Quantitative Evaluation of the Performance of Water Management System in the Washington Metropolitan Area

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Abstract

The water management system for the Washington Metropolitan Area (WMA), like many other public utilities, is reaching its maximum service potential in the face of this rapid growth and climate change. Frequent droughts have not only prompted pricy withdrawals from reserve water supplies more than once, fall of 2010 being the latest case of such water releases, but also have generated varied responses from different local governments that make up the WMA, reflecting lack of cooperation. This also reflects that WMA water supply system is not adequate enough to meet daily demand using only Potomac, Patuxent and Occoquan resources. Prior information about time and volume of releases will not only help in the efficient allocation of water but it will also help in well-informed decision making. Therefore, this paper does the following: 1) Model the demand and supply dynamics for the WMA; 2) Analyze the impact of historical droughts on water availability; and 3) Assesses the performance of the system under various demand scenarios and drought conditions. Finally, the paper concludes that WMA water supply system is susceptible to shortages in future and performance of the system is expected to deteriorate in the coming years with recurrence of historical droughts.

Keywords: *Water management, WMA, Performance Measurement*

1. Introduction

The Washington Metropolitan Area (WMA) is the seventh largest U.S. metropolitan area and is expected to grow by 25% by 2030. The Water Management System for the WMA, like many other public utilities, is reaching its maximum service potential in the face of this rapid residential and commercial growth. Projections place future steady-state consumption needs in excess of 26% over current demand by 2020. For the present, episodic surges in demand, largely due to population and economic growth, have already demonstrated they can exceed current capacity leading to off-strategy spending and inefficient work-arounds. Moreover, climate change is expected to strain the system further by increasing demand and reducing supplies. Frequent droughts have already prompted pricy withdrawals from reserve water supplies of the region and associated water studies confirm that further taxing of reserve supplies is not a viable longer-term strategy.

The objective of this paper is to assess the adequacy of current WMA water supply system to meet the future water demand for the WMA region. This is accomplished by creating a water demand-supply model to assist in water resource planning and decision making for the entire WMA region that spans over 15 counties and 6 county-equivalent cities, plus the District of Columbia. The

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model is developed within a system dynamics framework for the purposes of 1) quantitatively assessing the adequacy of current water resources, available to the region, to meet future water demand, 2) analyzing the impact of historical droughts and low flows on water availability and 3) assessing the performance of the system under various demand scenarios and drought conditions.

The System Dynamic (SD) methodology is used for this research to build and assess quantitative models. The SD methodology stands as a proven approach and tool used in the past both domestically and globally to diagnose similar water systems. SD affords the engineering team the ability to a) isolate key causal relationships between the system elements, and b) graphically represent the constellation of subsystems for lay policy-maker comprehension and consideration. Moreover, system dynamics is a continuous modeling process which allows for an examination of the effects of multi-year droughts on different reservoirs.

This paper is organized as follows: Section (2) articulates the problem context. An overview of the study area and its water resources is provided in section (3). Section (4) covers System Dynamics methodology and previous research. Section (5) builds up the quantitative demand supply model, section (6) assesses the performance of the current water management system and the last section provides conclusions and future research.

2. Problem Context

The Washington metropolitan Area (WMA) is one of the fastest growing regions in US. This growth can be attributed to the strength of the region's economy and high rates of in-migration and international immigration, becoming the seventh largest U.S. metropolitan area. Currently, WMA has a population in excess of five million inhabitants and is expected to grow at the rate of approximately 64,000 persons a year (COG 2008). Historically the WMA has experienced population growth rates higher that the national average. Between 1980 and 1990 the WMA had a population growth rate of 17% compared to the national average of 10% over the same time period (Garling 1998). Population of the Washington metropolitan region is expected to grow by 25% by 2030. To meet the future demands of this growing metropolis, it is expected that nearly 1.5 million housing units and 180 million square meters of commercial or institutional space will need to be replaced or added. (see: http://www.nvta.com, www.demographia.com). Consequently, such high growth will place a tremendous additional burden on WMA's resources, i.e., more water and more energy will be demanded.

Historically, periods of drought place an extra strain on the WMA region's resources. The WMA water supply system has made releases in three drought seasons since completion of the Jennings Randolph Reservoir. In 1999, 2002 and 2010, low precipitation levels resulting in a water supply which proved to be insufficient to fulfill the region's demand projections during the summer months of those years. Episodes like this, prompted authorities to pay premium prices for additional water resources from Jennings Randolph and Little Seneca reservoirs, which are the reserve water supplies for the WMA. These repositories are referred to as the "savings account" for the WMA. The first release, totaling 2.9 billion gallons, was made during the summer of 1999 from the Jennings Randolph Reservoir. The 1999 drought also highlighted the need for coordinated water conservation measures and also highlighted the importance of knowing about the shortfall in advance. It was observed that the water in the Potomac was not sufficient to meet water demands. Thus, prompting releases. Also, Maryland imposed mandatory water restrictions in lieu of the impending drought while Virginia and DC did not impose any such restrictions.

It is apparent from numerous studies (ICPRB) that the WMA is facing problems of an increasing water demand, limited resources and climate change. It is important to understand the limitations of the current system and the periods and frequency of water shortages so that policy makers can plan for better reservoir operations in advance. WMA is already a very vast metropolitan area and with its heterogeneity and diversity it is becoming more difficult for water managers to satisfactorily meet future water demand without causing unpleasant water use restrictions. And since there is no unified authority to manage this region as a one cohesive entity, it poses a huge challenge for policy makers and regional governments to include all stakeholders during strategic and operational decision making in times of crises. Thus, it is important to model the area's supply and demand as a complete entity and to gauge its performance under different demand, drought and low flow scenarios.

3. Overview of the Study Area and its Water Resources

The WMA is comprised of 15 counties, 6 county equivalent cities and the District of Columbia. Figure 1 provides an overview of the study area. Since WMA is comprised of different administrative units, the Metropolitan Washington Council of Governments (MWCOG) was created in 1957 for the purpose of discussing regional issues and to guide the development of the region as a whole. MWCOG, more commonly known as COG, is the regional organization comprised of 21 WMA local governments, members of the Maryland and Virginia state legislatures, the U.S. Senate, and the U.S. House of Representatives. Other than that, there are numerous other local jurisdictions in the WMA that have independent general purpose governments.

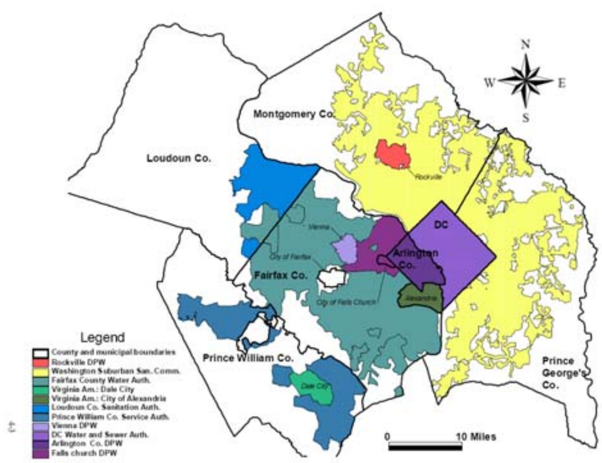

Figure 1: Water Supplier Service Areas in the Washington Metropolitan Area (Hagen and Steiner 2000).

The main source of water in WMA is the Potomac River. There are around twenty water utilities operating in the region. There are three main suppliers: the Fairfax County Water Authority (FCWA), the Washington Suburban Sanitary Commission (WSSC), and the Washington Aqueduct. Approximately 90 percent of the WMA's population relies on water provided by these three main agencies. The main suppliers also provide treated water to many wholesale or independent utilities. The main suppliers are also called CO-OP suppliers because their function is coordinated by the ICPRB (Interstate Commission on the Potomac River Basin) Section for Cooperative Water Supply Operations on the Potomac (CO-OP). Other than coordinating between suppliers, the ICPRB also manages water supply during droughts, forecasts demand, flood control, and facilitates source water protection (see: http://www.potomacriver.org/cms/abouticprbdocs/staffexpertise.pdf).

The three major regional water suppliers have collectively paid for water storage in Jennings Randolph and Little Seneca Reservoir. Jennings Randolph holds 13.4 billion gallons (bg) of water. It is located 200 miles upstream of the utility water intakes located at Great Falls. Releases made from Jennings Randolph take more than a week to reach intakes. The Little Seneca reservoir is a smaller reservoir that holds 3.8 bg of water. It is used to "fine tune" the larger releases from the Jennings Randolph. Releases made from Little Seneca take less than a day to reach the utilities' intakes.

There are two additional reservoirs that are operated by the utilities separately. The WSSC operates the Patuxent Reservoirs in the neighboring Patuxent River watershed. Total usable storage available at these reserve water supplies is about 10.2 bg. The water stored in these reservoirs is used along with Potomac River withdrawals throughout the year. Similarly, FCWA operates a reservoir on the Occoquan River with a total storage volume of 8.0 bg. The Potomac River still remains the main source of water for WMA residents. 75% percent of the water treated by the CO-OP suppliers comes from the Potomac River. Patuxent and Occoquan reservoirs that do not fill from the Potomac account for the remaining 25% of the regional demand (Hagen and Steiner 2000). Figure 2 gives a schematic of the WMA's water resources.

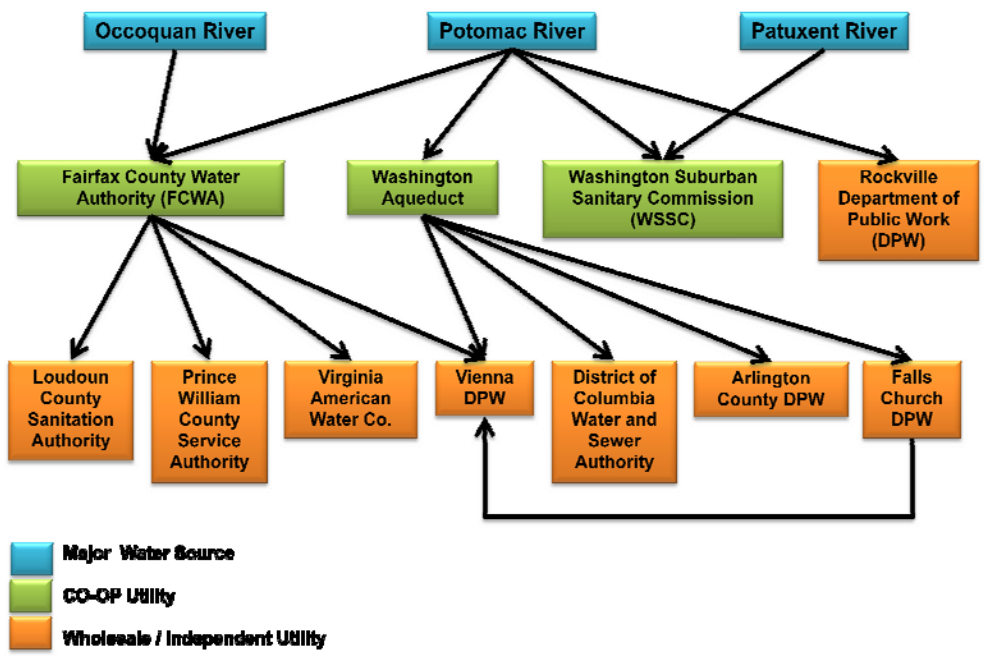

Figure 2: Overview of WMA's Water Resource (ICPRB 2010a).

In summary, the WMA has a complex water management system that has to cater five million residents spanning over 15,000 square kilometers. Being the nation's capital with diverse demographics and distinct local governments gives the WMA its unique character and provides challenges for policy makers and regional government institutions.

4.Water System Modeling Addressing Demand, Supply, and Environmental Issues

Water resources are modeled on both global and local levels. Global water models, although philosophically very intuitive and informative, provide little help to policy makers because global models are highly aggregated and do not address day-to-day operational concerns of municipal water managers (Winz, Brierley et al. 2009). So, local temporal and spatial models are developed to facilitate decision making by local and regional governments since local governments have authority to make water withdrawal, distribution and conservation related policies. Although local models are more practical from a regional policy formulation and implementation point of view, it is important to have a global perspective on water availability and to assess its impact on overall development of human civilization. For that purpose, various global water scarcity studies have been conducted (Saysel and Barlas 2001); (Alcamo and Henrichs 2002); (Chung, Kim et al. 2008). One such study conducted by (Kojiri, Hori et al. 2008) depict that overall civilization development will be retarded if there is a deficit in water resources.

Among the local water models, most have focused on managing water for droughts of heavily populated regions. One such demand supply study was conducted in the Okanagan Basin, Canada, where the research tried to investigate the impact of population growth and climate change on water demand and supply. The mounting instances of water deficit trigger conservation policies that come into play and balance the deficit. Groundwater pumping and water imports balance the deficit by augmenting available supplies whereas municipal, agriculture and ecosystem demand reinforces it (Langsdale, Beall et al. 2007).

Similar demand and supply modeling was conducted for the Middle Rio Grande river basin, where water deficit has been on a constant rise (Passell, Tidwell et al. 2003; Tidwell, Passell et al. 2004). This study explored demand and supply dynamics of the region where climate change and population growth were key variables that affected supply and demand respectively. Various competing management strategies were assessed including the reliability of the current system to meet future water demand.

Various regions of the world have analyzed their water resources for climatic change vulnerability and risks associated with possible water shortages. Like a study conducted in Las Vegas concluded that reducing outdoor water consumption can reduce the vulnerability of the water supply system and increase its robustness (Stave 2003). A similar study conducted by Mariño in 2008 have similar conclusions regarding current state of water policies for Zayandeh-Rud river basin in Central Iran (Mariño 2008).

Many researchers have used different methodologies to understand the processes responsible for spatial and temporal distribution of water resources in a river basin. Oel et al. 2010 use a multi-agent simulation approach to develop a model to represent local water use of the Jaguaribe basin in Northeast Brazil. Various water supply system managers have used combination of optimization and simulation techniques for improving water resource efficiency and effective reservoir management (Sheer 1977; Palmer et al. 1979; 1982).

Once the water supply system has been accurately represented both temporally and spatially through numerous methodologies like system dynamics, multi-agent modeling, etc. the system performance should be evaluated under a wider range of feasible demand, supply and weather scenarios. The literature discusses various performance metrics that are relevant for water management systems, such as, reliability (the probability that the system will remain in a non-failure state), resilience (the ability of the system to return to non-failure state after a failure has occurred), vulnerability (the likely damage of a failure event), and robustness (flexibility to adapt to wide range of scenarios) (Hashimoto et al. 1982; Kjeldsen and Rosbjerg, 2004; McMahon et al. 2006; Siminovic et al. 1992). The literature also discusses the use of single metrics for performance assessment like a drought risk index (DRI) or sustainability index instead of using multiple metrics like resilience, reliability, vulnerability etc. concurrently. These single metrics are just a multiplicative or additive combination of reliability, resilience and vulnerability concepts. (Zongxue et al. 1998; Loucks, 1997; McMahon et al. 2006)

This paper uses the SD methodology to model the WMA water management system because SD affords the engineering team the ability to a) isolate key causal relationships between the system elements, and b) graphically represent the constellation of subsystems for lay policy-maker comprehension and consideration. Moreover, system dynamics is a continuous modeling process which allows for an examination of the effects of multi-year droughts on reservoir.

5.Modeling

In this study, the model has two main components: Water demand and supply. We provide a discussion of both components subsequently.

5.1 Water Demand

Forecasting annual average water demand is a multi-step process. It requires data from various agencies like the Metropolitan Washington Council of Governments (MWCOG), which is a regional planning agency for Washington Metropolitan Area, utility providers like Washington Aqueduct, WSSC, Rockville, etc.

MWCOG provides estimates of population, households, and employees for the Washington Metropolitan Area from 2010 through 2040 (MWCOG, 2009) and the WMA utility suppliers like WSSC, FCWA provide area specific billing information, water use data and demographic data along with assumptions regarding changes in water use patterns in the region.

Figure 3 describes the annual average water demand forecasting process in detail. Firstly, billing and production data is collected from each utility supplier along with the demographic data specific to its area. The difference between the amount of water produced or purchased by the utility and the amount billed to its customer gives a fairly good estimate of 'unmetered water use'. The ICPRB has come up with an estimate for unmetered water for all WMA water suppliers, which is approximately 10 percent. This 10 percent value provides a conservative planning-level estimate of future water demand that accounts for increased losses as infrastructure ages (ICPRB 2010a). Second, billing information collected above is also used to calculate 'unit use factors' for each category (single family, multifamily and employee). The unit use factor for each category is calculated by dividing billing information for that category by its demographic data. Unit use factor basically describes average daily water use. Future unit use factors are impacted by water use policies for the region. For example, due to the Energy Policy Act of 1992 water use is expected to fall in future due to the installation of water conserving fixtures and fittings. Other than that government keeps coming up with numerous programs that promote voluntary water conservation that may also affect consumer's future water use behavior. Moreover, global climate change may result into significant changes in regional temperature and precipitation trends and patterns that could impact summertime outdoor water use, which is a significant component of annual average demand.

Similarly, the number of single family and multi-family households is obtained from each county's planning office. This information is then used to calculate 'dwelling unit ratio' (which is calculated as the ratio of single family households to multi-family households) for each supplier's service area. Later, the dwelling unit ratio is utilized to separate household forecasts made by MWCOG into the number of single family and multi-family households for each supplier's service area. Other than dwelling unit ratio, the above information is also an input for calculating unit use factors.

According to the MWCOG forecast (MWCOG, 2009), households are expected to increase by 29% by 2040, population by 24% and employees by 38%. The employee data is reflective of economic growth of the region (see Table 1). The numbers reflect that the WMA economy is growing due to its metropolitan character and federal job creation.

Similarly, unit use factors are also expected to exhibit long-term decreasing trends due to changes in the water use behavior and the Energy Policy Act. ICPRB expects a total savings of 16 million gallon per day (mgd) per household by 2040 due to the provisions of the Energy Policy Act of 1992 that require the use of more efficient plumbing fixtures. The figures given by ICPRB are conservative because unit water use may fall further due to government led education campaigns like "Water Use It Wisely" (run by MWCOG) that promotes wise water use in the region (ICPRB 2010a).

Table 1: The MWCOG Forecast for the Percentage Increase in Demographics for the WMA Water Suppliers from 2010 to 2040. Source: ICPRB (2010a)

	Households	Population	Employees
FWCA	36%	32%	54%
Aqueduct	28%	26%	24%
WSSC	22%	17%	42%
Average (Including Rockville)	29%	24%	38%

Hereafter, two demand scenarios are developed (Figure 5):

Demand Scenario 1: This scenario is based on MWCOG forecasts and assumes that both single family household and multi-family household unit use will decrease throughout the forecast period due to the effects of the Energy Policy Act of 1992.

Demand Scenario 2: This scenario is also based on MWCOG Round 7.2 growth forecasts but it assumes that the reduction in single family unit use will be offset by increases in summertime outdoor water use. Thus, we shall only see significant reduction in multi-family households water use due to provisions of the Energy Policy Act.

Both demand scenarios were developed for the three major utility suppliers for the WMA and also for the Rockville PWD. Both scenarios provide the average annual demand for water for each water utility. But, water demand has very strong seasonal component. Summer water demand is much higher than winter because more water is utilized to irrigate lawns, gardens, golf courses, etc. and for keeping swimming pools full. Similarly, indoor water use also increases because people take more frequent baths in summer. This becomes even more critical because stream flow rates are typically low in summer months (Figure 4). Therefore, 'monthly production factors' were used to convert the annual demand forecasts to forecasts of monthly demand. The monthly production factor is basically the ratio of average monthly to average annual production. The ICPRB has calculated monthly production factors for each of WMA's suppliers and they reflect typical seasonal variations in water production.

The model developed for this study basically generates two demand scenarios and the supply system is analyzed to see whether it is able to meet the 30 year projected demand for both scenarios.

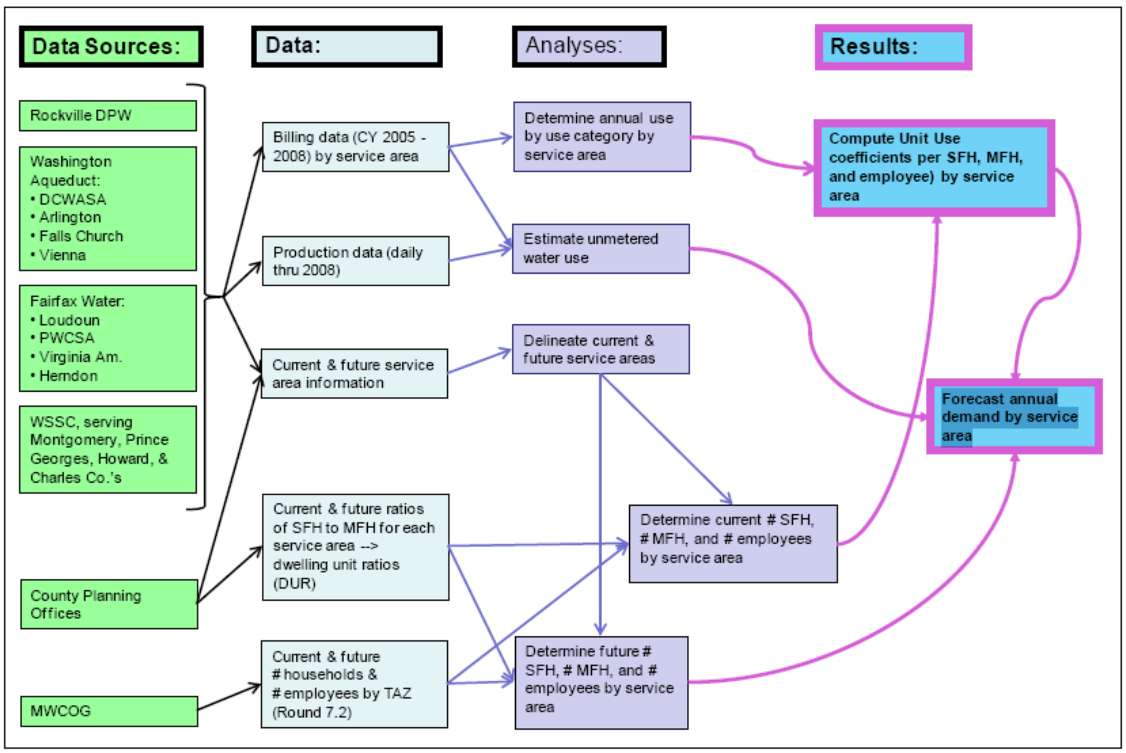

Figure 3: Annual Average Water Demand Forecasting Process (Source: ICPRB 2010a)

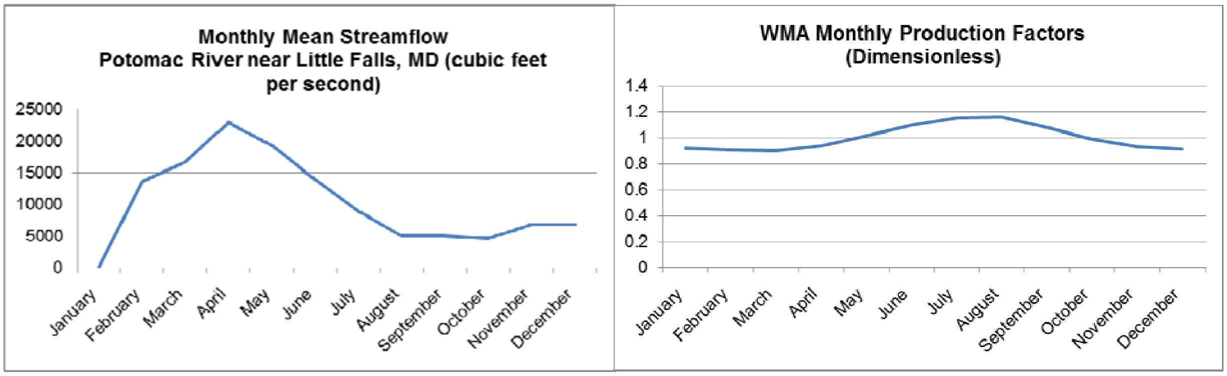

Figure 4: Monthly Mean Stream Flow for the Potomac River near Little Falls[3], WMA Monthly Production Factors

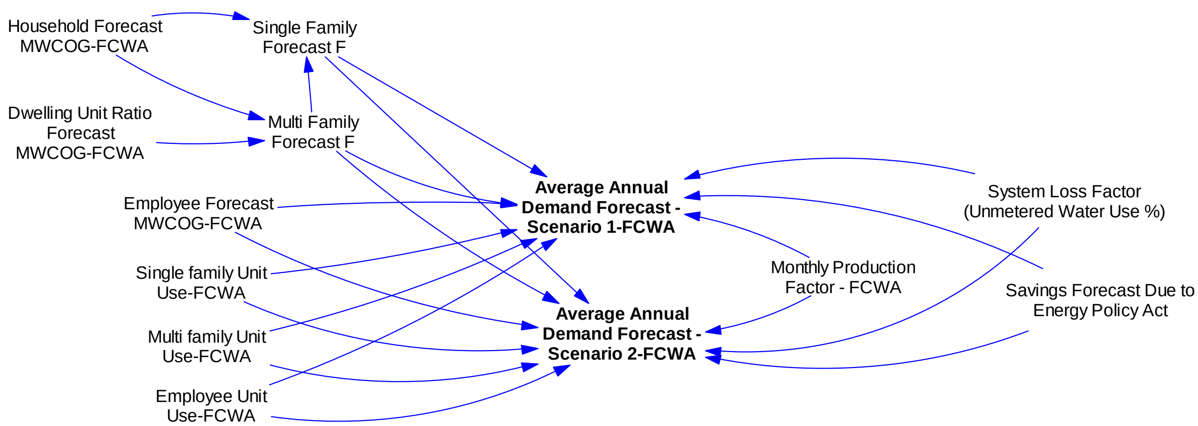

Figure 5: Demand Side Model: Demand Scenarios for the FCWA

5.2 Water Supply

The main source of water drinking supply for the majority of people in the WMA is the non-tidal Potomac River. There are three main suppliers: FCWA, WSSC and the Washington Aqueduct. Each of the three major suppliers withdraws water from the Potomac River upstream of Great Falls. There is an additional intake at Little Falls which is used by Washington Aqueduct.

5.2.1 The Supply Side Model: Potomac River System

The average annual stream flow values for the Potomac River is around 7 billion gallons per day (bgd), with higher flows typically occurring in the winter months and lower flows in the summer months (Figure 4). For much of the year, water supply withdrawals from the Potomac remain a small fraction of river's flow because the average summer demand for water by WMA suppliers is approximately 500 million gallons per day (mgd), or 0.5 bgd (ICPRB 2010a). This may give a false

[3] http://md.water.usgs.gov/surfacewater/streamflow/

sense of water security for the region. The critical aspect here is the stream flow variability. Potomac stream flows may even drop to values as low as 530 cubic feet per sec (summer of 1966, the flow was less than projected demand), which is quite low and about 22 times less than the average annual flow. Over a course of a year a typical high discharge can be 11,000 cubic feet per sec and typically low discharge can be 2000 to 3000 cubic feet per sec. Due to such high flow variability, chances of water supply system, relying solely on Potomac water, not meeting the daily demand targets may increase. Therefore, during periods of low flow, which typically occur in summer and early fall, the natural flow of the Potomac may require augmentation to satisfy predicted demand plus environmental flow requirements.

The total available Potomac water is constrained by two factors: Minimum environmental requirement and upstream consumptive demand. There is a minimum low-flow requirement of 100 mgd at Little falls and 300 mgd at Great Falls necessary for protecting aquatic life forms (Kiang and Hagen 2003). Changes to the 'Minimum Inflow Requirements' will influence water availability in the system. Other than that, water withdrawals from the Potomac River and its tributaries by upstream users also have an impact on the amount of water available to meet demand in the WMA. Although most of the water withdrawn upstream is returned to the Potomac River as wastewater treatment plan discharge, some portion of this water is lost due to evaporation, transpiration, incorporation into products, consumption by humans or livestock, etc. The portion of water that is not available for downstream use is termed "consumptive use". Figure 6 shows the Supply Side Model for the Potomac River System.

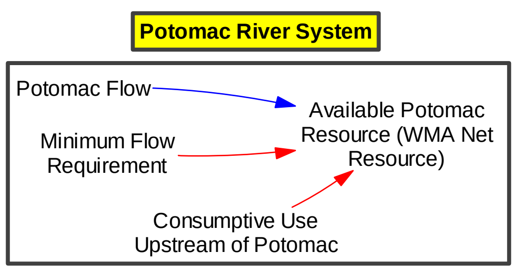

Figure 6: Supply Side Model: Potomac River System

5.2.2 Supply Side Model: Additional Reservoir Systems

There are two additional reservoirs that are operated by the utilities separately. WSSC operates the Patuxent Reservoirs in the neighboring Patuxent River watershed. Total usable storage available at these reserve water supplies is about 10.2 bg. The water stored in these reservoirs is used along with Potomac River withdrawals throughout the year. Similarly, FCWA operates a reservoir on the Occoquan River with a total storage volume of 8.0 bg.

All of the above mentioned reservoirs have been modeled separately for this study. Figure 7 shows the Occoquan Reservoir System. The Occoquan Reservoir Model calculates daily storage available in the Reservoir using the water balance approach that calculates the reservoir storage at each time step (inflow-outflow = change in reservoir storage). Reservoir can be understood as a stock having a fixed capacity (reservoir capacity) that accumulates the difference between its inflow and outflow.

$$Stock(t) = \int_{t_0}^{t_n} [Inflow(t) - Outflow(t)]dt + Stock(t_0)$$

Where: *Stock(t)* = the amount of stock at time *t*, *Inflow(t)* = is the inflow at time *t*, and *Outflow(t)* = the outflow at time *t*, and *t* is any time between t_o and t_n ($t_o \leq t \leq t_n$). (Madani and Marino 2008)

Inflows to the reservoir typically consist of natural[4] 'reservoir inflow' and water pouring into the reservoir due to direct precipitation. The model incorporates 'natural' inflows because it allows for separate accounting of natural flows and human influence activities. This is more advantageous because it facilitates the user to modify inflows based on upstream diversions or return flows simply by subtracting it from natural inflows (ICPRB Report 98-3). Another inflow to the reservoir is the rain water pouring directly onto the reservoir. This inflow is calculated as the regional precipitation rate multiplied by area of the reservoir.

Outflows to the reservoir typically consist of loss of water due to evaporation, water supply releases and reservoir spill. It may vary from one reservoir to another. For example, unlike the Patuxent reservoir, the Occoquan reservoir has to make releases for hydropower generation. But care has to be taken while modeling outflows because reservoir stock cannot go negative. The physical system has to be transformed into mathematical representation representing real physical conditions. For example, outflow due to evaporation should drop to zero when reservoir is empty. This condition is modeled by using table functions reflecting the impact of reservoir volume on reservoir evaporation. Similarly, reservoir volume cannot go beyond its capacity. Any flow over and above the capacity goes out in form of 'reservoir spill'. Reservoir spill is calculated as:

Max (0,(Occoquan Reservoir storage- Reservoir Capacity)/ Reservoir Spill Time)

Which means any volume of water over and above reservoir capacity will be discharged with a rate equal to 'Reservoir Spill Time'. Similar constraints have to be placed on other outflows like hydropower generation and water supply releases. Full releases cannot be made if there is not enough water in the reservoir to satisfy water supply release requirements. Usually releases are made in bulk instead of random amounts because the water also has to be treated before it is supplied to homes and offices. Therefore, we have a 'delta load shift' for both Occoquan and Patuxent facilities that determines the maximum water production that can be shifted from the Potomac water treatment facilities to Occoquan and Patuxent water treatment facilities in any one day (in mgd). In case of the Jennings Randolph reservoir, water has to be released in bulk (on the order of at least 100 to 200 mgd) to increase its travel time. Thus, in case of a predicted shortfall, an initial day's release of 200 mgd is made from the Jennings Randolph reservoir so that water reaches Potomac intakes as a "wave."

Other constraints on the reservoir storage capacity include the sedimentation rate[5]. Reservoir sedimentation rates are highly variable and dependent on hydrologic conditions, with the majority of

[4] The inflow is called 'natural' because it represents those inflows to the reservoir that would have occurred without any human influence like upstream withdrawals, return flows, or reservoir regulations (ICPRB Report 98-3).

[5] "Rivers carry different types of sediment down their riverbeds, allowing for the formation of riverbanks, levees and shores. The construction of a dam blocks the flow of sediment downstream, leading to downstream erosion of these Sedimentary depositional environment, depositional environments, and increased sediment build-up in the

sediment deposition occurring during very large storm events. Reservoir storage capacities decrease with time due to the deposition of sediment. The model uses the data on sedimentation rates compiled by the ICPRB for all the reservoirs.

Once supply and demand side was modeled, water withdrawals were modeled based on reservoir rules and conditions.

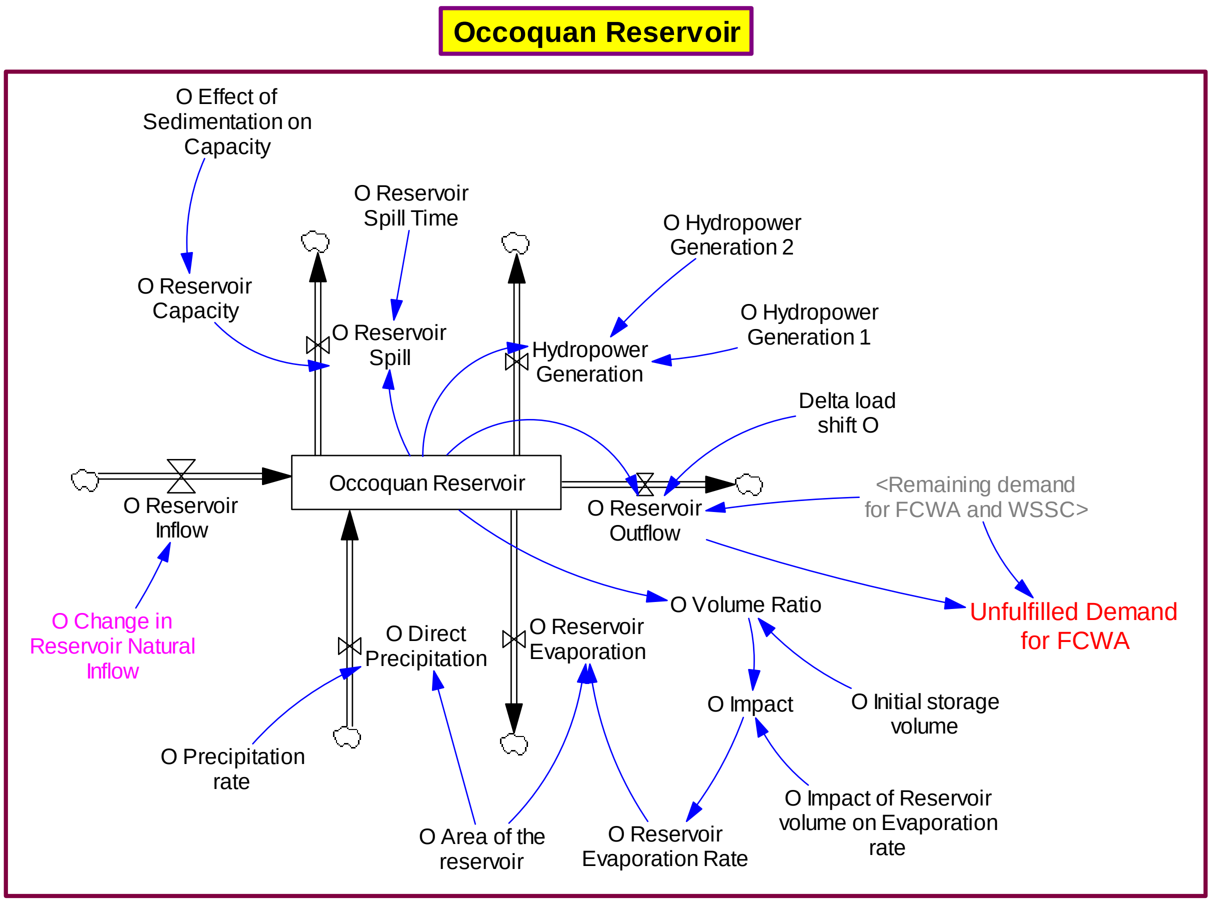

Figure 7: Supply Side Model: Occoquan Reservoir System

5.3 Balancing Demand and Supply

The ICPRB makes demand projections for the WMA region. Based on the demand projections water is withdrawn from Potomac River or reservoirs. Each of the three major suppliers withdraws water from the Potomac River upstream of Great Falls. There is an additional intake for Washington Aqueduct at Little Falls.

FCWA and WSSC also rely on water stored in reservoirs that are outside of the drainage area above their Potomac River intakes, on the Occoquan River and the Patuxent River, respectively. But they first make withdrawals from the Potomac River from their water treatment plants located at

reservoir. The rate at which these sediments build up in a reservoir is called rate of sedimentation."
http://en.wikipedia.org/wiki/Environmental_problems_of_dams

Great Falls. The short fall is augmented by their other water treatment plants located at the Occoquan and Patuxent reservoirs respectively. However, the Washington Aqueduct and Rockville PWD only have Potomac River as their only source of water. Therefore, the model assumes priority for Washington Aqueduct's and Rockville PDW's withdrawals. The left over water is utilized to fulfill FCWA and WSSC water demand. If there is still some shortfall, releases from Jennings Randolph and Little Seneca can be used to augment Potomac River's flow during times of drought. Figures 8a and 8b show how demand and supply equations are balanced in the WMA water supply system. The 'Total WMA unfulfilled demand' and 'Demand Component still remaining after all resources for WMA are completely exhausted' are key variables to assess WMA water supply system performance.

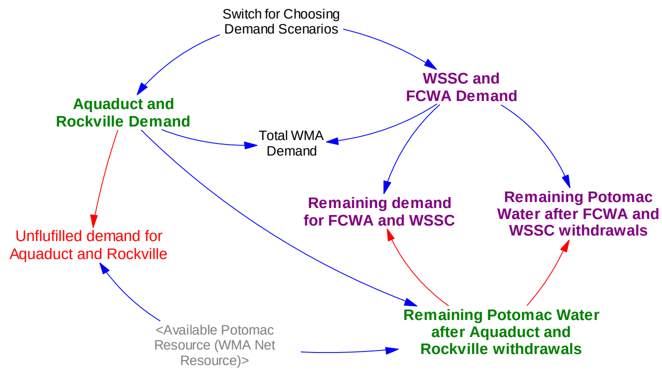

Figure 8a: Balancing Demand and Supply

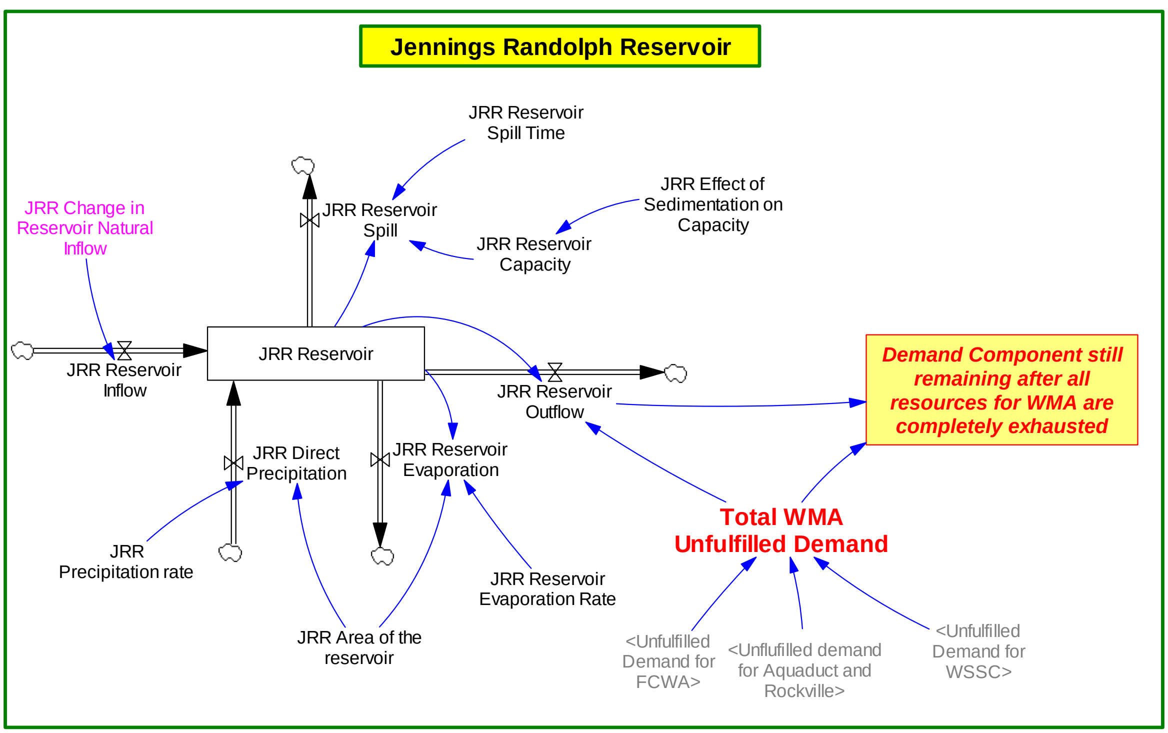

Figure 8b: Balancing Demand and Supply

5.4 The Simulation

The model is run for a 30 year simulation period, from the year 2011 to year 2040. The data for the demand projections are taken from the MWCOG and WMA utility suppliers. The model is run for two demand scenarios. The supply side is run for three scenarios: one normal condition and two drought conditions. There have been two instances of significant droughts in the history of the WMA. The first being the drought of 1930-31, which is the longest drought recorded in history. It is noteworthy since it lasted from the summer of 1930 through the winter of 1931 (Kame'enui et al. 2005). Another instance of low flows occurred in 1966. The WMA demand levels exceeded the 1966 low-flow of the Potomac River 41 times during 1971 through 1982 (Ways, 1993). The model was run to examine the impact of such extreme weather conditions and to determine the ability of the WMA water supply system to fulfill future demand (2010-2040). Moreover, system dynamics is a continuous modeling process which allows for an examination of the effects of multi-year droughts on reservoir.

The Simulation Results

The model's results for each scenario are shown in Figures 9a through 9f. The first two graphs simulate the WMA water supply system for normal weather conditions where there is no drought in the WMA region. In that situation, the WMA water supply system will be sufficient to meet the predicted water supply demand through year 2040. Although, the system is able to fulfill future year demands for both scenarios, it will require pricy withdrawals from the Jennings Randolph reservoir a few times.

The third and fourth graph show that the water supply system will not be able to meet future supply demand if low flow conditions of the year 1966 are repeated. In that case, not only will the system require frequent withdrawals from Jennings Randolph reservoir, but it will not be able to meet the WMA demand for specific low flow periods. This will cause triggering of the Low Flow Allocation Agreement's (LFAA) low-flow stages. The LFAA establishes a set of stages for low river flow that would prompt action by the agreement signatories to monitor and eventually restrict water withdrawals[6]. It also established a formula that allocates the amount of water each supplier can withdraw from the Potomac River in the event that the total flow is not sufficient to meet all needs. Although, LFAA's low-flow stages have never been triggered in the past, the model predicts that it will be triggered if low flow conditions of the year 1966 are repeated in future (2030's). Similarly, during a repeat of the worst drought of record (1930-1931), model predicts that WMA water system will fail to meet future demand (Figures 9c and 9f)

What is more important here is the behavior of the system, not the numbers generated in model runs. Different scenarios were developed merely to understand the system behavior. Thus, they are mostly qualitative and may not represent any realistic future scenario since the population forecast (and corresponding demand forecast) beyond the 2030 horizon is only a rough approximation (Hagen and Steiner 2000).

[6]http://www.mwcog.org/environment/water/watersupply/aggreements.asp

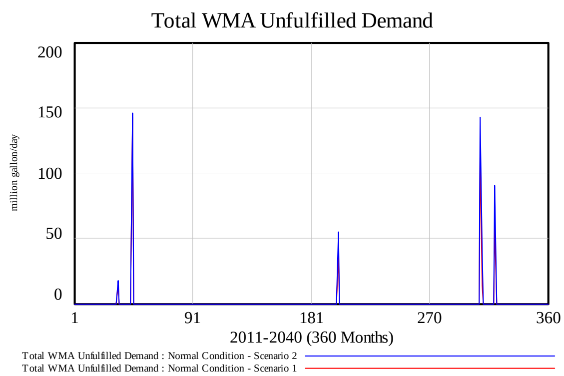

Figure 9a: Model Simulation Results - Normal Condition

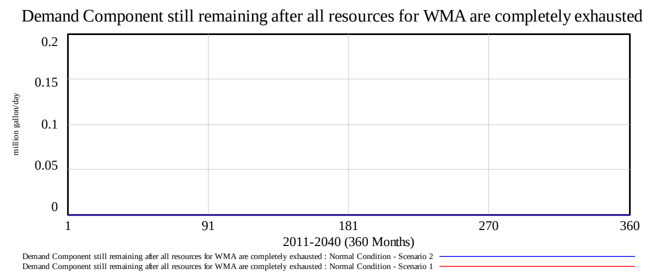

Figure 9d: Model Simulation Results - Normal Condition

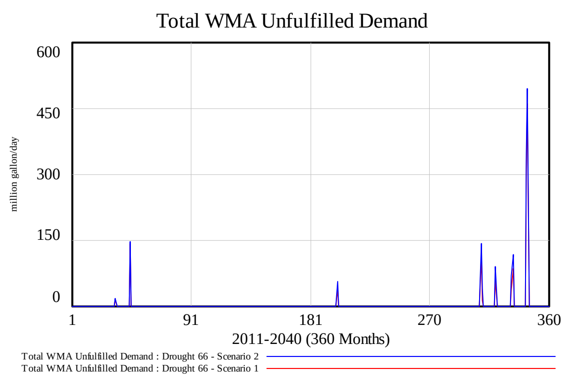

Figure 9b: Model Simulation Results – Drought - 66

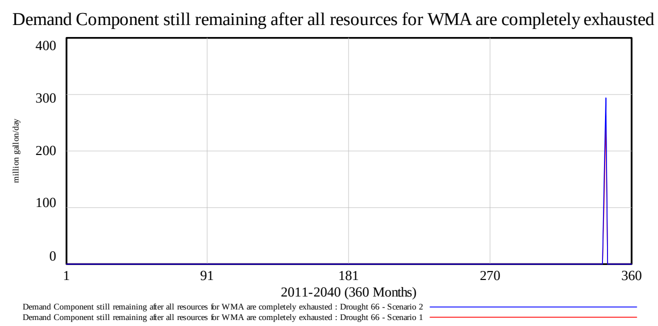

Figure 9e: Model Simulation Results - Drought - 66

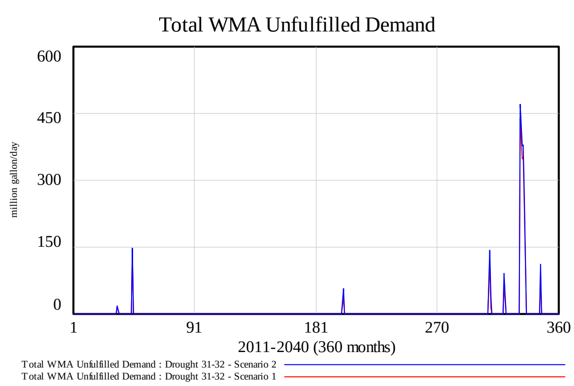

Figure 9c: Model Simulation Results – Drought – 31-32

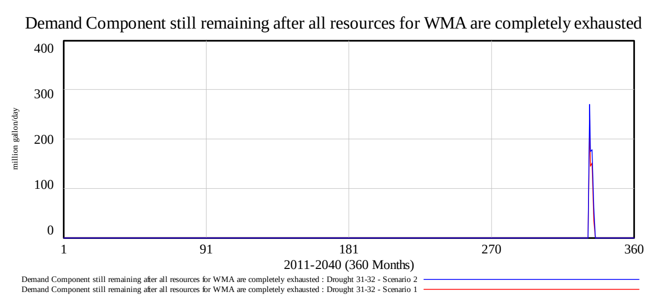

Figure 9f: Model Simulation Results - Drought – 31-32

Figure 9: Model Simulation Results

6. The Performance Analysis

WMA was faced with severe drought in the summer of 1966, which forced Washington DC to declare its first "water emergency". Other than that, population forecast generated in 1960's indicated that demand would exceed supply in the future (natural low flows in the Potomac River).

To address the future water deficit, the U.S. Army Corps of Engineers conducted a study that identified 16 potential dam sites on the Potomac River upstream of Washington, D.C., which led to considerable public opposition due to environmental concerns regarding the building of these dams. Concurrent research conducted at Johns Hopkins University concluded that the WMA future water supply could be met through the cooperation amongst WMA water suppliers and the coordinated operation of the Jennings Randolph, Occoquan and Patuxent reservoirs. This was how the WMA water management system came into being, which basically involves managing the reservoirs and the cooperation amongst the WMA water supply system entities through various agreements among agencies including the U.S. Army Corps of Engineers, the states of Maryland and Virginia, the District of Columbia, local water utilities, and the Interstate Commission on the Potomac River Basin (Sheer and Flynn 1983).

To gauge whether the system is doing what it was intended for, it is necessary to assess its performance under the wide range of scenarios expected during their operating life. Also, performance has become an important issue over the past decade or so since environmental flows have been considered a component of system yield (McMahon et al. 2006).

This study gauges the WMA water supply system's performance using various performance metrics including time based reliability, volumetric reliability, resilience and vulnerability. They are discussed in the following sections along with their values for the WMA water supply system.

6.1 Reliability

Reliability of a water supply system is one of the most important matrices for performance assessment. It is defined as the probability that water supply system is able to meet the target demand. McMahon et al. (2006), calculates time-based reliability as proportion of intervals during the simulation period that the water supply system can meet the target demand. Mathematically, it is expressed as:

$$Reliability_t = \frac{N_s}{N}, \qquad 0 < Reliability_t \leq 1 \qquad (1)$$

Where $Reliability_t$ is the time-based reliability, N_s is the number of intervals that the target demand was fully met and N is the total number of intervals in the simulation.

We also calculate volumetric reliability, which is based on the volume of water demand met by the water supply system divided by the total target demand during the entire simulation period. Mathematically, it is expressed as (McMahon et al. 2006):

$$Reliability_v = 1 - \frac{\sum_{i=1}^{N}(D_i - D_i')}{\sum_{i=1}^{N} D_i}; \quad 0 < Reliability_v \leq 1 \qquad (2)$$

Where $Reliability_v$ is the volumetric reliability, D_i is the target demand during the i^{th} period, D_i' is the volume supplied during the i^{th} period and N is the number of intervals in the simulation.

6.2 Resilience

Resilience of any system is defined as the ability of the system to recover from any shock. For a water supply system, it is an indicator of how readily a water supply system will recover from a failure. Hashimoto et al. (1982) define the resilience of water supply system as:

$$Resilience = \frac{f_s}{f_d}, \qquad f_d \neq 0;\;\; 0 < \varphi \leq 1 \qquad (3)$$

Where $Resilience$ is the resilience, f_s is the number of individual failure periods and f_d is the total duration of all failures. Resilience therefore can also be understood as the inverse of the average failure duration. When f_d is zero, by definition, φ , should be 1.

6.3 Vulnerability

Finally, vulnerability measures the average volumetric severity of failure during a failure period. Mathematically, Hashimoto et al. (1982) define vulnerability as:

$$Vulnerability' = \frac{\sum_{j=1}^{f_s} max \quad (s_j)}{f_s} = \frac{Sum\ of\ maximum\ shortfall\ during\ each\ failure\ period}{Number\ of\ continuous\ sequences\ of\ failure} \qquad (4)$$

Where, s_j is the volumetric shortfall $(D_i - D_i')$ during the j^{th} continuous failure sequence and f_s is the number of individual failure periods. This measure of vulnerability has same unit as volume therefore it has to be normalized diving it by the target demand (D) to create a dimensionless measure similar to other performance criteria:

$$Vulnerability \;= \frac{Vulnerability'}{D};\;\; 0 < Vulnerability \leq 1 \qquad (5)$$

Finally, all the three concepts of reliability, resilience and vulnerability are combined into one single metric termed the drought risk index (DRI), which is dimensionless and is expressed as (Zongxue et al., 1998):

$$DRI = \xi_1(1 - Reliability) + \xi_2(1 - Resilience) + \xi_3(Vulnerability\ );\; 0 < DRI \leq 1$$

Where, ξ is the weight associated with each performance dimension and $\xi_1 + \xi_2 + \xi_3 = 1$. In this study, the weights are set equal to 0.33.

Tables 2a and 2b give the performance matrices for the WMA water supply system. Table 2a gives performance matrices for the WMA supply system without its "savings account" (Jennings Randolph and Little Seneca Reservoir). Table 2b expresses the performance matrices for the whole system. As expected, reliability of the system goes down as the severity of drought increases. The drought of 1930-31 was the longest and most severe and longest drought in history of the WMA. It is noteworthy that it lasted from the summer of 1930 through the winter of 1931. Therefore, we observe reliability and resilience of the system to be lower for 1931-32 drought conditions when compared with normal conditions and 1966 low flow conditions. Reliability and resilience values are also lower for scenario 2 because this scenario assumes a higher demand. The model simulation runs and performance indices reveal that the WMA water supply system will require frequent releases from their savings accounts in the future if historical drought conditions are repeated. There are instances expected in the future when water will not be enough to meet WMA demands. This is also reflected by the increasing vulnerability of the system as the severity of drought increases from normal to drought conditions of 1931-32. We also observe that the vulnerability ratio is approximately the complement of resilience values.

There is one unexpected observation; we expected that resilience of the WMA water supply system without Jennings Randolph reservoir would be lower than the system with it because it provides additional source of water to the system. But, the outcome was contrary to our expectation. It is observed that resilience actually went down for the system when it included additional resources (Jennings Randolph reservoir). The reason behind it could be the method by which resilience is calculated. Equation 3 defines $Resilience$ as the ratio of f_s and f_d where, f_s is the number of individual failure periods and f_d is the total duration of all failures. If we observe model runs in Figures 9e, 9f we shall see that the system with additional resource has just one failure in both runs, whereas, the system without additional resources had multiple failures scattered through time. Thus, when we have just one failure scattered over few time periods contrary to multiple failure periods, resilience for the single failure case will go down. These results are contrary to each other and can be misleading for policy makers.

In order to remove the confusion caused by such contradictory performance indices, we can use a single measure for evaluating the overall performance of reservoirs. Therefore, we also calculate drought risk index (DRI) (Table 2a and 2b) using equal weights ($\xi_1 = \xi_2 = \xi_3 = 0.33$). The convenience of these metrics is that they offer a single measure for evaluating the overall performance of reservoirs rather than having to consider each of the constituent metrics, a situation complicated by the numerous trade-offs between them (McMahon et al. 2006). Moreover, since DRI is an additive metric, hence, it is not so easily nullified by any of its constituent metrics being zero. The drought risk index (DRI), as calculated in Table 2, gives the expected outcome. It increases as severity of drought increases.

Table 2a: Performance Matrices for WMA Water Supply System (Without Jennings Randolph Reservoir)

		WMA Water Supply System (Potomac River + Occoquan Reservoir + Patuxent Reservoir)				
		Reliability_t	Reliability_v	Resilience	Vulnerability	Drought Risk Index*
Normal Condition	Scenario 1	0.9833	0.9983	0.888	0.1340	0.0867
	Scenario 2	0.9833	0.9979	0.888	0.1599	0.0952
Drought 66	Scenario 1	0.9388	0.9968	0.857	0.1750	0.1251
	Scenario 2	0.9722	0.9935	0.857	0.2064	0.1245
Drought 31-32	Scenario 1	0.9694	0.9920	0.833	0.1818	0.1252
	Scenario 2	0.9694	0.9911	0.833	0.2040	0.1325

* $\xi_1 = \xi_2 = \xi_3 = 0.33$

Table 2b: Performance Matrices for WMA Water Supply System (With Jennings Randolph Reservoir)

		WMA Water Supply System (Potomac River + Occoquan Reservoir + Patuxent Reservoir + Jennings Randolph Reservoir)				
		Reliability_t	Reliability_v	Resilience	Vulnerability	Drought Risk Index*
Normal Condition	Scenario 1	1	1	1	0	0
	Scenario 2	1	1	1	0	0
Drought 66	Scenario 1	0.9861	0.999	0.833	0.274	0.1501
	Scenario 2	0.9944	0.9981	0.833	0.351	0.1728
Drought 31-32	Scenario 1	0.9888	0.9975	0.75	0.297	0.3492
	Scenario 2	0.9888	0.997	0.75	0.324	0.1931

* $\xi_1 = \xi_2 = \xi_3 = 0.33$

7. Conclusions and Future Research

To sum up, we conclude that the WMA water supply system is susceptible to shortages in future caused by increasing customer demand for water and alarming trends in climate. The performance of the system is expected to deteriorate in the coming years and the recurrence of historical droughts and low flow conditions can strain the system even further. Current resources are not sufficient to meet the demand and there is a very high probability that water restrictions will be imposed due to the triggering of Low Flow Allocation Agreement (LFAA).

The model predicts that frequent releases will be made from the Jennings Randolph reservoir even during normal conditions. Drought will further increase the frequency of releases. The releases are often coupled with coordinated water conservation measures that are not very popular with consumers. Thus, knowing when the releases will be required in future may help in coordinating the operations of all the three major reservoirs of the region. The policy makers can plan reservoir operations in such a way that the Patuxent and Occoquan reservoirs are full in the beginning of the period of expected shortfall. This can be done by exploiting the Potomac River flow to meet water supply demands during its periods of high flows while letting the Patuxent and Occoquan reservoirs get filled in the meantime.

Finally, this model is part of an ongoing research effort to understand and assess the Washington Metropolitan Area's water resource management system. The next step to this research would be to incorporate institutional interactions among various entities of the water supply system and to simulated and test competing policy alternatives for the WMA.

The methodology used in this paper to address the future of WMA water supply system can be utilized for various other water supply systems. System dynamics can be used to simulate supply demand dynamics any water supply system. The scope can be expanded further to explicitly capture the dynamic feedbacks between institutions responsible for managing water resources and water availability, demand management strategies, growth and climate factors, and hydrological and environmental concerns.

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9.Glossary

CLD	Causal Loop Diagram
CO-OP	Cooperative Water Supply Operations on the Potomac
FCWA	Fairfax County Water Authority
GCM	General Circulation Models
ICPRB	Interstate Commission on the Potomac River Basin
LFAA	Low Flow Allocation Agreement
MWCOG/COG	Metropolitan Washington Council of Governments
USGS	U.S. Geological Survey
WMA	Washington Metropolitan Area
WSSC	Washington Suburban Sanitary Commission