account	3.66	3.95	3.92
Jennings Randolph water quality account	2.84	5.26	3.48
Patuxent Reservoir	0.00	1.67	1.64
Occoquan Reservoir	1.24	1.25	2.03
Savage Reservoir	0.62	0.65	0.66
Loudoun Water Quarry A	0.33	0.33	0.97
Loudoun Water/Luck Stone Quarries B-C	0.32	0.38	1.06
Vulcan Quarry	0.00	0.00	0.00
Travilah Quarry	0.00	0.00	0.00
Beaverdam Reservoir	0.00	0.00	0.00
Little Seneca Reservoir and Jennings Randolph water supply account, combined	4.7	4.97	5.27
Patuxent, Occoquan, Little Seneca, and Jennings Randolph water supply, combined	8.2	8.26	10.80
Loudoun Water Quarry A and B-C, Vulcan, Travilah, Beaver Dam, Patuxent, Occoquan, Little Seneca reservoirs and Jennings Randolph water supply, combined	9.6	9.60	12.96
Miscellaneous			
Number of simulation years	84	1	1
WMA average annual unrestricted demand without climate change, MGD	545		
WMA average July unrestricted demand without climate change, MGD	642		
WMA average annual unrestricted demand, MGD	549		
WMA average July unrestricted demand, MGD	666		
Minimum average flow			
Minimum average natural flow late summer, MGD	609	661	609
Minimum average natural flow fall, MGD	528	528	3,604
Minimum average late summer flow downstream of intakes, MGD	283	366	283
Minimum average fall flow downstream of intakes, MGD	244	244	3,258
System mass balance, MGD	0	0	0
Number of years where reservoirs refill to 90 percent full by June 1 (percent probability)			
Little Seneca Reservoir	83 (99)	1	1
Jennings Randolph water supply account	84 (100)	1	1
Jennings Randolph water quality account	84 (100)	1	1
Patuxent Reservoir	70 (83)	1	0
Occoquan Reservoir	84 (100)	1	1
Savage Reservoir	82 (98)	1	1

TABLE C-2: 2040 TRAVILAH

Historical period for simulation of variability:	1930-2013	1930	1966
Reliability, Vulnerability, Resiliency			
Percentage with no Potomac deficits	100.00%	0.00%	0.00%
Maximum number of days in a row of Potomac deficits	-	-	-
Number of days in which Potomac deficits must be allocated	-	-	-
Maximum amount of deficit allocated in a single day, MGD	-	-	-
Total amount of deficit allocated, full simulation period, MG	-	-	-
Number of Patuxent water supply shortfalls over simulation period	-	-	-
Number of Occoquan water supply shortfalls over simulation period	-	-	-
Number of days in which Patuxent plant production is less than 30 MGD	3,767	166	224
Percentage of years with restrictions (Percentage of days for 1930 and 1966)			
Voluntary restrictions	0.20%	0.00%	0.16%
Emergency restrictions	0.00%	0.00%	0.00%
Minimum reservoir storage, BG			
Little Seneca Reservoir	2.62	3.17	2.62
Jennings Randolph water supply account	7.66	8.20	7.68
Jennings Randolph water quality account	2.84	5.26	3.53
Patuxent reservoirs	0.85	0.90	1.64
Occoquan Reservoir	2.17	2.31	2.75
Savage Reservoir	0.62	0.65	0.66
Loudoun Water Quarry A	0.32	0.32	0.96
Loudoun Water/Luck Stone Quarries B-C	0.00	0.00	0.00
Vulcan Quarry	0.00	0.00	0.00
Travilah Quarry	6.95	7.36	7.00
Beaverdam Reservoir	0.00	0.00	0.00
Little Seneca Reservoir and Jennings Randolph water supply account, combined	10.30	11.38	10.30
Patuxent, Occoquan, Little Seneca, and Jennings Randolph water supply, combined	14.82	14.86	15.90
Loudoun Water Quarry A and B-C, Vulcan, Travilah, Beaverdam, Patuxent, Occoquan, Little Seneca reservoirs and Jennings Randolph water supply, combined	23.04	23.20	23.90
Miscellaneous			
Number of simulation years	84	1	1
WMA average annual unrestricted demand without climate change, MGD	545		
WMA average July unrestricted demand without climate change, MGD	642		
WMA average annual unrestricted demand, MGD	549		
WMA average July unrestricted demand, MGD	666		
Minimum average flow			
Minimum average natural flow late summer, MGD	609	661	609
Minimum average natural flow fall, MGD	528	528	3,604
Minimum average late summer flow downstream of intakes, MGD	221	301	221
Minimum average fall flow downstream of intakes, MGD	184	184	3,259
System mass balance, MGD	0	0	0
Number of years where reservoirs refill to 90 percent full by June 1 (percent)			
Little Seneca Reservoir	84 (100)	1	1
Jennings Randolph water supply account	84 (100)	1	1
Jennings Randolph water quality account	84 (100)	1	1
Patuxent Reservoir	70 (83)	1	0
Occoquan Reservoir	84 (100)	1	1
Savage Reservoir	82 (98)	1	1

TABLE C-3: 2040 VULCAN 1

Historical period for simulation of variability:	1930-2013	1930	1966
Reliability, Vulnerability, Resiliency			
Percentage with no Potomac deficits	100.00%	0.00%	0.00%
Maximum number of days in a row of Potomac deficits	-	-	-
Number of days in which Potomac deficits must be allocated	-	-	-
Maximum amount of deficit allocated in a single day, MGD	-	-	-
Total amount of deficit allocated, full simulation period, MG	-	-	-
Number of Patuxent water supply shortfalls over simulation period	9	-	-
Number of Occoquan water supply shortfalls over simulation period	0	0	-
Number of days in which Patuxent plant production is less than 30 MGD	3,964	180	356
Percentage of years with restrictions (Percentage of days for 1930 and 1966)			
Voluntary restrictions	4.18%	37.73%	21.80%
Emergency restrictions	0.00%	0.00%	0.00%
Minimum reservoir storage, BG			
Little Seneca Reservoir	0.88	0.90	1.23
Jennings Randolph water supply account	2.99	3.50	3.21
Jennings Randolph water quality account	2.84	5.26	3.50
Patuxent reservoirs	0.00	1.69	1.64
Occoquan Reservoir	0.93	0.98	1.97
Savage Reservoir	0.62	0.64	0.65
Loudoun Water Quarry A	0.33	0.33	0.97
Loudoun Water/Luck Stone Quarries B-C	0.00	0.00	0.00
Vulcan Quarry	0.10	0.11	0.11
Travilah Quarry	0.00	0.00	0.00
Beaverdam Reservoir	0.00	0.00	0.00
Little Seneca Reservoir and Jennings Randolph water supply account, combined	3.9	4.40	4.44
Patuxent, Occoquan, Little Seneca, and Jennings Randolph water supply, combined	7.6	7.67	9.91
Loudoun Water Quarry A and B-C, Vulcan, Travilah, Beaverdam, Patuxent, Occoquan, Little Seneca reservoirs and Jennings Randolph water supply, combined	8.3	8.31	10.92
Miscellaneous			
Number of simulation years	84	1	1
WMA average annual unrestricted demand without climate change, MGD	545		
WMA average July unrestricted demand without climate change, MGD	642		
WMA average annual unrestricted demand, MGD	549		
WMA average July unrestricted demand, MGD	666		
Minimum average flow			
Minimum average natural flow late summer, MGD	609	661	609
Minimum average natural flow fall, MGD	528	528	3,604
Minimum average late summer flow downstream of intakes, MGD	289	371	289
Minimum average fall flow downstream of intakes, MGD	241	241	3,266
System mass balance, MGD	0	0	0
Number of years where reservoirs refill to 90 percent full by June 1 (percent)			
Little Seneca Reservoir	83 (99)	1	1
Jennings Randolph water supply account	84 (100)	1	1
Jennings Randolph water quality account	84 (100)	1	1
Patuxent Reservoir	70 (83)	1	0
Occoquan Reservoir	84 (100)	1	1
Savage Reservoir	82 (98)	1	1

TABLE C-4: RO PLANT

Historical period for simulation of variability:	1930-2013	1930	1966
Reliability, Vulnerability, Resiliency			
Percentage with no Potomac deficits	100.00%	0.00%	0.00%
Maximum number of days in a row of Potomac deficits	-	-	-
Number of days in which Potomac deficits must be allocated	-	-	-
Maximum amount of deficit allocated in a single day, MGD	-	-	-
Total amount of deficit allocated, full simulation period, MG	-	-	-
Number of Patuxent water supply shortfalls over simulation period	9	-	-
Number of Occoquan water supply shortfalls over simulation period	75	45	1
Number of days in which Patuxent plant production is less than 30 MGD	3,656	140	244
Percentage of years with restrictions (Percentage of days for 1930 and 1966)			
Voluntary restrictions	4.25%	38.59%	16.94%
Emergency restrictions	0.00%	0.00%	0.00%
Minimum reservoir storage, BG			
Little Seneca Reservoir	1.18	1.63	1.18
Jennings Randolph water supply account	4.56	5.73	4.56
Jennings Randolph water quality account	2.84	5.26	3.49
Patuxent reservoirs	0.00	1.68	1.64
Occoquan Reservoir	2.17	3.65	2.58
Savage Reservoir	0.62	0.65	0.66
Loudoun Water Quarry A	0.31	0.31	0.97
Loudoun Water/Luck Stone Quarries B-C	0.00	0.00	0.00
Vulcan Quarry	0.00	0.00	0.00
Travilah Quarry	0.00	0.00	0.00
Beaverdam Reservoir	0.00	0.00	0.00
Little Seneca Reservoir and Jennings Randolph water supply account, combined	5.7	7.36	5.74
Patuxent, Occoquan, Little Seneca, and Jennings Randolph water supply, combined	11.7	13.46	11.79
Loudoun Water Quarry A and B-C, Vulcan, Travilah, Beaverdam, Patuxent, Occoquan, Little Seneca reservoirs and Jennings Randolph water supply, combined	12.7	14.04	12.81
Miscellaneous			
Number of simulation years	84	1	1
WMA average annual unrestricted demand without climate change, MGD	545		
WMA average July unrestricted demand without climate change, MGD	642		
WMA average annual unrestricted demand, MGD	549		
WMA average July unrestricted demand, MGD	666		
Minimum average flow			
Minimum average natural flow late summer, MGD	609	661	609
Minimum average natural flow fall, MGD	528	528	3,604
Minimum average late summer flow downstream of intakes, MGD	285	364	285
Minimum average fall flow downstream of intakes, MGD	231	231	3,276
System mass balance, MGD	0	0	0
Number of years where reservoirs refill to 90 percent full by June 1 (percent)			
Little Seneca Reservoir	83 (99)	1	1
Jennings Randolph water supply account	84 (100)	1	1
Jennings Randolph water quality account	84 (100)	1	1
Patuxent Reservoir	70 (83)	1	0
Occoquan Reservoir	84 (100)	1	1
Savage Reservoir	82 (98)	1	1

TABLE C-5: 2040 COOPERATIVE USE OF QUARRY A

Historical period for simulation of variability:	1930-2013	1930	1966
Reliability, Vulnerability, Resiliency			
Percentage with no Potomac deficits	99.99%	0.00%	0.00%
Maximum number of days in a row of Potomac deficits	-	-	-
Number of days in which Potomac deficits must be allocated	0	-	-
Maximum amount of deficit allocated in a single day, MGD	(0.1)	-	-
Total amount of deficit allocated, full simulation period, MG	(0.1)	-	-
Number of Patuxent water supply shortfalls over simulation period	8	-	-
Number of Occoquan water supply shortfalls over simulation period	0	0	-
Number of days in which Patuxent plant production is less than 30 MGD	4,030	186	356
Percentage of years with restrictions (Percentage of days for 1930 and 1966)			
Voluntary restrictions	3.92%	38.16%	25.33%
Emergency restrictions	0.01%	0.12%	0.00%
Minimum reservoir storage, BG			
Little Seneca Reservoir	0.74	0.78	1.08
Jennings Randolph water supply account	2.39	2.90	2.74
Jennings Randolph water quality account	2.84	5.26	3.48
Patuxent reservoirs	0.00	1.69	1.64
Occoquan Reservoir	0.65	0.65	2.06
Savage Reservoir	0.61	0.64	0.65
Loudoun Water Quarry A	0.63	0.63	0.86
Loudoun Water/Luck Stone Quarry B-C	0.00	0.00	0.00
Vulcan Quarry	0.00	0.00	0.00
Travilah Quarry	0.00	0.00	0.00
Beaverdam Reservoir	0.00	0.00	0.00
Little Seneca Reservoir and Jennings Randolph water supply account, combined	3.18	3.68	3.83
Patuxent, Occoquan, Little Seneca, and Jennings Randolph water supply, combined	6.38	6.41	9.39
Loudoun Water Quarry A and B-C, Vulcan, Travilah, Beaver Dam, Patuxent, Occoquan, Little Seneca reservoirs and Jennings Randolph water supply, combined	7.60	7.64	10.27
Miscellaneous			
Number of simulation years	84	1	1
WMA average annual unrestricted demand without climate change, MGD	545		
WMA average July unrestricted demand without climate change, MGD	642		
WMA average annual unrestricted demand, MGD	549		
WMA average July unrestricted demand, MGD	666		
Minimum average flow			
Minimum average natural flow late summer, MGD	609	661	609
Minimum average natural flow fall, MGD	528	528	3,604
Minimum average late summer flow downstream of intakes, MGD	284	366	284
Minimum average fall flow downstream of intakes, MGD	235	235	3,257
System mass balance, MGD	0	0	0
Number of years where reservoirs refill to 90 percent full by June 1 (percent)			
Little Seneca Reservoir	82.8 (99)	1	1
Jennings Randolph water supply account	84 (100)	1	1
Jennings Randolph water quality account	84 (100)	1	1
Patuxent Reservoir	70 (83)	1	0
Occoquan Reservoir	84 (100)	1	1
Savage Reservoir	82 (98)	1	1

TABLE C-6: 2040 BEAVERDAM

Historical period for simulation of variability:	1930-2013	1930	1966
Reliability, Vulnerability, Resiliency			
Percentage with no Potomac deficits	99.99%	0.00%	0.00%
Maximum number of days in a row of Potomac deficits	-	-	-
Number of days in which Potomac deficits must be allocated	0	-	-
Maximum amount of deficit allocated in a single day, MGD	(0.1)	-	-
Total amount of deficit allocated, full simulation period, MG	(0.1)	-	-
Number of Patuxent water supply shortfalls over simulation period	9	-	-
Number of Occoquan water supply shortfalls over simulation period	-	-	-
Number of days in which Patuxent plant production is less than 30 MGD	3,776	126	355
Percentage of years with restrictions (Percentage of days for 1930 and 1966)			
Voluntary restrictions	3.81%	37.88%	21.52%
Emergency restrictions	0.00%	0.00%	0.00%
Minimum reservoir storage, BG			
Little Seneca Reservoir	0.84	0.85	1.23
Jennings Randolph water supply account	2.92	3.26	3.24
Jennings Randolph water quality account	2.84	5.26	3.49
Patuxent reservoirs	0.00	1.67	1.64
Occoquan Reservoir	1.03	1.03	2.19
Savage Reservoir	0.62	0.64	0.65
Loudoun Water Quarry A	0.32	0.32	0.97
Loudoun Water/Luck Stone Quarries B-C	0.00	0.00	0.00
Vulcan Quarry	0.00	0.00	0.00
Travilah Quarry	0.00	0.00	0.00
Beaverdam Reservoir	0.24	0.24	0.41
Little Seneca Reservoir and Jennings Randolph water supply account, combined	3.8	4.11	4.48
Patuxent, Occoquan, Little Seneca, and Jennings Randolph water supply, combined	7.2	7.17	10.16
Loudoun Water Quarry A and B-C, Vulcan, Travilah, Beaverdam, Patuxent, Occoquan, Little Seneca reservoirs and Jennings Randolph water supply, combined	8.1	8.15	11.58
Miscellaneous			
Number of simulation years	84	1	1
WMA average annual unrestricted demand without climate change, MGD	545		
WMA average July unrestricted demand without climate change, MGD	642		
WMA average annual unrestricted demand, MGD	549		
WMA average July unrestricted demand, MGD	666		
Minimum average flow			
Minimum average natural flow late summer, MGD	609	661	609
Minimum average natural flow fall, MGD	528	528	3,604
Minimum average late summer flow downstream of intakes, MGD	285	365	285
Minimum average fall flow downstream of intakes, MGD	241	241	3,264
System mass balance, MGD	0	0	0
Number of years where reservoirs refill to 90 percent full by June 1 (percent)			
Little Seneca Reservoir	83 (100)	1	1
Jennings Randolph water supply account	84 (100)	1	1
Jennings Randolph water quality account	84 (100)	1	1
Patuxent Reservoir	70 (83)	1	0
Occoquan Reservoir	84 (100)	1	1
Savage Reservoir	82 (98)	1	1

TABLE C-7: 2040 IMPROVED FORECASTS

Historical period for simulation of variability:	1930-2013	1930	1966
Reliability, Vulnerability, Resiliency			
Percentage with no Potomac deficits	100.00%	0.00%	0.00%
Maximum number of days in a row of Potomac deficits	-	-	-
Number of days in which Potomac deficits must be allocated	-	-	-
Maximum amount of deficit allocated in a single day, MGD	-	-	-
Total amount of deficit allocated, full simulation period, MG	-	-	-
Number of Patuxent water supply shortfalls over simulation period	8	-	-
Number of Occoquan water supply shortfalls over simulation period	-	-	-
Number of days in which Patuxent plant production is less than 30 MGD	3,911	181	355
Percentage of years with restrictions (Percentage of days for 1930 and 1966)			
Voluntary restrictions	3.60%	37.86%	16.25%
Emergency restrictions	0.00%	0.00%	0.00%
Minimum reservoir storage, BG			
Little Seneca Reservoir	0.84	0.90	1.10
Jennings Randolph water supply account	3.39	3.44	4.50
Jennings Randolph water quality account	2.84	5.26	3.49
Patuxent reservoirs	0.00	1.67	1.64
Occoquan Reservoir	1.23	1.23	2.45
Savage Reservoir	0.62	0.65	0.65
Loudoun Water Quarry A	0.29	0.29	0.98
Loudoun Water/Luck Stone Quarries B-C	0.00	0.00	0.00
Vulcan Quarry	0.00	0.00	0.00
Travilah Quarry	0.00	0.00	0.00
Beaverdam Reservoir	0.00	0.00	0.00
Little Seneca Reservoir and Jennings Randolph water supply account, combined	4.2	4.34	5.60
Patuxent, Occoquan, Little Seneca, and Jennings Randolph water supply, combined	7.6	7.62	11.53
Loudoun Water Quarry A and B-C, Vulcan, Travilah, Beaverdam, Patuxent, Occoquan, Little Seneca reservoirs and Jennings Randolph water supply, combined	8.3	8.30	12.64
Miscellaneous			
Number of simulation years	84	1	1
WMA average annual unrestricted demand without climate change, MGD	545		
WMA average July unrestricted demand without climate change, MGD	642		
WMA average annual unrestricted demand, MGD	549		
WMA average July unrestricted demand, MGD	666		
Minimum average flow			
Minimum average natural flow late summer, MGD	609	661	609
Minimum average natural flow fall, MGD	528	528	3,604
Minimum average late summer flow downstream of intakes, MGD	277	362	277
Minimum average fall flow downstream of intakes, MGD	235	235	3,256
System mass balance, MGD	0	0	0
Number of years where reservoirs refill to 90 percent full by June 1 (percent)			
Little Seneca Reservoir	83 (99)	1	1
Jennings Randolph water supply account	84 (100)	1	1
Jennings Randolph water quality account	84 (100)	1	1
Patuxent Reservoir	70 (83)	1	0
Occoquan Reservoir	84 (100)	1	1
Savage Reservoir	82 (98)	1	1

TABLE C-8: 2040 JRR WATER QUALITY STORAGE

Historical period for simulation of variability:	1930-2013	1930	1966
Reliability, Vulnerability, Resiliency			
Percentage with no Potomac deficits	100.0%	0.00%	0.00%
Maximum number of days in a row of Potomac deficits	-	-	-
Number of days in which Potomac deficits must be allocated	-	-	-
Maximum amount of deficit allocated in a single day, MGD	-	-	-
Total amount of deficit allocated full simulation period, MG	-	-	-
Number of Patuxent water supply shortfalls over simulation period	9	-	-
Number of Occoquan water supply shortfalls over simulation period	0	0	-
Number of days in which Patuxent plant production is less than 30 MGD	3,923	186	356
Percentage of years with restrictions (Percentage of days for 1930 and 1966)			
Voluntary restrictions	4.42%	38.68%	22.59%
Emergency restrictions	0.00%	0.12%	0.00%
Minimum reservoir storage, BG			
Little Seneca Reservoir	0.63	0.66	0.99
Jennings Randolph water supply account	2.53	2.75	2.70
Jennings Randolph water quality account	2.55	4.12	3.49
Patuxent Reservoir	0.00	1.71	1.64
Occoquan Reservoir	1.39	1.40	2.45
Savage Reservoir	0.56	0.57	0.65
Loudoun Water Quarry A	0.36	0.36	0.97
Loudoun Water/Luck Stone Quarry B-C	0.00	0.00	0.00
Vulcan Quarry	0.00	0.00	0.00
Travilah Quarry	0.00	0.00	0.00
Beaverdam Reservoir	0.00	0.00	0.00
Little Seneca Reservoir and Jennings Randolph water supply account, combined	3.3	3.45	3.70
Patuxent, Occoquan, Little Seneca and Jennings Randolph water supply, combined	7.2	7.18	9.77
Loudoun Water Quarry A and B-C, Vulcan, Travilah, Beaver Dam, Patuxent, Occoquan, Little Seneca reservoirs and Jennings Randolph water supply, combined	8.0	7.98	10.80
Miscellaneous			
Number of simulation years	84	1	1
WMA average annual unrestricted demand without climate change, MGD	545		
WMA average July unrestricted demand without climate change, MGD	642		
WMA average annual unrestricted demand, MGD	544		
WMA average July unrestricted demand, MGD	666		
Minimum average flow			
Minimum average natural flow late summer, MGD	609	661	609
Minimum average natural flow fall, MGD	528	528	3,604
Minimum average late summer flow downstream of intakes, MGD	288	369	288
Minimum average fall flow downstream of intakes, MGD	250	250	3,257
System mass balance, MGD	0	0	0
Number of years where reservoirs refill to 90 percent full by June 1 (percenty)			
Little Seneca Reservoir	82.8 (99)	1	1
Jennings Randolph water supply account	84 (100)	1	1
Jennings Randolph water quality account	84 (100)	1	1
Patuxent Reservoir	70 (83)	1	0
Occoquan Reservoir	84 (100)	1	1
Savage Reservoir	82 (98)	1	1

Table C-9: CU Reduction

Historical period for simulation of variability:	1930-2013	1930	1966
Reliability, Vulnerability, Resiliency			
Percentage with no Potomac deficits	99.99%	0.00%	0.00%
Maximum number of days in a row of Potomac deficits	-	-	-
Number of days in which Potomac deficits must be allocated	0	-	-
Maximum amount of deficit allocated in a single day, MGD	(0.0)	-	-
Total amount of deficit allocated, full simulation period, MG	(0.0)	-	-
Number of Patuxent water supply shortfalls over simulation period	8	-	-
Number of Occoquan water supply shortfalls over simulation period	-	-	-
Number of days in which Patuxent plant production is less than 30 MGD	3,999	190	355
Percentage of years with restrictions (Percentage of days for 1930 and 1966)			
Voluntary restrictions	3.73%	38.11%	23.41%
Emergency restrictions	0.00%	0.00%	0.00%
Minimum reservoir storage, BG			
Little Seneca Reservoir	0.84	0.89	1.12
Jennings Randolph water supply account	2.72	3.31	2.99
Jennings Randolph water quality account	2.84	5.26	3.50
Patuxent reservoirs	0.00	1.70	1.64
Occoquan Reservoir	1.38	1.38	2.43
Savage Reservoir	0.62	0.64	0.65
Loudoun Water Quarry A	0.43	0.43	0.98
Loudoun Water/Luck Stone Quarries B-C	0.00	0.00	0.00
Vulcan Quarry	0.00	0.00	0.00
Travilah Quarry	0.00	0.00	0.00
Beaverdam Reservoir	0.00	0.00	0.00
Little Seneca Reservoir and Jennings Randolph water supply account, combined	3.6	4.20	4.11
Patuxent, Occoquan, Little Seneca, and Jennings Randolph water supply, combined	7.6	7.66	10.03
Loudoun Water Quarry A and B-C, Vulcan, Travilah, Beaverdam, Patuxent, Occoquan, Little Seneca reservoirs and Jennings Randolph water supply, combined	8.5	8.55	11.05
Miscellaneous			
Number of simulation years	84	1	1
WMA average annual unrestricted demand without climate change, MGD	545		
WMA average July unrestricted demand without climate change, MGD	642		
WMA average annual unrestricted demand, MGD	544		
WMA average July unrestricted demand, MGD	666		
Minimum average flow			
Minimum average natural flow late summer, MGD	623	675	623
Minimum average natural flow fall, MGD	538	538	3,613
Minimum average late summer flow downstream of intakes, MGD	290	372	290
Minimum average fall flow downstream of intakes, MGD	243	243	3,268
System mass balance, MGD	0	0	0
Number of years where reservoirs refill to 90 percent full by June 1 (percent)			
Little Seneca Reservoir	83 (99)	1	1
Jennings Randolph water supply account	84 (100)	1	1
Jennings Randolph water quality account	84 (100)	1	1
Patuxent Reservoir	70 (83)	1	0
Occoquan Reservoir	84 (100)	1	1
Savage Reservoir	82 (98)	1	1

TABLE C-10: 2040 MORE WATER USE RESTRICTIONS

Historical period for simulation of variability:	1930-2013	1930	1966
Reliability, Vulnerability, Resiliency			
Percentage with no Potomac deficits	100.00%	0.00%	0.00%
Maximum number of days in a row of Potomac deficits	-	-	-
Number of days in which Potomac deficits must be allocated	-	-	-
Maximum amount of deficit allocated in a single day, MGD	-	-	-
Total amount of deficit allocated, full simulation period, MG	-	-	-
Number of Patuxent water supply shortfalls over simulation period	7	-	-
Number of Occoquan water supply shortfalls over simulation period	-	-	-
Number of days in which Patuxent plant production is less than 30 MGD	4,201	194	356
Percentage of years with restrictions (Percentage of days for 1930 and 1966)			
Voluntary restrictions	8.23%	9.92%	31.66%
Mandatory restrictions	3.56%	31.60%	7.73%
Emergency restrictions	0.00%	0.00%	0.00%
Minimum reservoir storage, BG			
Little Seneca Reservoir	0.99	1.05	1.18
Jennings Randolph water supply account	3.07	3.89	3.15
Jennings Randolph water quality account	2.84	5.26	3.49
Patuxent reservoirs	0.00	1.72	1.64
Occoquan Reservoir	1.83	1.88	2.61
Savage Reservoir	0.61	0.63	0.65
Loudoun Water Quarry A	0.46	0.46	0.99
Loudoun Water/Luck Stone Quarries B-C	0.00	0.00	0.00
Vulcan Quarry	0.00	0.00	0.00
Travilah Quarry	0.00	0.00	0.00
Beaverdam Reservoir	0.00	0.00	0.00
Little Seneca Reservoir and Jennings Randolph water supply account, combined	4.1	4.94	4.33
Patuxent, Occoquan, Little Seneca, and Jennings Randolph water supply, combined	8.9	8.93	10.44
Loudoun Water Quarry A and B-C, Vulcan, Travilah, Beaverdam, Patuxent, Occoquan, Little Seneca reservoirs and Jennings Randolph water supply, combined	9.7	9.78	11.46
Miscellaneous			
Number of simulation years	84	1	1
WMA average annual unrestricted demand without climate change, MGD	545		
WMA average July unrestricted demand without climate change, MGD	642		
WMA average annual unrestricted demand, MGD	549		
WMA average July unrestricted demand, MGD	666		
Minimum average flow			
Minimum average natural flow late summer, MGD	609	661	609
Minimum average natural flow fall, MGD	528	528	3,604
Minimum average late summer flow downstream of intakes, MGD	287	371	287
Minimum average fall flow downstream of intakes, MGD	253	253	3,284
System mass balance, MGD	0	0	0
Number of years where reservoirs refill to 90 percent full by June 1 (percent)			
Little Seneca Reservoir	83 (99)	1	1
Jennings Randolph water supply account	84 (100)	1	1
Jennings Randolph water quality account	84 (100)	1	1
Patuxent Reservoir	70 (83)	1	0
Occoquan Reservoir	84 (100)	1	1
Savage Reservoir	82 (98)	1	1

TABLE C-11: 2085 BASELINE

Historical period for simulation of variability:	1929-2013	1930	1966
Reliability, Vulnerability, Resiliency			
Percentage with no Potomac deficits	99.00%	0.93%	0.00%
Maximum number of days in a row of Potomac deficits	1	1	-
Number of days in which Potomac deficits must be allocated	3	3	-
Maximum amount of deficit allocated in a single day, MGD	(32.6)	(33)	-
Total amount of deficit allocated full simulation period, MG	(95.4)	(95)	-
Number of Patuxent water supply shortfalls over simulation period	-	-	-
Number of Occoquan water supply shortfalls over simulation period	43	43	-
Number of days in which Patuxent plant production is less than 30 MGD	4,390	146	351
Percentage of years with restrictions (Percentage of days for 1930 and 1966)			
Voluntary restrictions	6.17%	19.20%	29.48%
Emergency restrictions	2.37%	21.48%	0.00%
Minimum reservoir storage, BG			
Little Seneca Reservoir	0.00	0.00	0.47
Jennings Randolph water supply account	0.01	0.01	2.34
Jennings Randolph water quality account	0.02	0.24	3.02
Patuxent reservoirs	0.05	0.96	1.61
Occoquan Reservoir	0.00	0.00	0.73
Savage Reservoir	0.01	0.01	0.64
Loudoun Water Quarry A	0.27	0.27	0.76
Loudoun Water/Luck Stone Quarries B-C	0.00	0.00	0.39
Vulcan Quarry	0.10	0.10	0.10
Travilah Quarry	0.00	0.00	0.00
Beaverdam Reservoir	0.00	0.00	0.15
Little Seneca Reservoir and Jennings Randolph water supply account, combined	0.0	0.01	2.89
Patuxent, Occoquan, Little Seneca, and Jennings Randolph water supply, combined	1.4	1.43	7.66
Loudoun Water Quarry A and B-C, Vulcan, Travilah, Beaverdam, Patuxent, Occoquan, Little Seneca reservoirs and Jennings Randolph water supply, combined	2.1	2.11	9.19
Miscellaneous			
Number of simulation years	84	1	1
WMA average annual unrestricted demand without climate change, MGD	665		
WMA average July unrestricted demand without climate change, MGD	774		
WMA average annual unrestricted demand, MGD	663		
WMA average July unrestricted demand, MGD	810		
Minimum average flow			
Minimum average natural flow late summer, MGD	577	631	577
Minimum average natural flow fall, MGD	509	509	3,629
Minimum average late summer flow downstream of intakes, MGD	252	329	252
Minimum average fall flow downstream of intakes, MGD	209	209	3,152
System mass balance, MGD	0	0	0
Number of years where reservoirs refill to 90 percent full by June 1 (percent probability)			
Little Seneca Reservoir	82 (98)	1	1
Jennings Randolph water supply account	84 (100)	1	1
Jennings Randolph water quality account	84 (100)	1	1
Patuxent Reservoir	72 (86)	1	0
Occoquan Reservoir	84 (100)	1	1
Savage Reservoir	81 (96)	0	1

TABLE C-12: 2085 LUCK 2

Historical period for simulation of variability:	1929-2013	1930	1966
Reliability, Vulnerability, Resiliency			
Percentage with no Potomac deficits	99.07%	0.24%	0.00%
Maximum number of days in a row of Potomac deficits	0	0	-
Number of days in which Potomac deficits must be allocated	1	1	-
Maximum amount of deficit allocated in a single day, MGD	(16.3)	(16)	-
Total amount of deficit allocated full simulation period, MG	(18.6)	(19)	-
Number of Patuxent water supply shortfalls over simulation period	-	-	-
Number of Occoquan water supply shortfalls over simulation period	25	23	1
Number of days in which Patuxent plant production is less than 30 MGD	4,201	142	355
Percentage of years with restrictions (Percentage of days for 1930 and 1966)			
Voluntary restrictions	5.93%	28.88%	24.95%
Mandatory restrictions	1.29%	10.95%	0.00%
Emergency restrictions	0.00%	0.00%	0.00%
Minimum reservoir storage, BG			
Little Seneca Reservoir	0.04	0.04	0.80
Jennings Randolph water supply account	0.49	0.49	2.56
Jennings Randolph water quality account	0.46	0.91	2.76
Patuxent reservoirs	0.05	1.28	1.48
Occoquan Reservoir	0.00	0.00	0.93
Savage Reservoir	0.08	0.08	0.65
Loudoun Water Quarry A	0.18	0.18	0.54
Loudoun Water/Luck Stone Quarries B-C	0.13	0.13	1.41
Vulcan Quarry	0.10	0.10	0.10
Travilah Quarry	0.00	0.00	0.00
Beaverdam Reservoir	0.03	0.03	0.25
Little Seneca Reservoir and Jennings Randolph water supply account, combined	0.5	0.53	3.69
Patuxent, Occoquan, Little Seneca, and Jennings Randolph water supply, combined	2.4	2.38	8.64
Loudoun Water Quarry A and B-C, Vulcan, Travilah, Beaverdam, Patuxent, Occoquan, Little Seneca reservoirs and Jennings Randolph water supply, combined	3.4	3.37	11.00
Miscellaneous			
Number of simulation years	84	1	1
WMA average annual unrestricted demand without climate change, MGD	665		
WMA average July unrestricted demand without climate change, MGD	774		
WMA average annual unrestricted demand, MGD	663		
WMA average July unrestricted demand, MGD	809		
Minimum average flow			
Minimum average natural flow late summer, MGD	577	631	577
Minimum average natural flow fall, MGD	509	509	3,629
Minimum average late summer flow downstream of intakes, MGD	252	329	252
Minimum average fall flow downstream of intakes, MGD	224	224	3,152
System mass balance, MGD	0	0	0
Number of years where reservoirs refill to 90 percent full by June 1 (percent probability)			
Little Seneca Reservoir	82 (98)	1	1
Jennings Randolph water supply account	84 (100)	1	1
Jennings Randolph water quality account	84 (100)	1	1
Patuxent Reservoir	72 (86)	1	0
Occoquan Reservoir	84 (100)	1	1
Savage Reservoir	81 (96)	0	1

Table C-13: 2085 Travilah

Historical period for simulation of variability:	1929-2013	1930	1966
Reliability, Vulnerability, Resiliency			
Percentage with no Potomac deficits	100.00%	0.00%	0.00%
Maximum number of days in a row of Potomac deficits	-	-	-
Number of days in which Potomac deficits must be allocated	-	-	-
Maximum amount of deficit allocated in a single day, MGD	-	-	-
Total amount of deficit allocated full simulation period, MG	-	-	-
Number of Patuxent water supply shortfalls over simulation period	-	-	-
Number of Occoquan water supply shortfalls over simulation period	2	2	0
Number of days in which Patuxent plant production is less than 30 MGD	4,335	172	231
Percentage of years with restrictions (Percentage of days for 1930 and 1966)			
Voluntary restrictions	3.54%	36.73%	10.36%
Mandatory restrictions	0.000%	0.00%	0.00%
Emergency restrictions	0.00%	0.00%	0.00%
Minimum reservoir storage, BG			
Little Seneca Reservoir	1.78	1.97	1.81
Jennings Randolph water supply account	4.61	4.64	4.90
Jennings Randolph water quality account	1.87	4.16	2.64
Patuxent reservoirs	0.90	0.99	1.46
Occoquan Reservoir	0.67	0.68	1.32
Savage Reservoir	0.60	0.62	0.64
Loudoun Water Quarry A	0.63	0.63	0.77
Loudoun Water/Luck Stone Quarries B-C	1.02	1.11	1.08
Vulcan Quarry	0.10	0.10	0.10
Travilah Quarry	2.80	2.80	6.20
Beaverdam Reservoir	0.47	0.50	0.50
Little Seneca Reservoir and Jennings Randolph water supply account, combined	6.4	6.61	6.70
Patuxent, Occoquan, Little Seneca, and Jennings Randolph water supply, combined	8.6	8.57	10.51
Loudoun Water Quarry A and B-C, Vulcan, Travilah, Beaverdam, Patuxent, Occoquan, Little Seneca reservoirs and Jennings Randolph water supply, combined	15.1	15.10	19.12
Miscellaneous			
Number of simulation years	83	1	1
WMA average annual unrestricted demand without climate change, MGD	586	637	632
WMA average July unrestricted demand without climate change, MGD	690	45	44
WMA average annual unrestricted demand, MGD	662		
WMA average July unrestricted demand, MGD	808		
Minimum average flow			
Minimum average natural flow late summer, MGD	1,572	636	572
Minimum average natural flow fall, MGD	1,503	503	3,593
Minimum average late summer flow downstream of intakes, MGD	1,168	259	168
Minimum average fall flow downstream of intakes, MGD	1,125	125	3,146
System mass balance, MGD	0	0	0
Number of years where reservoirs refill to 90 percent full by June 1 (percent probability)			
Little Seneca Reservoir	82 (99)	1	1
Jennings Randolph water supply account	83 (100)	1	1
Jennings Randolph water quality account	83 (100)	1	1
Patuxent Reservoir	71 (86)	1	0
Occoquan Reservoir	83 (100)	1	1
Savage Reservoir	80 (96)	0	1

TABLE C-14: 2085 VULCAN 2

Historical period for simulation of variability:	1929-2013	1930	1966
Reliability, Vulnerability, Resiliency			
Percentage with no Potomac deficits	99.71%	0.06%	0.01%
Maximum number of days in a row of Potomac deficits	-	-	-
Number of days in which Potomac deficits must be allocated	0	0	0
Maximum amount of deficit allocated in a single day, MGD	(2.1)	(2)	(0)
Total amount of deficit allocated full simulation period, MG	(2.2)	(2)	(0)
Number of Patuxent water supply shortfalls over simulation period	-	-	-
Number of Occoquan water supply shortfalls over simulation period	2	2	-
Number of days in which Patuxent plant production is less than 30 MGD	4,299	117	299
Percentage of years with restrictions (Percentage of days for 1930 and 1966)			
Voluntary restrictions	5.29%	39.66%	25.19%
Mandatory restrictions	0.048%	0.39%	0.00%
Emergency restrictions	0.00%	0.00%	0.00%
Minimum reservoir storage, BG			
Little Seneca Reservoir	0.58	0.59	0.99
Jennings Randolph water supply account	1.67	1.67	2.81
Jennings Randolph water quality account	0.97	1.43	3.15
Patuxent reservoirs	0.05	1.38	1.58
Occoquan Reservoir	1.20	1.90	2.63
Savage Reservoir	0.15	0.15	0.65
Loudoun Water Quarry A	0.01	0.01	0.41
Loudoun Water/Luck Stone Quarries B-C	0.49	0.49	0.91
Vulcan Quarry	3.23	5.13	9.94
Travilah Quarry	0.00	0.00	0.00
Beaverdam Reservoir	0.27	0.27	0.41
Little Seneca Reservoir and Jennings Randolph water supply account, combined	2.3	2.26	3.90
Patuxent, Occoquan, Little Seneca, and Jennings Randolph water supply, combined	5.9	5.91	10.39
Loudoun Water Quarry A and B-C, Vulcan, Travilah, Beaverdam, Patuxent, Occoquan, Little Seneca reservoirs and Jennings Randolph water supply, combined	7.6	7.58	12.24
Miscellaneous			
Number of simulation years	84	1	1
WMA average annual unrestricted demand without climate change, MGD	655	637	635
WMA average July unrestricted demand without climate change, MGD	774	45	45
WMA average annual unrestricted demand, MGD	663		
WMA average July unrestricted demand, MGD	809		
Minimum average flow			
Minimum average natural flow late summer, MGD	577	631	577
Minimum average natural flow fall, MGD	509	509	3,629
Minimum average late summer flow downstream of intakes, MGD	262	340	262
Minimum average fall flow downstream of intakes, MGD	234	234	3,192
System mass balance, MGD	0	0	0
Number of years where reservoirs refill to 90 percent full by June 1 (percent probability)			
Little Seneca Reservoir	83 (99)	1	1
Jennings Randolph water supply account	84 (100)	1	1
Jennings Randolph water quality account	84 (100)	1	1
Patuxent Reservoir	72 (86)	1	0
Occoquan Reservoir	80 (96)	1	1
Savage Reservoir	81 (96)	0	1

TABLE C-15: 2085 RO PLANT

Historical period for simulation of variability:	1929-2013	1930	1966
Reliability, Vulnerability, Resiliency			
Percentage with no Potomac deficits	99.23%	0.12%	0.00%
Maximum number of days in a row of Potomac deficits	-	-	-
Number of days in which Potomac deficits must be allocated	1	0	-
Maximum amount of deficit allocated in a single day, MGD	(6.5)	(6)	-
Total amount of deficit allocated full simulation period, MG	(7.5)	(6)	-
Number of Patuxent water supply shortfalls over simulation period	-	-	-
Number of Occoquan water supply shortfalls over simulation period	5	3	1
Number of days in which Patuxent plant production is less than 30 MGD	4,354	124	349
Percentage of years with restrictions (Percentage of days for 1930 and 1966)			
Voluntary restrictions	6.06%	40.47%	27.43%
Mandatory restrictions	0.012%	0.13%	0.00%
Emergency restrictions	0.00%	0.00%	0.00%
Minimum reservoir storage, BG			
Little Seneca Reservoir	0.47	0.50	0.65
Jennings Randolph water supply account	2.01	2.01	2.78
Jennings Randolph water quality account	0.94	1.41	2.98
Patuxent reservoirs	0.05	1.35	1.58
Occoquan Reservoir	1.51	2.23	2.03
Savage Reservoir	0.16	0.16	0.65
Loudoun Water Quarry A	0.48	0.49	0.62
Loudoun Water/Luck Stone Quarries B-C	0.47	0.49	0.58
Vulcan Quarry	0.10	0.10	0.10
Travilah Quarry	0.00	0.00	0.00
Beaverdam Reservoir	0.17	0.18	0.25
Little Seneca Reservoir and Jennings Randolph water supply account, combined	2.5	2.54	3.52
Patuxent, Occoquan, Little Seneca, and Jennings Randolph water supply, combined	7.5	7.49	9.46
Loudoun Water Quarry A and B-C, Vulcan, Travilah, Beaverdam, Patuxent, Occoquan, Little Seneca reservoirs and Jennings Randolph water supply, combined	9.2	9.20	11.01
Miscellaneous			
Number of simulation years	84	1	1
WMA average annual unrestricted demand without climate change, MGD	655	637	635
WMA average July unrestricted demand without climate change, MGD	774	45	44
WMA average annual unrestricted demand, MGD	663		
WMA average July unrestricted demand, MGD	809		
Minimum average flow			
Minimum average natural flow late summer, MGD	577	631	577
Minimum average natural flow fall, MGD	509	509	3,629
Minimum average late summer flow downstream of intakes, MGD	227	310	227
Minimum average fall flow downstream of intakes, MGD	189	189	3,182
System mass balance, MGD	0	0	0
Number of years where reservoirs refill to 90 percent full by June 1 (percent probability)			
Little Seneca Reservoir	83 (99)	1	1
Jennings Randolph water supply account	84 (100)	1	1
Jennings Randolph water quality account	84 (100)	1	1
Patuxent Reservoir	72 (86)	1	0
Occoquan Reservoir	84 (100)	1	1
Savage Reservoir	81 (96)	0	1