INFRASTRUCTURE PERFORMANCE AND RISK ASSESSMENT UNDER EXTREME WEATHER AND CLIMATE CHANGE CONDITIONS

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ABSTRACT

This dissertation explores the impact of climate change and extreme weather events on critical infrastructures as defined by US Department of Homeland Security. The focus is on two important critical infrastructure systems – Water and Transportation. Critical infrastructures are always under the risk of threats such as terrorist attacks, natural disasters, faulty management practices, regulatory policies, and defective technologies and system designs. Measuring the performance and risks of critical infrastructures is complex due to its network, geographic and dynamic characteristics and multiplicity of stakeholders associated with them. Critical infrastructure systems in crowded urban and suburban areas like the Washington Metropolitan Area (WMA) are subject to increased risk from geographic proximity. Moreover, climate is challenging the assumption of stationary (the idea that natural systems fluctuate within an unchanging envelope of variability) that is the foundation of water resource engineering and planning. Within this context, this research uses concepts of systems engineering such as 'systems thinking' and 'system dynamics' to understand, analyze, model, simulate, and critically assess a critical infrastructure system's vulnerability to extreme natural events and climate change. In most cases, transportation infrastructure is designed to withstand either the most extreme or close to the most extreme event that will add abnormal stresses on a physical structure. The system may fail to perform as intended if the physical structure faces an event larger than what it is designed for. The results of the transportation study demonstrate that all categories of roadways are vulnerable to climate change and that the magnitude of bridge vulnerability to future climate change is variable depending on which climate model projection is used. Results also show that urbanization and land use patterns affects the susceptibility of the bridge to failures. Similarly, results of the water study indicate that the WMA water supply system may suffer from water shortages accruing due to future droughts but climate change is expected to improve water supply reliability due to an upward trend in precipitation and streamflow.

DEDICATION

To God and my little angel Chia!

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Chapter 1: Introduction

1. Research Motivation

Water and transportation systems are two of the sixteen critical infrastructure sectors as defined by the US Department of Homeland Security, "…..whose assets, systems, and networks, whether physical or virtual, are considered so vital to the United States that their incapacitation or destruction would have a debilitating effect on security, national economic security, national public health or safety, or any combination thereof" (White House Press Office, 2013). Critical infrastructure is always under the risk of threats such as terrorist attacks, natural disasters, unintended consequences of operator actions, management practices, regulatory policy, and inadequate technology and system designs (Auerswald, Branscomb, Shirk, Kleeman, Porte and Ellis, 2008). The National Infrastructure Protection Plan outlines the importance of systems understanding and stakeholder participation for managing risks and achieving reliable outcomes (DHS, 2015; NIPP, 2013). Thinking about critical infrastructure as interdependent lifelines or "lifeline systems" can help provide insights into the engineering challenges that are associated with improving the performance of large systems (O'Rourke, 2007). But, measurement of lifeline system performance and risks is very complex due to its network, spatial and dynamic characteristics and multiplicity of stakeholders (Chang and Nojima, 1998).

The management, performance and risk assessment of critical infrastructure has gained momentum in systems engineering. This research attempts to examine the performance of water and transportation infrastructure, which are among the sixteen critical infrastructures, as defined by DHS, under the risk of natural events such as floods and droughts. The Washington Metropolitan Area (WMA) is particularly chosen to carry out the performance and risk assessment of critical infrastructure due to its urban characteristics which can be mirrored in a multitude of cities worldwide. Moreover, critical systems in crowded urban and suburban areas like the WMA are subject to increased risk from proximity, meaning they are physically very closely located near each other (O'Rourke, 2007). This research uses concepts of systems engineering such as 'systems thinking' and 'system dynamics' to understand, analyze, model, simulate, and critically assess critical infrastructure system's vulnerability to natural events and climate change. The systems approach is a problem solving paradigm. The systems approach considers the attributes of a whole system to achieve the objective of a system (Jackson, Hitchins and Eisner, 2009) and system dynamics is a computer-aided approach to policy analysis and design. It applies to any dynamic system that is characterized by interdependence, mutual interaction, information feedback, and circular causality (SDS, 2016).

Although systems thinking has been developed into a well-defined concrete interdisciplinary field of study by the West, the philosophy and theory behind the systems thinking is not new. An ancient Indian fable about the blind men and an elephant illustrates the concept of systems thinking. The moral of the story is that when we are confronted with a problem, we should view the whole picture instead of looking at a small part which appears to cause or to be affected by the problem (Chen, 1975). As humans, our perceptions are limited to what we can sense and perceive, meaning all of us suffer from the blindmen's syndrome (Chen, 1975). The blindmen's syndrome has caused more problems by providing faulty solutions to existing problems like prohibition in United States. Prohibition was the blindmen's solution to the problem of alcoholism, hence it failed miserably (Thornton, 1991). These 'solutions' opened the Pandora's Box of new problems. Therefore it is important to look at the total picture and to locate the key issues underlying the problem which may lie beyond the obvious or may be obscured from the surface of the problem (Chen, 1975).

This research takes the systems thinking to examine the consequences of highway bridge design for flooding under the influence of climate change. This research started by questioning the adequacy of the current infrastructure design standards. Design standards are based on the basic understanding of forces of man and nature that act upon an engineering structure. In most cases, transportation infrastructure is designed to withstand either the most extreme or close to the most extreme event that will add abnormal stresses on a structure. For example, a highway bridge might be designed for a 100-year storm event. Failure may occur if the structure faces an event larger than this. This problem involves multiple systems. It requires the understanding of what constitutes an infrastructure design standard and how design standards are created. It also requires an understanding of the external influences on the infrastructure design, both of which have been accounted for and unaccounted for while planning. It involves rallying together the understanding of local hydrology, bridge design components, transportation networks and climate change in order to identify and focus on the critical elements pertaining to the problem in hand (see Figure 1). In other words, it requires a systems approach to understand the nature of the problem.

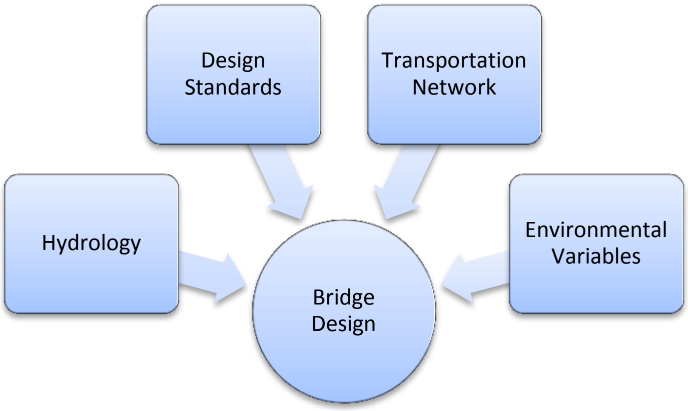

Figure 1: Systems Approach to Bridge Design

Like transportation infrastructure, water infrastructure is also vulnerable to the impact of extreme weather conditions and climate change. According to The American Society of Civil Engineers (ASCE), the water sector is the most important critical infrastructure (Hinman, 2011). Water not only has a profound influence on public health but it also affects other infrastructure sectors including transportation and power. A reliable water supply is an important determinant of the health and wellbeing of individuals and of whole communities. Therefore, the next logical step for this research was to examine the impact of extreme weather events and climate change on the WMA's water supply system. We explore the use of a system dynamics paradigm for the performance assessment of the WMA water supply system. System dynamics (SD) is one of the approaches of systems engineering that can be applied to analyze complex, interdependent, dynamic and systemic problems. The WMA water supply system involves multiple resources, stakeholders, information delays, feedbacks and policy triggers that make it suitable case for SD analysis. WMA water supply system is modeled and simulated in an integrated way as a complete entity so as to gauge its performance under different climate change, policy, drought and low flow scenarios. Multiple sbsystems, like the water demand subsystem, the reservoir subsystem, the free flowing river subsystem, climate and policy variables are interconnected. Feedback from a subsystem affects the other subsystems. For example, restrictions caused by falling reservoir volumes can cause discomfort to people, triggering a fall in the growth rate. The dynamics of water demand is also captured by including key variables that determine water use.

In this research, the systems approach is used to explore the impacts of extreme weather events and climate change on critical infrastructure (transportation and water). Current bridge design criteria are evaluated under the influence of flooding and climate change (Chapter 2). Also, a classical system dynamics approach is used to model, explore and analyze how droughts and climate change will impact future water availability for Washington Metropolitan Area and how various policy interventions mitigate the damage caused by prolonged periods of droughts (Chapter 3 and 4). For each case, model formulation and results are fully discussed in each corresponding chapter.

Critical infrastructure is constantly battling against forces of man and nature. Events such as terror attacks, design flaws, bad management, etc. constitute man-made forces while extreme weather events like tornados, floods, droughts, earthquake, landslides etc. fall under the realm of forces of nature. Both man-made and natural hazards may cause loss of lives, property damage, destruction, and the interruption of business causing immediate and long-term economic, social, and environmental losses. It is important for policy makers to plan appropriate mitigation measures to significantly reduce losses that accrue from such forces (ASCE, 2014). Critical infrastructure is designed to withstand either the most extreme or close to the most extreme event that will add abnormal stresses on a structure. But climate is no longer stationary. The assumption of stationarity, "….the idea that natural systems fluctuate within an unchanging envelope of variability" (Milly, Betancourt, Falkenmark, Hirsch, Kundzewicz, Lettenmaier and Stouffer, 2008, page 573) is the foundation of water resource engineering and planning. However, this assumption is being challenged. Climatologists argue that climate change is shifting the means and extremes of precipitation, evapotranspiration, and stream flows and this problem cannot be fixed by more observations, more efficient estimators or higher resolution data. Even aggressive mitigation cannot reverse this trend (Milly et al. 2008). Planning agencies have tools to adjust their designs and analysis for known human disturbances within river basins. Planners have, until recently, considered climate change and variability to be sufficiently small to allow stationarity-based design, which is a central and the default assumption in water-resource risk assessment and planning (Milly et al. 2008).

2. Climate Change

The Intergovernmental Panel on Climate Change (IPCC 2014) findings state that climate change is likely to increase the frequency of precipitation events and storm frequencies (Wehner 2005). Also, most climate models predict that increases in temperature will be higher over land areas than over oceans and higher in the interior of continents than in coastal areas (Koetse and Rietveld 2009). Climate change studies conducted for our study area predict an upward trend in temperature, precipitation and stream flows (Neff , Chang, Knight, Najjar, Yarnal and Walker, 2000; Wolock and McCabe, 1999; Meehl, Stocker, Collins, Friedlingstein, Gaye, Gregory, Kitoh, Knutti, Murphy, Noda, Raper, Watterson, Weaver and Zhao, 2007; Najjar, Walker, Anderson, Barro, Bord, Gibso, Kennedy, Knight, Megonigal, O’Connor, Polsky, Psuty, Richards, Sorenson, Steele and Swanson, 2000). Out of the three climate variables, streamflow in the Potomac watershed has much greater variability than temperature or precipitation. Temperature predictions have the least variability. The reason for this difference in variability among climate variables is that streamflow predictions require assessing water balance equations including temperature, precipitation and also groundwater levels. Streamflow predictions also have the most variability due to the offsetting effects of increased temperature and precipitation.

Additionally, our study area is predominantly urban and heavily populated, which increases not only the infrastructure vulnerability to extreme events but also the runoff that must be handled by rivers and storm-water infrastructure (Suarez, Anderson, Mahal and Lakshmanan, 2005). And with the increases in precipitation intensity from climate change, increases in impervious land cover from urbanization generally leads to larger flood peaks. In this way, both urbanization and climate change stress the water infrastructure.

Despite climatologists strongly arguing in favor of including climate change for policy making and planning, there has been widespread resistance to consider climate change in policies regarding the design and planning of infrastructures. Reasons for this resistance include the fact that the effects of climate change are uncertain and the time horizon extends for decades or longer. Meanwhile, there are insufficient resources even for routine maintenance activities. This research therefore, attempts to take the systemic view regarding the problem of flooding of roads and water shortages by include climate change into the design and planning of critical infrastructure.

3. Research Objectives

The research has been conducted as three separate essays. The first essay (Chapter 2) is focused on the transportation infrastructure, specifically bridges. Chapter 2 examines the consequences of highway bridge design for flooding under the influence of climate change. The research focuses on the portfolio of bridges in a region (Washington Metropolitan Area). Flooding of bridges may cause temporary or, under extreme circumstances, permanent failure of bridge functions in the context of its service to the transportation network if the bridge is subjected to a flood in excess of its design criterion. We specifically look at the freeboard criteria for bridges of different road classifications and how performance would change under future climate conditions. We attempt to examine how the margin of safety, represented by a designed freeboard, may be insufficient to protect the bridge against excessive lateral loads, enhanced scour beneath the bridge and blockages associated with debris jams (especially for smaller bridges). We also examine the impact of imperviousness, which is a function of land use and urbanization, on the susceptibility of the bridge to failure.

The second essay (Chapter 3) examines various factors that determine residential water demand in Washington DC such as climate variables including temperature and precipitation, household variables including household size, demographics, age, etc., economic and policy variables specific to Washington DC. We further attempt to econometrically analyze the impact of some of these variables on the water demand in Washington DC. Besides prices, temperature and precipitation, we also consider the effects of regulatory variables like the impact of the energy policy act on per capita water use. We undertake this exercise to find the cause for the decrease in per capita water demand in Washington DC over the period of twenty years. Another objective of the second essay is to build a foundation for the modeling undertaken in the third essay. It is important to understand the relationships between water use and variables that determine water use before structuring the system that represents various facets of a water demand and supply system for a region.

Finally, the third essay (Chapter 4) attempts to use the knowledge generated from the second essay to model and examine the WMA water supply system to achieve two major objectives. The first objective is to assess the adequacy of the current Washington Metropolitan Area's water supply system to meet the future water need under the influence of historical droughts and climate change. The second objective is more philosophical. We hope this interactive model, developed as a result of this comprehensive research, will be instrumental in facilitating a dialogue and provoking water managers, policy makers and stakeholders into developing potential policy scenarios directed towards mitigation of potential climate impacts on water availability.

In conclusion, this research attempts to analyze the vulnerability of a metropolitan's critical infrastructure to extreme weather events and climate change. We take the systems approach to understand, critically examine, and provide potential solutions to problems concerning an urbanized and highly populated area in the context of its transportation and water supply infrastructures.

4. Research Impact: Points of Departure

The vulnerability of critical infrastructure has been a topic of great interest among researchers and policy makers. Planners and decision makers are also analyzing the impact of climate change on the reliability of service provided by transportation and water supply infrastructures. The exploration of how a systems approach might help to bring together various facets of infrastructure systems so as to assess and provide solutions to problems affecting them is a general point of departure from the current transportation design and water supply management literature. In the first essay, we began with a problem of frequent flooding of roadways in the WMA. Taking a systems perspective, the research attempted to first inquire about the nature of the problem. The research is an attempt to point out the root cause of the problem and to analyze how the problem is further exasperated by climate change. The general point of departure in the analysis of bridge design standards (Chapter 2) comes from the approach taken by the researcher by zooming in on a critical design parameter to examine (freeboard) that is crucial for the performance of a bridge under flooding and then zooming out to include all the factors that impact and get impacted by this design parameter. Factors like local hydrology, transportation network, road classifications, design standards, land use patterns are all taken into consideration while making a judgment on the adequacy of the design standards under the looming threat of flooding and climate change.

Similarly, on the essay on water supply system performance and reliability under the influence of droughts and climate change, the general point of departure originates from the ability of the research to include all sub-systems that constitute the WMA water supply system.

The research attempts to capture key feedbacks and delays that are latent in a purely physical and hydrological representation of a system. The research departs from the current WMA water reliability studies (ICPRB 2010, 2013) in terms of its ability to capture and reproduce the dynamics of demand and supply gaps accruing in the WMA water supply system. Moreover, the research potentially has an ability to be taken directly to the public and policy makers with the aim of developing and implementing comprehensive mitigation and adaptation strategies that potentially can lead stakeholders and policy makers to an agreement on key policy decisions, due to the systems approach and the system dynamics platform that was used for its construction and analysis.

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Chapter 2: Changes to Bridge Flood Risk under Climate Change

Abstract: Bridge designs are commonly based on a criterion to withstand the n-year flood event. For example, a highway bridge might be designed to pass the 100-year flood. Failure may occur if the structure faces an event larger than this. Climate change may necessitate different design criteria because of changes to flood frequency behavior. This study examines the consequences for bridge design for flooding under the influence of climate change. In this study, climate change is quantified simply as a change in the frequency of a given precipitation or flood event. Flood discharges for current conditions are estimated from the applicable US Geological Survey regression equations. Natural Resources Conservation Service methods are used to inverse calculate the causal precipitation for such floods. Return frequency for this causal precipitation is determined from both NOAA Atlas 14 and future climate intensity-duration-frequency curves. This study specifically looks at the freeboard criteria for bridges of different road classifications and how the margin of safety associated with a designed freeboard is reduced under future climate conditions. The results demonstrate that all categories of roadways are vulnerable to climate change and that the magnitude of bridge vulnerability to future climate change is variable depending on which climate model projection is used. The results show that increases in impervious area upstream of a bridge crossing increase the susceptibility of the bridge to failure. Holding other watershed characteristics constant, increased impervious cover leads to a greater loss in the margin of safety represented by the designed freeboard, suggesting that limiting development to control imperviousness can bolster resilience of bridge infrastructure to climate change. A sensitivity analysis shows that uncertainty in both flood and precipitation frequency estimates is at least of comparable magnitude to projected changes in flood risk posed by climate change.

1. Introduction

“Design standards provide uniform applications of the best engineering knowledge that has been developed over time through experimental studies and real-time experience” (Meyer 2008, page 1). This design knowledge is based on a basic understanding of forces of man and nature that act upon an engineering structure. In most cases, transportation infrastructure is designed to withstand either the most extreme or close to the most extreme event that will add abnormal stresses on a structure. For example, a highway bridge might be designed for a 100-year storm event. Failure may occur if the structure faces an event larger than this. Climate change may require different design criteria, capital management policies, maintenance checks, and operating strategies (NRC 2008). It is important to re-assess design standards with an eye towards how climate change may potentially change understood risks (Meyer 2008).

Climate change manifests itself in many ways including an increase in average global temperatures, changes in precipitation patterns, and rising sea levels. Most climate models predict that increases in temperature will be higher over land areas than over oceans and higher in the interiors of continents than in coastal areas (Koetse and Rietveld 2009). Higher temperatures amplify the ability of the atmosphere to hold and transport water vapor, which in turn leads to an increase in rainfall rates. According to the Intergovernmental Panel on Climate Change (IPCC) findings, climate change is likely to increase the frequency of heavy precipitation (IPCC 2014). However, the potential impact of climate change on precipitation is more complex depending largely on local factors such as proximity to water, topography, soil moisture conditions, and wind speed.

In some locations, the intensity of precipitation events will be greater in the twenty-first century (Najjar et al. 2000, Neff et al. 2000, Solomon et al. 2007). Many projections have been made with respect to the change in storm frequency. For example, Wehner (2005) made a projection that the current 20-year return period storm will reduce to a six to eight year frequency over North America. Additionally, population and economic growth will increase the pressure to develop land, thereby increasing not only the infrastructure vulnerability to extreme events but also the runoff that must be handled by rivers and storm-water infrastructure (Suarez et al. 2005). This increased pressure to develop will exist regardless of policy changes concerning land use and/or climate change.

Urbanization has long been understood to be a driver of a range of hydrologic changes (Carter 1961, Leopold 1968, Anderson 1970). As with the anticipated increases in precipitation intensity from climate change, increases in impervious land cover from urbanization generally leads to larger flood peaks. In this way, both urbanization and climate change stress stormwater infrastructure. But while urbanization and land cover have long been considered in drainage design, there is widespread resistance to considering climate change in policies regarding design and planning of infrastructure. Reasons for this resistance include the fact that the effects of climate change are uncertain and the time horizon extends to decades or longer. Meanwhile, there are insufficient resources even for routine maintenance activities.

Climatologists, on the other hand, argue in favor of including climate change for policy making and planning. Scientists are concluding with increasing certainty that the climate is warming. New extremes will occur due to the already existing variability in the climate. Additionally, many climate models suggest changes in precipitation volumes and intensity. Such findings suggest that existing infrastructure design standards may not be adequate to handle possible future precipitation intensity, duration, and frequency (Guo 2006, Maihot and Duchesne 2010, Moglen and Rios Vidal 2014).

Most transport modes and systems perform worse under extreme weather conditions. This is especially true in densely populated regions, where a single event may lead to a cascade of disruptions that influence large parts of the transportation system. Climate variability and change influence transportation mainly through changes in weather-related extreme events, such as severe storms or extreme temperatures. Changes in climate extremes increase the likelihood of intense precipitation (NRC 2008). These events cause transportation difficulties, such as failures of roads and critical links due to flooding and accidents from heavy rainfall or snowfall.

The assumption of stationarity, "….the idea that natural systems fluctuate within an unchanging envelope of variability" (Milly et al. 2008, page 573), is the foundation of water resource engineering. This assumption is being challenged. Researchers argue that climate change is altering means and extremes of precipitation, evapotranspiration, and streamflows and this problem cannot be fixed by more observations, more efficient estimators or higher resolution data. Even aggressive mitigation cannot reverse this trend (Milly et al. 2008). On the other hand, researchers contest that the demise of stationarity is a difficult concept to prove (Villarini et al. 2009a) as it is extremely challenging to clearly distinguish the impact of climate change on peak discharges (Villarini et al. 2010). Villarini et al. (2009) also point to the difficulty of establishing the presence (or absence) of long-term persistence in hydrometeorological variables. Countering the above argument, Milly et al. (2015) assert that although the trends are difficult to decipher, we should be sensitive to the possibility of a type-II error (the perceived absence of a trend), especially when there is a convincing reason to suspect a trend.

This study examines the consequences of highway bridge design for flooding under the influence of climate change. The portfolio of bridges in a region represents a significant investment in transportation infrastructure. Flooding of bridges certainly represents a temporary failure of bridge function in the context of its service to the transportation network. Under extreme circumstances, permanent failure can also result if the bridge is subjected to a flood in excess of its design criterion. In this study, climate change is quantified simply as a change in the frequency of a given precipitation and associated flood event. For instance, the 100-year flood under the historical climate may, under a changed climate, correspond to what is currently a more frequent, say 50- or 75-year event. This study specifically looks at the freeboard criteria for bridges of different road classifications and how performance would change under future climate conditions. We examine how the margin of safety represented by a designed freeboard may be reduced under future climate projections. Reductions in the margin of safety may render bridges impassible, vulnerable to excessive lateral loads, enhanced scour beneath the bridge, blockages associated with debris jams (especially for smaller bridges) that may divert flow around bridge supports at either side of the channel or other conditions that could contribute to temporary or permanent failure.

2. Climate Change Models

Most infrastructure design standards are based on the assumption of a stationary climate. NOAA Atlas 14 (Bonnin et al. 2006) provides the most current values of precipitation intensity, depth, and frequency (IDF) for most locations in the US. One approach to quantify the effects of climate change on infrastructure flood risks is to develop or obtain IDF curves based on climate model products for direct comparison to current IDF curves. This is the approach we use in this study.

There are many climate models and, although these climate models vary, the majority concurs with the positive trends in storm intensity (Solomon et al. 2007). This study uses IDF curves developed by Moglen and Rios Vidal (2014) for four future climate models to calculate storm frequency for future climate conditions. Moglen and Rios Vidal (2014) performed frequency analysis on 30 year long time series data provided by the North American Regional Climate Change Assessment Program (NARCCAP; Mearns et al. 2009) to determine the 2- and 10-year rainfall depths for various time durations. The NARCCAP information is presented as a regional climate model plus a general circulation model (RCM+GCM) pair. Climate models used in this study are listed in Table 1.

Table 1: Climate model pairs used in this study from NARCCAP (adapted from Mearns et al. 2009).

Climate Model Name	Description (Resolution - 0.5° by 0.5° grid)
CM 1: CRCM+CCSM	Canadian regional climate model + the community climate system model, version 3.0
CM 2: ECP2+GFDL	Experimental climate prediction center regional spectral model + the geophysical fluid dynamics laboratory general circulation model
CM 3: HRM3+GFDL	Hadley regional model 3 + the geophysical fluid dynamics laboratory general circulation model
CM 4: RCM3+GFDL	Regional climate model version 3 + the geophysical fluid dynamics laboratory general circulation model

The IDF characterization of McCuen (2005) was used to construct climate model IDF curves. Rainfall intensity for shorter durations was approximated as:

$$i = \frac{a}{D+b} \tag{1}$$

where *i* is in units of mm/hour and *D* is in hours. Durations longer than one hour were modeled as a power law function:

$$i = cD^d \tag{2}$$

Moglen and Rios Vidal (2014) determined the parameters *a, b, c* and *d* using numerical optimization. These IDF curves were then used in this study to assess potential changes in storm frequency produced by the climate change models listed in Table 1. Frequency curves for more extreme events were not established by Moglen and Rios Vidal (2014) because of the limited time series length of the NARCCAP sources.

3. Overview of the Study Area

This study focuses on Montgomery County, Maryland, located immediately north of Washington DC (see Figure 1). This study employs IDF curves developed by Moglen and Rios Vidal (2014) as their work was focused on this same area. The regional portfolio of bridges examined in this study is comprised of 30 stream crossings, covering four major road classifications (Table 2), located near Rockville, Maryland (see Table 7 in Appendix A for their watershed characteristics). These crossings are indicated by various symbols in Figure 1.

Table 2: Road classification and freeboard criteria.[1]

Road Category	Design Flood Frequency (years)	Description	Freeboard cm(inch)
A1	100	Primary highway with limited access	30.5 (12)
A2	50	Primary road without limited access	25.4 (10)
A3	25	Secondary and connecting road	20.3 (8)
A4	10	Local, neighborhood, and rural road	15.2 (6)

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[1] Freeboard criteria vary from state to state. It is generally provided in every state's transportation manual but some state transportation manuals may only contain freeboard criteria for larger design floods. Freeboard is directly proportional to the design flood of a hydraulic structure i.e. larger is the design flood of a hydraulic structure, larger will be the freeboard. Therefore, in absence of a specific design criteria regarding freeboard (which is the case with our study area), we assume the values of freeboard as given in Table 2.

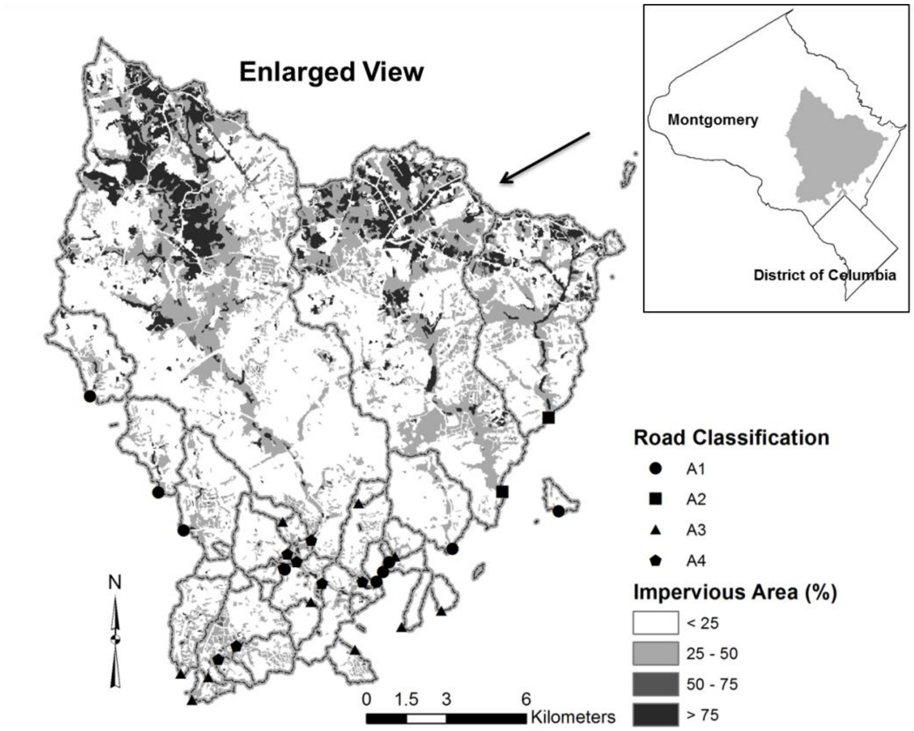

Figure 1: Location map showing stream crossings. Shading indicates intensity of impervious cover.

4. Methodology

The US Federal Highway Administration groups the nation's roadways according to their functional class. Each functional class is based on the type of service the road provides to the drivers. The interstate system (A1 classification) provides the highest level of mobility and the highest speeds while local roads (A4 classification) provide more limited mobility to residential areas, businesses, farms, and other local areas. Each functional class is built to a specific design standard. This study focuses on the freeboard for bridges built to different roadway classifications (Table 2) and quantifies the margin of safety provided by the freeboard in terms of the storm magnitude at which the design freeboard is exhausted and flood flows begin to engage with the bridge structure. The range of future storm frequencies estimated for the different climate models provides a sense of the variability or uncertainty in the climate model predictions.

In simple terms, freeboard can be understood as a margin of safety. Freeboard is the elevation difference between the bottom of the bridge structure and the design flood level. Its role in the bridge design is to compensate for the many unknown factors that could contribute to a flood stage greater than the stage calculated for a selected design flood. The freeboard criterion is different for different roadway classifications and may not be sufficient to manage large climate change driven floods.

In order to estimate the consequences of climate change in terms of the adequacy of the margin of safety, this study combines hydrologic analysis of watersheds, channel geometry, and normal depth calculations with future IDF curves derived from climate models to estimate the reduction in the margin of safety resulting from climate change.

The study is conducted in three parts: hydrologic analysis to estimate the discharge that will begin to engage the bridge (Part 1), urban hydrologic analysis using an inverse approach to SCS (Soil Conservation Service) methods to estimate precipitation depths (Part 2), and IDF curves from NOAA Atlas 14 and future climate models to assign probability to these precipitation depths (Part 3).

Part 1. Hydrologic Analysis to Estimate Flow/Bridge Engagement Discharge

The first step of the hydrologic analysis is to identify the stream crossings and the associated bridges. The National Elevation Dataset (NED) (USGS, 2015) for the study area is used to determine stream locations in the watershed. The regional road network (USCB, 2015) is overlaid on the resulting stream network. Intersections of all streams and roads are identified as the watershed outlets corresponding to bridge locations. The outlets are used to delineate the watershed draining for each intersection point across the entire network. Finally, each delineated watershed is used to determine a suite of watershed characteristics such as the drainage area, curve number, watershed slope, channel slope, and impervious area (see Table 7 in Appendix A).

Calculating Peak Discharges

In Maryland, different sets of regional peak flow regression equations (Thomas and Moglen 2010) correspond to the five physiographic provinces within the state (Appalachian Plateaus, Blue Ridge, Piedmont, Eastern Coastal Plain, and Western Coastal Plain). Regional regression equations may include many independent variables such as drainage area, channel slope, channel length, average basin elevation, forest cover percentage, and impervious area.

This study focuses on the urbanized Piedmont physiographic province where the drainage area and the impervious area are the predictor variables required for the region. Peak discharges, Q_a, were calculated using the regression equations provided in Table 3. These regression equations tie drainage area (DA, in km^2) and impervious area (IA, in percent) to peak discharges (Q_x, in m^3/s) corresponding to different flood frequencies, x, for urbanized watersheds in Maryland's Piedmont region.

Table 3:Peak flow regression equations for the Urban Piedmont region of Maryland (adapted from Thomas and Moglen 2010). Drainage area, DA, is in km2 and impervious area, IA, is in percent.

Storm Frequency, x (years)	Regression Equation	Standard Error (percent)
10	$Q_{10} = 3.57DA^{0.622}(IA+1)^{0.435}$	26.2
25	$Q_{25} = 7.21DA^{0.619}(IA+1)^{0.349}$	26.0
50	$Q_{50} = 11.9DA^{0.619}(IA+1)^{0.284}$	27.7
100	$Q_{100} = 19.0DA^{0.619}(IA+1)^{0.222}$	30.7

Calculating Channel Geometry

Regression equations are also used to calculate channel geometry based on the drainage area. In this study we simply assume a rectangular channel with width w and depth h. A study focused on the Maryland Piedmont (McCandless and Everett 2002) found that the greatest percent of the variability in width is explained by the drainage area. Channel width (in m) is calculated as:

$$w = 3.11DA^{0.39} \tag{3}$$

Determining the Depth of Water in a Stream

Although other considerations might place the bridge at higher elevations, the assumption in this study is that the bridge elevation is set by discharge. In order to find the depth of water in a channel, we require channel width and slope. Uniform flow is assumed and the normal depth associated with Q_a based on channel geometry and slope is calculated. Freeboard is added to the normal depth for Q_a to determine the depth of water that would exceed the freeboard design criterion. The corresponding discharge, Q_b, which will lead to this water elevation is calculated. At the end of Part 1 of the methodology, we have a value of discharge that may cause the failure of the bridge corresponding to a flood of a particular frequency.

Computed findings from Step 1:-

- Q_a (m^3/s) – flow in the stream corresponding to the design flood. The design flood will be for n years depending upon the type of roadway, which comes from the Maryland highway drainage manual standards (MDOT 1981).
- Q_b (m^3/s) – flow in the stream corresponding to the depth of water that will cause the flow to begin to engage with the bridge structure.

Differences between Q_a and Q_b are a function of bridge classification, freeboard criteria and watershed characteristics. In the remainder of this paper, references to the "failure frequency" or "failure return period" are with respect to Q_b as defined above. Although the bridge may not be permanently damaged by floods in excess of Q_b, we interpret here a flow that begins to engage with the bridge structure as representing a failure of the design freeboard, if nothing else.

Part 2. Urban Hydrological Analysis Using SCS (Soil Conservation Service) Method in Reverse

The flow/bridge engagement discharge, Q_b, serves as the input for the second step. In this study, we employ SCS methods to back-calculate the depth of precipitation that generates a given peak discharge. SCS methods require drainage area, curve number (*CN*), channel slope, and watershed slope. The curve number, which reflects the land use and soil conditions of the watershed, determines the storage, *S*. Curve number is related to *S* (in m) using (SCS, 1986),

$$S = 0.0254(\frac{1000}{CN} - 10) \tag{4}$$

Further, the initial abstraction (I_a, in m), which represents water retained in surface depressions and intercepted by vegetation, is a simple fraction of the storage. Although, there is a renewed debate on this fraction (Hawkins et al. 2006), we employed the traditional I_a=0.2*S*. Runoff (Q, in m) is calculated using the following formula (SCS 1986),

$$Q = \frac{(P - I_a)^2}{(P - I_a) + S} \quad (5)$$

where P is the 24-hour precipitation depth (in m). Employing the simple TR-55 graphical method (SCS 1986), peak discharge (Q_p in m^3/s) is calculated.

$$Q_p = 2.32 q_u (DA) Q F_p \quad (6)$$

In equation (6), DA is the drainage area in km^2, F_p is the pond and swamp adjustment factor (assumed equal to 1), and q_u is the unit peak discharge having the units of (m^2/sec-km^2). Unit peak discharge is a function of two variables: time of concentration (in hours) and the ratio of the initial abstraction to the 24-hour precipitation (I_a/P). Unit peak discharge is calculated as (SCS 1986),

$$q_u = 0.43(10^{C_0 + C_1 \log(T_c) + C_2 [\log(T_c)]^2}) \quad (7)$$

where C_0, C_1, and C_2 depend on I_a/P and an assumed SCS Type II rainfall distribution. The time of concentration depends on flow length (l in m), average watershed land slope (Y in percentage), and storage (S in m) of the watershed. Main channel flow length is first determined using equation (8) (NRCS 2010).

$$l = 1740 DA^{0.6} \quad (8)$$

The time of concentration, T_c (in hours), is then estimated using equation (9) (NRCS 2010).

$$T_c = 6.65 \frac{l^{0.8}(0.03S + 1)^{0.7}}{1140 Y^{0.5}} \quad (9)$$

Finally, equations (5) to (9) are solved iteratively to obtain the value of precipitation corresponding to peak discharge Q_p from equation (6). Specifically, a search algorithm is used to find the precipitation value that produces the discharge, $Q_p = Q_b$ from Part 1, symbolically called $P(Q_b)$, the precipitation depth (in m) that produces the discharge, Q_b.

Part 3. Determining the Frequency Associated with Precipitation Depth

Calculations for Current Climate

Table 4 provides 24-hour precipitation depths near the study watersheds for various frequencies ranging from 1 to 1000 years based on observed climate. The 24-hour precipitation depth $P(Q_b)$ generated in Part 2 that exceeds the freeboard may lie between two storm frequencies. To determine the storm frequency in such a case, we use a log-normal interpolation as shown in equation (10),

$$\boldsymbol{Z_{F_f} = Z_{Upper} - (Z_{Upper} - Z_{Lower})(\frac{log(P_{Upper}) - log(P(Q_b))}{log(P_{Upper}) - log(P_{Lower})})} \quad (10)$$

where Z_{F_f} is the z-score for cumulative probability, F_f (where F_f is the return period in years corresponding to $P(Q_b)$). Z_{Upper} is the z-score for the cumulative probability for the upper-bound storm frequency and Z_{Lower} is the z-score for the cumulative probability for the lower-bound storm frequency. P_{Upper} and P_{Lower} are the precipitation depths corresponding to the upper- and lower-bounds of storm frequency, respectively. The failure frequency or return period, F_f (in years) is then calculated using equation 11,

$$\boldsymbol{F_f = \frac{1}{1 - Prob(Z_{F_f})}} \quad (11)$$

where $Prob(Z_{F_f})$ is the non-exceedance probability corresponding to Z_{F_f} .

Table 4: Current climate precipitation depths (24 hours) near Rockville, MD for various recurrence intervals ranging from 1 to 1000 years (adapted from Bonnin et al. 2006).

Average recurrence interval (years)	1	2	5	10	25	50	100	200	500	1000
24-hr Precipitation depths (mm)	66.0	80.0	102	122	153	180	211	246	300	348

Calculations for Future Climate

This study, by its nature, requires estimates of much larger return periods. We extrapolated to larger return periods using an index flood approach (McCuen 2005). Extrapolation adds to the uncertainty of the process, but the behavior of the equations and approach convey the concept of increased flood risk owing to climate change. Greater accuracy, achievable with interpolation, will be obtained in the future when climate models are further refined and available time series projections cover periods greater than 30 years.

Table 5 provides 2- and 10-year (24 hour duration) precipitation depths for four climate models (Moglen and Rios Vidal 2014) in the vicinity of Rockville, Maryland, located near the study watersheds. Equation (12) extrapolates precipitation depths for larger return periods for four different climate models CM1, CM2, CM3, and CM4,

$$P_{24}(CM_j, x_{year}) = P_{24}(CM_j, b_{year})\left[\frac{P_{24}(NOAA, x_{year})}{P_{24}(NOAA, b_{year})}\right] \tag{12}$$

where $P_{24}(CM_j, x_{year})$ is the precipitation depth for climate model j (j=1, 2, 3, and 4) for the x year (x = 5, 10, 25, 50, 100, 200, 500, 1000) return period and $P_{24}(NOAA, x_{year})$ is the precipitation depth for current climate taken from NOAA Atlas 14 for return period, x. The argument, "b_{year}" is the "base year" data to be used. These base year values may correspond to either 2- or 10-year values. Finally, once the precipitation depths are computed for all four climate models, equations (10) and (11) are used to find the storm frequency associated with the flow that just begins to engage with the bridge structure.

Table 5: 2- and 10-year, 24 hour, precipitation depths near Rockville, MD for climate models used in this study (adapted from Moglen and Rios Vidal 2014).

Return Period (years)	CM 1 (CRCM+CCSM) depth (mm)	CM 2 (ECP2+GFDL) depth (mm)	CM 3 (HRM3+GFDL) depth (mm)	CM 4 (RCM3+GFDL) depth (mm)
2	107	83.3	92.2	103
10	169	121	166	164

5. Results and Discussion

The distributions of precipitation frequency estimates (in years) that will exceed the bridge freeboard for current and future climate are illustrated in Figure 2. These results are determined using 10-year estimates as the base year in equation 12. The results demonstrate that all categories of roadways (A1, A2, A3 and A4) are vulnerable to climate change. The return period at which flow/bridge engagement occurs for current (NOAA) precipitation is higher compared to future climate scenarios from CM1, CM3, and CM4 for all types of roads. Illustrating the variability and uncertainty in the climate modeling process, the CM2-based return period for flow/bridge engagement is actually slightly greater than the NOAA Atlas 14 return period because the 10-year, 24-hour precipitation depth for CM2 is slightly smaller than the corresponding NOAA value. Although the specific details are not shown for Bridge ID #1 (see Table 7 in Appendix A), its failure return period is 320 years based on the current climate, while this failure return period projects to 75, 333, 80, and 86 years for the CM1, CM2, CM3, and CM4 climate scenarios, respectively. This change in failure frequency quantifies the change in flood risk. Figure 2 also shows the variability between the four different climate models. Under CM 1 conditions, a bridge will be susceptible to failure at a lower storm frequency as compared to CM 2, CM 3 and CM 4. This observation holds across all categories of roadways. This is because CM1 (CRCM+CCSM) projects the largest 24 hour precipitation depths (see Table 5) relative to the other climate models examined.

Although not surprising, this study shows that local roads are more vulnerable to change in precipitation than highways. Current road design policies lead to precipitation depths that cause exceedance of freeboard more readily for local roads than for major roadways, meaning, local road bridges (A4 classification) will be flooded at lower rainfall depths (averaging 150 mm) compared to an average of 280 mm highway bridges (A1 classification). What is perhaps more alarming is the median projected frequency of flow/bridge engagement for A4 (local) roads. In this group, failure frequency changes from 23 years for current climate to 6, 24, 7, and 7 years for CM1, CM2, CM3, and CM4, respectively. Failure frequencies of 6 and 7 years for 3 of the four models are, indeed, very frequent projected levels of occurrence. CM2, as discussed earlier, projects a slightly smaller 10-year, 24 hour rainfall depth so failure frequency actually increases slightly for this model. Such a frequency of exceedance of the design freeboard is a concern because of service losses during flooding, and the stronger likelihood of bridge damage or loss. Concomitantly, bridge/flow interaction also causes upstream backwater effects, thus increasing the likelihood of flooding other areas in addition to the road itself. This may further lead to an increase in the risks associated with mapped flood inundation zones.

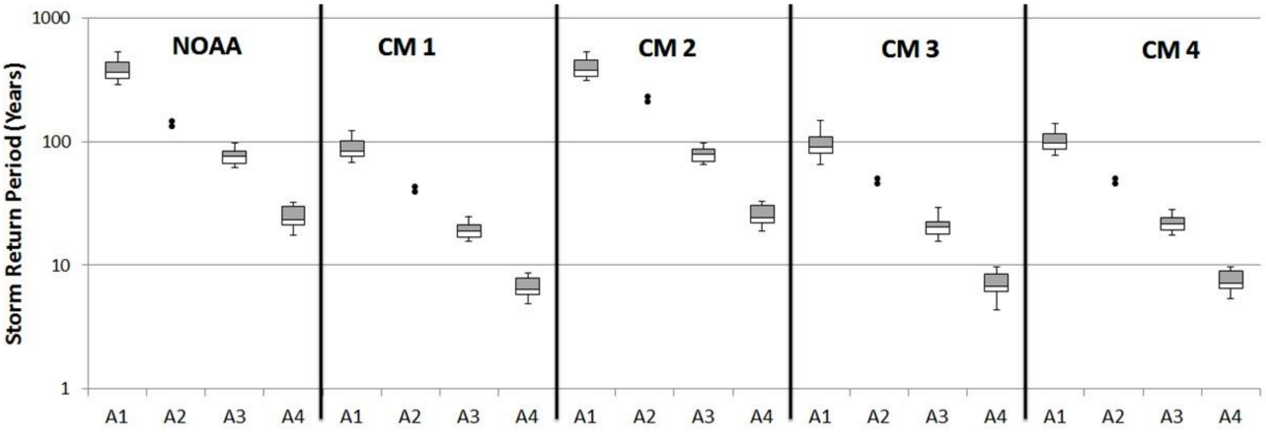

Figure 2: Distribution of flow/bridge engagement return period as a function of climate model and road classification.

We explored the hypothetical dependency of failure frequency on impervious area over a range from moderately to highly urbanized conditions. We focused on Bridge ID #1 (see Table 7 in Appendix A). The observed imperviousness for the watershed draining to this bridge is about 41.1 percent. We hypothetically varied the imperviousness from 25 percent to 55 percent. It is understood that curve number would co-vary coherently with imperviousness, so we followed the TR-55 (SCS, 1986) approach of developing a weighted curve number assuming lawns in good condition (curve number is 61 on “B” soils, the dominant hydrologic soil group in this watershed) for pervious areas and a curve number of 98 for impervious areas. The resulting dependency of curve number on imperviousness is thus,

$$CN(IA) = \left(1 - \frac{IA}{100}\right) \cdot 61 + \left(\frac{IA}{100}\right) \cdot 98 \qquad (13)$$

All other calculations proceeded as described previously. Our findings are shown in Figure 3.

This varying imperviousness experiment speaks to the changing resiliency of a bridge to climate change as urbanization (imperviousness) increases within the associated watershed. Figure 3a shows that the precipitation required to attain flow/bridge engagement decreases with increasing imperviousness. Each analyzed value of impervious area assumed the bridge elevation to be set based on the regression equation peak discharge. In fact, precipitation *decreases* for two reasons: 1) the modeled watersheds become more efficient at converting precipitation to runoff as *IA* increases; and 2) the time of concentration decreases as curve number (dependent on *IA*) increases (see equation 9), leading to a larger unit peak discharge (see equation 7). These results show that a single prescribed freeboard for a given roadway classification provides a varying margin of safety since the freeboard in a less urbanized system (low *IA*) would have a lower likelihood of failure than that same freeboard in a more urbanized system (high *IA*). All else being equal, the margin of safety provided by the bridge freeboard is smaller in a more urbanized watershed. From a land use planning perspective, limiting imperviousness in a watershed provides resiliency to infrastructure placed in that watershed, as a greater amount of precipitation is required to lead to flow/bridge engagement in a less urbanized watershed. Although it is advisable to limit imperviousness, such limits may be difficult to achieve. The most resilient bridge designs account not only for climate change, but also for changes in urbanization, recognizing the difficulty in partitioning the relative impact of climate change and urbanization flood magnitudes (Villarini et al. 2009b).

Climate change plays a pivotal role in future bridge flooding risk given anticipated increases in precipitation depths and intensities. Figures 3b and 3c show the relationship between the precipitation depths in Figure 3a and their corresponding return periods for current and projected future climate. In Figure 3b, return periods are estimated based on equation 12 using projected 2-year depths as the base year while Figure 3c uses projected 10-year depths as the base. It should be readily apparent that in all cases (except CM2, 10-year depths) future climate models project smaller return periods for a given precipitation depth relative to the current NOAA Atlas 14 frequencies. The difference between current and future climate return periods vary, with model CM1 (CRCM+CCSM) again differing the most. Thus, the greatest reduction in the margin of safety afforded by the designed freeboard would result from the future climate represented by CM1. Differences between Figures 3b and 3c illustrate the sensitivity of the return period estimation (equation 12) to the base return period used to extrapolate.

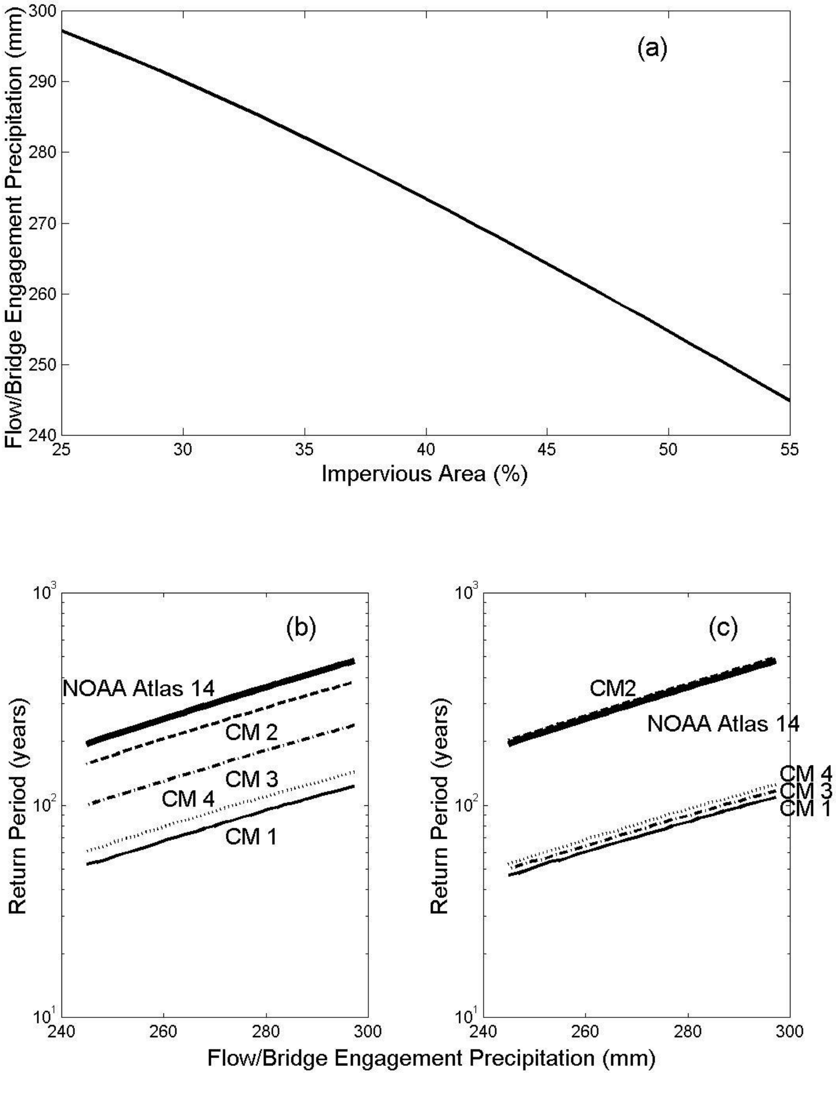

Figure 3: Impervious area experiment at Bridge ID #1: (a) Variation in flow/bridge engagement precipitation with imperviousness, (b) Return period for NOAA Atlas 14 and four climate models associated with flow/bridge engagement precipitation.

While this study has focused on the reduced margin of safety brought on by projections in changing precipitation depths as a function of climate change, it is useful to examine these changes in the context of uncertainty in both the peak discharge estimates and current climate precipitation estimates. To do this, we performed a sensitivity analysis employing the reported standard error of the peak discharge regression equations and the reported confidence limits for the NOAA Atlas 14 estimates to determine the 5th, 50th, and 95th percentile estimates of discharge and precipitation depth, respectively. These estimates were then carried through the same analyses previously described to estimate the failure return period corresponding to the associated precipitation depths. Table 6 shows a summary of our findings.

We continue our focused examination of Bridge ID #1. This is an A1 category road associated with a 100-year design flood frequency. From Table 3, the standard error of the 100-year regression equation is 30.7 percent (Thomas and Moglen 2010). This bridge has a 50th percentile flow/bridge engagement discharge, Q_b equal to 68 m^3/s, which (considering the design freeboard) has a failure return period of 320 years. Considering standard error in the peak discharge regression estimates, we estimate the 5th and 95th percentile discharges varying from 31 to 105 m^3/s, respectively. The NOAA Atlas 14 precipitation depths that result in these discharges are 157 to 384 mm with failure return periods of 28 years to greater than 1000 years, respectively. Similarly, considering the confidence intervals in the reported NOAA Atlas 14 precipitation depths, we estimate failure return periods ranging from a low of 160 years to 741 years for the estimated 273 mm of rainfall needed to produce the 50th percentile, 68 m^3/s discharge.

We can now put three different sources (peak discharge, precipitation, future climate model) of uncertainty into context. For the four climate models studied, the estimated future range of return periods for flow/bridge engagement vary a low of 75 years (CM1) to a high of 333 years (CM2). The ranges determined based on peak discharge and precipitation uncertainty were both broader than the range demonstrated across the four climate models examined. It should be noted that the choice of the 5th and 95th percentile values was arbitrary. If a smaller confidence interval, such as between the 25th and 75th percentiles, had been chosen, the range of return periods reflecting uncertainty in either peak discharge or current precipitation frequency would have been smaller than reported in Table 6. These results do not diminish the importance of considering climate change-driven effects on precipitation frequency in assessing future flood risk. These results simply convey the inherent uncertainty in other elements of these modeling calculations, giving context to the range of climate change results presented as the main element of this paper.

Table 6: Sensitivity of flow/bridge engagement return period to uncertainty in peak discharge and NOAA Atlas 14 precipitation frequency.

Q_p (Peak Discharge (m^3/s)	Percentile Estimate (%)	NOAA Atlas 14 Return Period (years)		
		5%	50%	95%
105	95%		>1000	
68	50%	741	320	160
31	5%		28	

6. Conclusions

This study concludes that bridges of all classifications are generally subject to a higher risk of flooding in the future due to climate change because of a general reduction in the return period corresponding to the precipitation depth that will lead to exceedance of the design freeboard. This is an important result for transportation policy makers who create and review bridge design standards. This study suggests that it may be necessary to revisit existing infrastructure and to re-evaluate future flood risks. For planned new infrastructure, it may be necessary to establish new design standards that somehow incorporate the non-stationarity in flood risk presented by climate change. New standards might consider specific climate models or work with an ensemble of many climate models on which to base pending designs.

Future climate-based failure frequencies depend on the roadway classification. All classification groups are projected to have an increase in flood risk as a result of climate change. The median failure frequency of the A4 classified roads (which have the smallest design freeboard) was projected to change from a current 23 years to a range of 6-24 years among the future climate models used in this study, with three of the climate models projecting median failure frequencies of 6 to 7 years. These are rather high frequencies at which to experience exceedance of freeboard. Although climate change does threaten to increase flood risk of existing infrastructure, a sensitivity analysis at one location showed that uncertainty in both flood and precipitation frequency estimates is at least of comparable magnitude to the projected changes in flood risk posed by climate change.

The finding that urbanized watersheds are more susceptible to increased flood risk from climate change suggests that a more nuanced planning approach to bridge design might be necessary. Any approach for future climate would obviously consider projected changes in climate. However, the fact that greater urbanization leads to freeboard exceedance at a smaller precipitation depth demands consideration for planning purposes as well. The findings here show that a bridge is somewhat buffered against changes in climate when less urbanization is present within the watershed draining to the said infrastructure. Thus, careful land use planning and management shows promise to limit the vulnerability of infrastructure to anticipated climate change.

Although the main findings presented here are solid, it is important to enumerate some of the simplifying assumptions and limitations in this study. Climate modeling was based on the 2- and 10-year, 24-hour depth estimates generally requiring equation 12 to extrapolate based on current (NOAA Atlas 14) precipitation frequency to much larger return periods. Extrapolation carries the potential for large errors. Additionally, regionalized regression equations for both peak discharge and channel geometry were used in lieu of at-a-site measurements to minimize the sources of variability presented by the unique circumstances of a particular location. Finally, results are limited by the assumptions inherent in the NRCS TR-55 model which was used to inverse calculate the causal precipitation associated with all estimated flood values.

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Chapter 3: The Estimation of Residential Water Demand in Washington DC

Abstract: In this essay, we examine various factors that determine residential water demand in Washington DC. The factors include climate change variables like temperature and precipitation, household variables like household size, demographics, age, etc., economic and policy variables specific to Washington DC. This essay builds a foundation for the modeling undertaken in the third essay. It is important to understand the relationships between water use and variables that determine water use before structuring the system that represents various facets of a water demand and supply system of a region. We also econometrically analyze the impact of variables on the per capita water demand in Washington DC. Besides prices, temperature and precipitation, we consider the effects of regulatory variables like impact of the energy policy act. The per capita demand in Washington DC is going down over the period of last twenty years. The estimation results suggest that price and people per household are most significant determinants for water demand in Washington DC. Washington DC is unique in terms of its metropolitan character. Due to its expanding size, household size it increasing, which helps reducing average water demand for the region. Increasing prices also cause water demand to fall. Water demand increases with temperature and decreases with precipitation. The energy policy act also causes the water demand to diminish because this act calls for the use of more efficient plumbing fixtures.

1. Introduction

One of the strategies for coping with increasing water demand has been to expand the supply of water, but this strategy is constrained by the limitation of water resources. Therefore, there has been a significant change in the approach to water management, which traditionally focused on supply-side policies.

The economic, social and environmental factors are changing very rapidly, which also affects the demand for water. Washington DC is a fast evolving region. Its population is growing at a fast rate. Being an economic hub, it also attracts young migrant and immigrant workers, which changes the demographics, household, household size and water use behavior for the region. Additionally, climate change is likely to alter temperature and precipitation patterns, which will again affect water use. The climate projection for our region shows an upward trend in temperature, precipitation and streamflow (Neff, Chang, Knight, Najjar, Yarnal and Walker, 2000). Najjar, Patterson, and Graham (2009) evaluated the four best performing Global Circulation Models (GCM's) in the Chesapeake Bay area and suggested an increase in temperature of around 4 °C by the end of the century. Similar results were found for rainfall, which is expected to increase over the next 100 years, by 15% and streamflow is expected to increase by 11% by the end of the century. The largest variability is found in streamflow as it is the most difficult to predict.

Thus policy makers and water managers have to take into account all of the above varying factors that impact water use, before making any decisions regarding future water security. For example, if the region's water demand is expected to increase in the future, investment has to be made for new water infrastructure or water conservation policies have to be initiated. If a drop in water consumption is anticipated, tariffs have to be managed so that consumption does not increase. Also, reduced water consumption may also pose technological challenges. For instance, a decreased flow-rate could exacerbate sedimentation of sludge in sewers and re-formation of germ layers in fresh water pipes (Schleich and Hillenbrand, 2009). Moreover, not only is the cost of changing and adapting water infrastructure is huge (Schleich and Hillenbrand, 2009) but also the acquisition of newer water resources is riddled with conflicts, legal, financial and environmental concerns. Therefore, it is important to make correct assessment and prediction of future water demand.

In this study, we examine various factors that determine residential water demand in Washington DC. The factors include climate variables like temperature and precipitation, household variables like household size, demographics, age, and, economic and policy variables specific to Washington DC. This essay builds a foundation for the modeling undertaken in the third essay (Chapter 4). It is important to understand the relationships between water use and variables that determine water use before structuring the system that represents various facets of a water demand and supply system for a region.

We also econometrically analyze the impact of variables on the per capita water demand in Washington DC. Besides prices, temperature and precipitation, we consider the effects of regulatory variables like impact of energy policy act, 1992. The per capita demand in Washington DC is decreasing over the period of the last twenty years. Knowledge of the determinants that influence domestic water demand constitutes an essential ingredient in the design of conservation policies for domestic water supply. The European Union (EU) in its Water Framework Directive also recommends the use of water prices in conjunction with other conservation methods to promote the reasonable use of water, such as information/education campaigns, prevention and reduction of leaks, installation of low flow appliances and faucets in homes, as the instruments to be used by a demand based water management strategy (Martins and Fortunato, 2007). The methodology involves using time series data for water demand. Most water use estimation studies are conducted in a static framework, which means water consumption is specified as a function of current price and other socioeconomic variables. But on the contrary, current water use is strongly influenced by past water use. Therefore, a dynamic model that explicitly takes this relationship into account may produce more robust explanations and predictions of domestic water demand behavior (Nauges and Thomas 2003).

2. Water Demand in Washington DC

Washington DC is the capital of United States. It is part of the larger Washington Metropolitan Area (WMA) and also houses the federal government. Historically the WMA has experienced population growth rates higher that the national average. The Washington Metropolitan Area is the seventh largest U.S. metropolitan area and according to Metropolitan Washington Council of Governments (MWCOG) Round 7.2 Cooperative Forecast for the year 2040, it is expected to grow from the 2010 levels by approximately 24 percent (MWCOG 2009; ICPRB 2010). Consequently, such high growth will place a tremendous additional burden on WMA's resources such as water, power and land, which are already quite constrained..

In the WMA, water demand is mainly driven by Public Supply (PS) and Thermoelectric Power withdrawals. According to United States Geological Survey, PS refers to water withdrawn by public and private water suppliers. This water is primarily used for domestic purposes. A non-trivial amount of water is also used to cover system losses. Examples of PS withdrawals for domestic uses include water for drinking, cooking, washing, toilet flushing, lawn watering, car washing, and so forth. In total, 97% of water withdrawals are surface water withdrawals thus making the WMA vulnerable to stream level fluctuations in times of low precipitation rates.

The District of Columbia Water and Sewer Authority (DCWASA) provides retail water and wastewater (sewer) service to the District of Columbia. DCWASA provides drinking water and collects and treats wastewater for more than 600,000 residential, commercial and governmental customers in the District of Columbia (DCWASA, 2016). The main source of water in the WMA is the Potomac River. There are three main utilities: 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 agencies. Of the three utilities, the Washington Aqueduct provides treated water to DCWASA. Also, the Washington Aqueduct takes water only from the Potomac River, thus making supply vulnerable to low stream-flow conditions in the river (ICPRB 2010; ICPRB 2013).

Remarkably, the per capita water use per year has declined in Washington DC (see Figure 1). The major reasons for this decline may be the passing of the Energy Policy Act of 1992, the increase in water prices and the increase in number of people per household residing in the region. The Energy Policy Act of 1992 calls for the use of more efficient plumbing fixtures for both commercial and residential use (Vickers, 1993). This policy aims at reducing water consumption solely by putting low flow restrictions on the type of appliances installed in homes and commercial establishments.

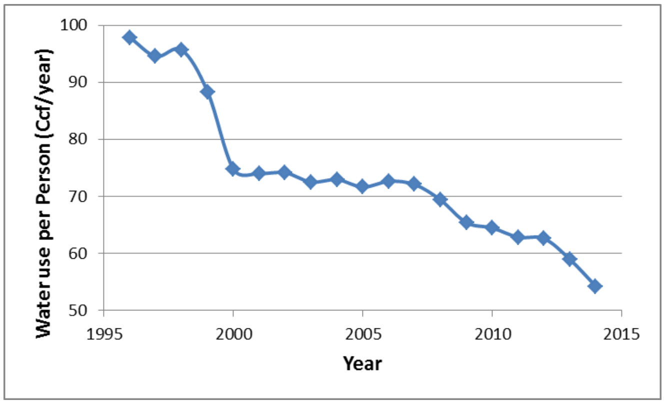

Figure 1: Per Capita Water Use in Washington DC[2]

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[2] Data Source: (DCWASA, 2015) (per capita water use is calculated as total water billed divided by DCWASA divided by population of Washington DC)

3. Variables and Data

The descriptive statistics of the variables used in the econometric analyses are displayed in Tables 1 and 2. The data are available in the form of a time series from the years 1996 to 2014.

Table 1: Variable Description

Variable	Description/Definitions	Units
water_use_per_capita	Water consumed per person per year	*Ccf/year*
price_per_ccf (100 cubic feet)	Price of water and sewer combined per ccf	*$/ccf*
people_per_household	Number of people living in a single house	*Persons*
impact_energy_policy_act	Number of dwellings with new low flow appliances installed	*Number of dwellings*
temperature	Extreme maximum temperature per month averaged over a year	*Celsius*
precipitation	Total precipitation amount for the month averaged over a year	*Millimeters*
operating_expenses	Annual WASA operating expenses	*(thousand)$/year*
operating_revenues	Annual WASA operating revenues	*(thousand)$/year*

Table 2 – Descriptive Statistics for Dependent and Independent Variables

	Min	Max	Mean	SD
water_use_per_capita	54	98	74	12

price_per_ccf	2.87	8.02	5.19	1.38
people_per_household	1.89	2.12	2.05	0.08
impact_energy_policy_act	14680	104336	60171	30019
temperature	27	31	29	1
precipitation	75	149	94	16
operating_expenses	157182	367319	253803	60674
operating_revenues	181036	521241	314182	94007

3.1 Dependent Variable

The dependent variable for this study is ‘water use per person’. This variable measures annual water consumption per person in the Washington DC area. The data were gathered from the District of Columbia Water and Sewer Authority (DCWASA, 2015). ‘Water use per person’ is calculated as the ratio of the total amount of water billed to the customers by the water utility and the total number of people residing in the city.

Explanatory Variables

There are many factors that impact water use, but some factors may have more significant impact than others. It is important to list all the factors before narrowing down the few that are most significant because even the direction of the relationship is critical, for example, we may expect water use to increase due to increasing summer temperature, but it may be not be true for all regions, for example, a study in Germany found the relationship to be opposite citing various reasons such as age of population (Schleich and Hillenbrand, 2009). Therefore, we try to list and study most of the variables that influence water use in our region. The variables have been broadly categorized in five basic categories: behavioral, climate, household, policy and economic.

Behavioral Variables

Water consumption can be regulated by many mechanisms. Regulating the type of appliances that are installed in homes is one of them. Although, these mechanisms are effective in curtailing water use they usually don’t impact peoples’ attitudes toward the various aspects of water supply and associated choices. For long-term and sustainable water conservation, is it necessary to encourage voluntary water conservation by the alteration of water use behavior (Gleick, 1998). For this reason, water agencies have conducted non-price focused campaigns to promote change in peoples' behavior. In Washington DC, MWCOG runs a year round 'wise water use' campaign to demonstrate simple wise water use practices. But due to the ubiquitous nature of conservation campaigns and their possible interaction with other policy instruments such as pricing changes, it is important to evaluate the effectiveness of the conservation campaigns in promoting voluntary household water conservation behavior (Syme, Nancarrow and Seligman, 2000). Such campaigns are both short and long run. The literature provides methods to evaluate these campaigns. But, most of the methods refer to the impact of these campaigns during extreme conditions like droughts and low-flows rather than the long-term effects of ongoing campaigns. The Interstate Commission on the Potomac River Basin (ICPRB), in a 2010 study, evaluated the impact of voluntary and mandatory emergency restrictions on the system water demand for the Washington Metropolitan Area. But in their forty year demand forecast they have not included the impact of ongoing awareness campaigns like 'wise water use' and the US Green Building Initiative (ICPRB 2010).

Many researchers have tried to study the effectiveness of such awareness campaigns (Maki, Hoffman, and Berk, 1978; Mercer and Morgan, 1980; Kamin, 1978; Berk, Schulman, McKeever and Freeman, 1993; Berk, Hoffman and Maki, 1980; Michelson, McGuckin, and Stumpf, 1999; Wang, Song, Byrne and Yun, 1999; Lee and Warren, 1981; Bruvold, 1979; Bruvold and Smith, 1988; Gilg and Barr, 2006). All campaigns that specifically dealt with education outreach and creating awareness amongst people were measured in terms of the annual or monthly budgets for these activities. It is important to make these evaluations because they show the amount of water use reduced as a consequence of the campaign. Problems often occur when studies try to incorporate various aspects of these campaigns like the printing of messages on water bills, education outreach programs for water conservation in schools, water bill rebate program for conservative water users, etc. This may result in multi-collinearity among different variables due to the close temporal proximity of the introduction of all aspects of the campaign. Many times, a failure to differentiate between different aspects of these campaigns leaves less scope for the policy makers to decide how to make improvements in such campaigns (Syme, Nancarrow, and Seligman, 2000).

For this study, we examined MWCOG's 'wise water use' campaign annual budget (in dollars) as one of the explanatory variables. This variable represents the amount of resources used to create awareness among the Washington DC population about water as a scarce resource. The MWCOG in cooperation with local water utilities adopted the national "Water, Use it Wisely" program to demonstrate simple wise water use practices. But yearly data for this variable was not available to be included in the econometric equation.

Climate Variables

Worthington and Hoffman (2008) classify domestic water demand into two components: non-discretionary and discretionary demand. Non-discretionary water use includes water use for basic human indoor needs like drinking, cooking, sanitation, and cleaning. Water use, for all other activities that are not necessary for human survival such as maintaining gardens and swimming pools, washing cars, etc., is considered as discretionary water use. Since discretionary water use is regarded as being more price responsive than non-discretionary water use, state agencies and water utilities focus on the reduction of discretionary water consumption per person. Moreover, discretionary water use is also directly impacted by climate. Several variables are used to reflect the impact of climate on domestic water use like rainfall, snow, humidity or temperature. It is important to estimate the sensitivity of domestic water consumption to climate variables since they suggest issues associated with the impact of global warming. Also, most conservation policies are voluntary, mandatory and/or based on emergency restrictions and are only meant to regulate discretionary water consumption (essential water use is not affected). An assessment of the sensitivity of water use to these variables can provide an effective policy approach.

Rainfall

The sensitivity of climate variables to domestic water consumption has been explored in the literature, but the response seems to be varied. Maidment and Miaou (1986) suggest that rainfall has a dynamic effect meaning, rainfall causes a reduction of water demand initially but the effect dampens over time. Sometimes, people have a psychological response to rainfall. Some studies, therefore, include the number of rain days as an explanatory variable (Mart´ınez-Espiñeira, 2002), (Schleich and Hillenbrand, 2009). Maidment and Miaou (1986) argue that rainfall occurrence is more critical than its magnitude, reiterating the point Mart´ınez-Espiñeira made in 2002. For our study, we include total precipitation amount for the month averaged over a year as an explanatory variable.

Temperature

Similarly, some researchers suggest a non-linear response to temperature change. There is a threshold beyond which temperature starts impacting water use. While examining daily water use in nine US cities, Maidment and Miaou (1986) found that there is no response for daily maximum air temperatures between 40° and 70°F (4–21°C).

The study area for this research is not considered to be water deficient and receives approximately forty inches of rainfall annually. The response of people living in Washington DC can be very different from people belonging to areas of water scarcity like Denver or Las Vegas. Consumers residing in areas with low annual rainfall are more sensitized to water conservation than those living in water abundant areas. Moreover, living conditions of consumers in Washington DC may impact their response to rainfall or temperature. Since the majority of dwellings in Washington DC are apartment types with no or non-existent lawns or gardens, the outdoor water use may not play a very important role in predicting domestic water consumption. Therefore, it is expected that climate variables will have a very low elasticity as compared to other explanatory variables. For this study, climate data were collected from National Oceanic and Atmospheric Administration (NOAA). Higher temperature may cause people to take showers, water their lawns more frequently and use their pools more frequently, thus increasing water usage. But as Maidment and Miaou (1986) pointed out, there is threshold over which the temperature starts to impact water use. For our study, we include extreme maximum temperature per month averaged over a year as an explanatory variable.

Household Variables

There are many household characteristics that impact domestic consumption such as the number of people living in a house, their ages, type of house, habits of people living in a household in terms of water usage, etc.

Household size

‘Household size’ or the ‘number of people living in a household’ is an important explanatory variable. An initial consideration of this variable gives the impression that this variable should be positively associated with domestic water use. In fact, some studies indicate that although the elasticity with respect to the number of residents indicates that the amount of water consumed increases with the number of household members, the increase in water use is often less than proportional (Arbu´es, Barberan and Villanua, 2000; Höglund 1999). However, if we aggregate this variable over a city that has limited number of dwellings and a growing population, and study its impact on ‘per person’ water consumption, we might observe different results. The reason behind the difference in outcomes could be peculiar characteristics of our study region. Big metropolitan cities like our study area (Washington DC) have a predominance of multi-family type dwelling units, with smaller housing lots and smaller gardens. It is more energy and resource efficient to live in a multifamily household because six people living in three houses consume more water and energy than six people living in two houses. Water consumed for common activities will be shared by three people instead of two, thus lowering the per person water use. A study conducted by the American Water Works Association on The Residential End Uses of Water, published in 1999 calculated the indoor per person water use. The study found that over 50% of the total domestic indoor water use is a shared resource (see Figure 2). If we include outdoor water use the shared portion increases further (see Figure 3). Thus, intuitively it should make sense if ‘per person’ water consumption decreases with an increase in ‘number of people living in a household’. Also, since Washington DC has a high population growth rate, but a limited number of dwelling units, the impact of ‘household size’ may be more significant for this region. The census data also shows that ‘occupancy per room’ has increased over the course of twenty years. But the ‘household size’ elasticity for water demand is not uniform over the entire domain of the explanatory variable. To incorporate this effect, we add the squared term of (the natural log of) ‘people per household’ along with the natural log of ‘people per household’. This specification allows the ‘household size’ elasticity to differ, thus capturing the effect of a large ‘household size’ on water use because water use cannot go on decreasing indefinitely with an increase in ‘household size’ (Schleich and Hillenbrand, 2009). Research also shows that there is an optimum household size beyond which these economies of scale vanish (Arbués et al. 2000). For this study, ‘people per household’ is used as one of the explanatory variables. The source of these data is US Census Bureau.

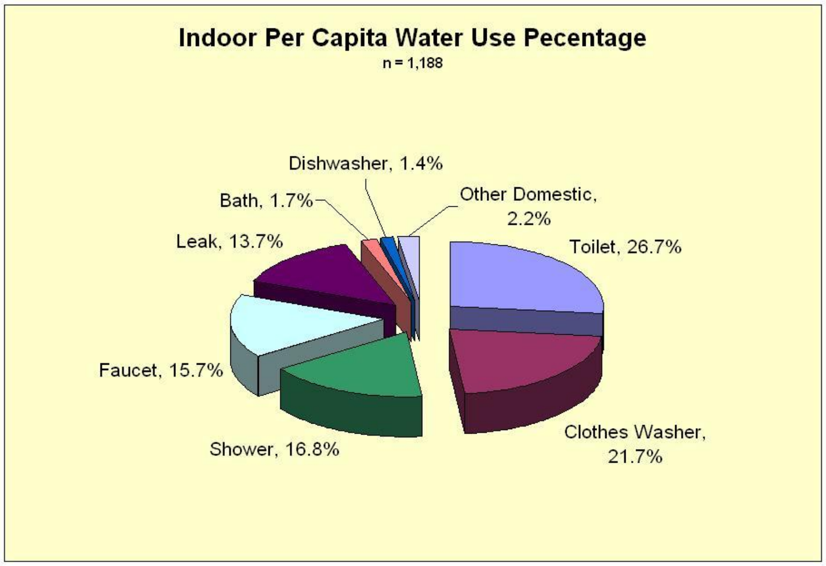

Figure 2: Indoor Per Person Water Use Percentage (Mayer, DeOreo, Opitz, Kiefer, Davis, Dziegielewski, and Nelson, 1999)

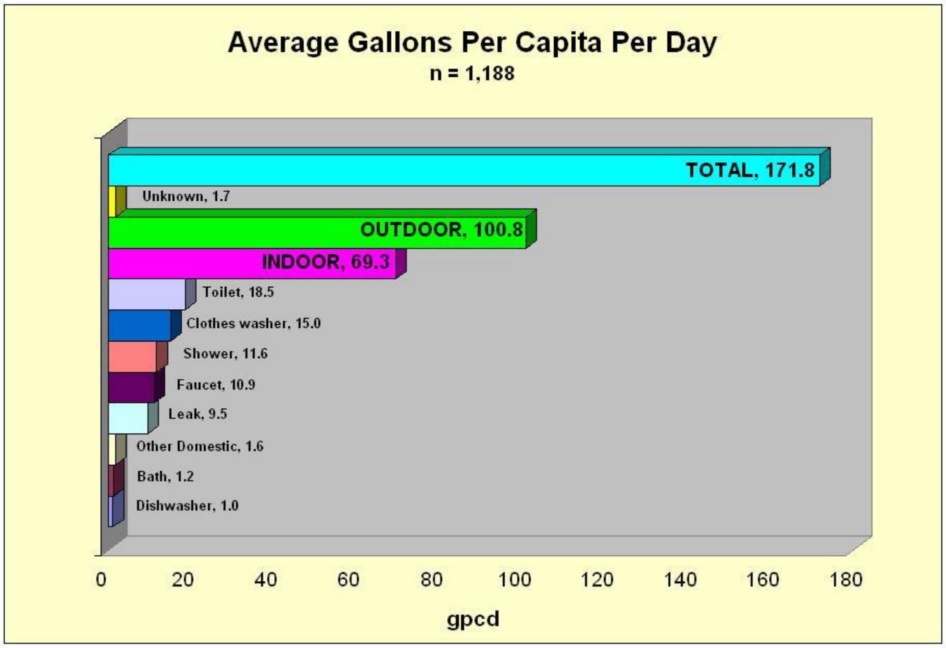

Figure 3: Average Gallons Per Person Per Day (Mayer et al., 1999)

Age

‘Age’ of household members also determines the domestic water use. Families with children use more water both indoors and outdoors. Young people generally use water less carefully; take more frequent showers or do laundry more frequently, while retired people might be more conservative Arbue´s, Garcı´aValin and Martınez-Espineira, (2003), Nauges and Thomas (2000), Martins and Fortunato (2007), and Musolesi and Nosvelli (2007) confirm the above stated hypothesis. But Billings and Day (1989) and Schleich and Hillenbrand (2009) found a positive relation between per person water use and age. They argue that old people use toilets more frequently due to health reasons and they spend lot of time at home in gardening (Billings and Day, 1989). For this study, we have not included age as an explanatory variable due to lack of data about population age.

Demographics

In addition, the background of people also impacts their water consumption. People coming from developing countries may be conservative in their water consumption because of the scarcity of municipal water supply in their countries. Some studies have explored the impact of background and culture on ‘per person’ water use. While studying the effects of socio-demographic factors on ‘per person’ residential water use in Texas, Murdock, Don, Albrecht, Hamm, Bachman, Parpia. (1988), found that the fraction of Hispanic immigrants had a significant negative impact on per person water use. Pfeffer and Mayone (2002) also found that immigrants were more likely than the native-born to save water, other individual characteristics being equal. Researchers like Smith and Ali (2006) similarly argue that immigrants from developing countries may be more frugal in consuming water. For this study, we looked at the share of immigrants in Washington DC population to compute the impact of demographics on ‘per person’ water use. But yearly data for this variable were not available to be included.

Type of House

Single family dwelling units consume more water compared to multi-family or apartment type dwelling units because single family homes have gardens and lawns that use large amounts of water. Also they have more bathrooms and faucets, thus losing more water due to leaks. For obvious reasons, this variable is expected to have a positive impact on per person water use. The data for this variable came from Census data. The census data have information about the number of housing structures. One unit detached and attached dwellings were bundled together to find the share of single family dwellings. This variable is critical for areas where the share of single family dwellings is comparable to multi-family dwellings because outdoor water use is quite high for single family houses. Most draoght restrictions (voluntary or mandatory) apply to this component of water use. For Washington DC, this variable might not have a considerable impact on domestic water use because the share of single family dwellings has not changed considerably over the past twenty years. Also, yearly data for this variable were not available to be included in the econometric equation.

Policy Variables

To manage water demand, various non-price controls can be put on consumption. These prohibitions and restrictions can be voluntary or mandatory. Policies can be behavior changing or non-behavior changing. A behavior changing policy targets people's attitude towards water consumption. Such policies rely on information campaigns to create awareness among people about scarcity of a resource and methods to curtail wasteful usage. On the other hand, non-behavior changing policies target technology to bring about reduction in water usage. For example, the Energy Policy Act or 1992 calls for the use of more efficient plumbing fixtures. With the passage of this law, the United States will have uniform water efficiency standards for nearly all toilets, urinals, showerheads, and faucets manufactured after January 1994 (Vickers, 1993). This policy aims at reducing water consumption solely by putting low flow restrictions on the type of appliances installed in homes. For our study, we have included the penetration of the Energy Policy Act of 1992, as one of the many explanatory variables. This variable is calculated based on the assumptions made by the ICPRB in their 2010 reliability study. They have assumed that all houses built after 1994 have low flow toilets and two percent of the original 1994 housing stock in the Washington DC area is remodeled each year with low flow toilets (ICPRB 2010). This variable is expected have a negative elasticity with respect to 'per person' water consumption and is expected to be significant.

Economic Variables

Price is the economic variable considered in this study as one of the key determinants of residential water demand. Intuitively, residential water consumption should be inversely related to water prices. In cases where customers are charged volumetrically, water demand estimation is relatively straightforward. Issues arise when utilities have block rates, meaning increasing/decreasing rate structures where prices increase/decrease as consumption increases/decreases (Hewitt and Hanemann, 1995; Dandy, Nguyen and Davies, 1997; Nordin 1976; Worthington and Hoffman, 2008). Worthington and Hoffman (2008) have discussed various research papers that deal with the price elasticity of demand.

DCWASA charges its customers volumetrically (dollars per hundred cubic feet). Customers are charged for water, sewer, customer metering and impervious area. Whereas the customer metering and impervious area charge is a fixed cost per ERU (Equivalent Residential Unit), water and sewer are billed volumetrically that is, they are based on how much water a household consumes. Rates charged to customers also cover the cost of delivery of water and sewer service.

In cases where prices are set to cover costs, an increase in water consumption results in lower prices and vice versa because the fixed cost components are distributed among higher consumption levels (Schleich and Hillenbrand, 2009). This method of setting prices that is based on average cost pricing rather than marginal cost pricing induces the problem of “endogeneity” or “simultaneity”, which means water prices actually depend on water demand. Since the price of water both determines and is determined by consumption, OLS yields biased and inconsistent estimates. Price, which is an explanatory variable, is correlated with the error component thus violating the orthogonality condition. To counter this we use the Instrument Variables (IV) technique, which is a two stage regression. This study uses an IV technique suggested by Nieswiadomy and Molina (1991), which is a two stage regression. This involves regressing observed price variable against other explanatory variables in the first stage along with other instruments which are uncorrelated with water demand. The predicted price is then specified as one of the regressors in the second stage equation that regresses water demand with rest of the explanatory variables. This technique improves the reliability of estimates.

Moreover, an Independent Comprehensive Budget Review in 2008 (DCWASA, 2008), commissioned by the DCWASA Board of Directors, observed that the fixed portion of the user charge of WASA's rate structure is in the bottom quartile (less than half of the average) of the fixed charges compared to the other large systems surveyed that have fixed charges. A higher fixed component of the user charge can provide greater revenue stability and reduce the size of rate increases needed to offset declining consumption and a lower fixed component may lead to a stronger dependency of rates on consumption. This means that the endogeneity problem may be significant for our study. Therefore, it is expected that there should not be a significant difference between the estimates yielded by one stage regression and IV regression, which is a two stage regression.

4. Estimation of Water Demand

Functional form

A functional form which is popularly used in water demand estimation is the log-log form, which yields direct estimates of elasticities. The disadvantage of the log–log model is that it assumes elasticities to be constant over the entire domain of explanatory variables (Schleich and Hillenbrand, 2009; Arbu´es et al., 2003; Williams, 1985; Dandy et al., 1997). There are many other functional forms that have been used in literature for water demand estimation like linear water demand functions, log-linear functions, Stone–Geary form, Box-Cox functional form, etc. (Arbu´es et al., 2003). The log-log functional form has been used for our study because the coefficients of the explanatory variables in a Log-Log regression equation can be directly interpreted as elasticities. This paper used Equation 1 to determine the annual water demand in Washington DC (all variables are in log).

$$\textit{water\_use\_per\_capita} = \beta_0 + \beta_{1*}\textit{lag\_water\_use\_per\_capita} + \beta_2 * \textit{price\_per\_ccf} + \beta_3 * \textit{people\_per\_household} + \beta_4 * \textit{impact\_energy\_policy\_act} + \beta_5 * \textit{temperature} + \beta_6 * \textit{precipitation} + \mu_0 \quad \ldots\ldots\ldots..\textit{Eq. (1)}$$

Econometric model

Water demand literature is analyzed for investigating all variables that impact domestic water use. Some variables are common for all regions like price of water, climate factors like rainfall and precipitation, etc. But some variables are specific to a particular region like the impact of the energy policy act, which is a variables specific to Washington DC. Although it is difficult to do a comparative analysis of the impact of such variables for different regions, these variables are important to capture the whole picture of domestic water use.

We have to count for serial correlation in time series data. Serial correlation occurs in time-series studies when the residuals in one period are correlated with residuals in previous periods. Examples of serially correlated data are tariff rates, debt, energy consumption, etc. Serial correlation does not affect the bias or consistency of OLS estimators, but it does affect their efficiency. If a positive serial correlation is present, the OLS estimates of the standard errors will be smaller than the true standard errors, which will lead us to a conclusion that the parameter estimates are more precise than they really are. There will be a tendency to reject the null hypothesis when it should not be rejected. It is also easy to identify serial correlation; a graph of the residuals can be one such indicator. The Durbin–Watson test can also be used. The null hypothesis for Durbin-Watson test is H_0: no autocorrelation. In the case of positive serial correlation, the ‘lag of water use per person’ is taken as one of the explanatory variables.

There is also a possibility of endogeneity in the model. WASA charges its customer for water, sewer, customer metering and impervious area. Rates charged to customers also cover the cost of delivery of water and sewer service. Also, WASA has low fixed charges as compared to other large utility systems, which means a decrease in water demand results in higher prices because the fixed costs are distributed among higher consumption levels. Therefore, prices may have an endogenous impact. To address the possible endogeneity problem, we attempted to use the Instrument Variables (IV) procedure. The first stage of the procedure regresses water prices based on a set of instruments (Eq. 2). In the second stage of IV, Eq. (1) is estimated using OLS, but now the predicted prices from the first stage (Eq. 2) are used instead of the price, as an explanatory variable. The instrument for the first stage contains ‘operating expenses’ and ‘operating revenues’ along with all the variables in Eq. (1).

$$\textit{price\_per\_ccf} = \beta_0 + \beta_1 * \textit{lag\_water\_use\_per\_capita} + \beta_2 * \textit{people\_per\_household} + \beta_3 * \textit{impact\_energy\_policy\_act} + \beta_4 * \textit{temperature} + \beta_5 * \textit{precipitation} + \beta_6 * \textit{operating\_revenues} + \beta_7 * \textit{operating\_expenses} + \mu_0 \;\ldots\ldots\ldots\text{Eq. (2)}$$

We also made a few changes in the model equation to incorporate the non-uniform elasticity of the variable ‘household size’. We add the squared term of (the natural log of) ‘people per household’ along with natural log of ‘people per household’ (Eq. 3).

$$\textit{water\_use\_per\_capita} = \beta_0 + \beta_1 * \textit{lag\_water\_use\_per\_capita} + \beta_2 * \textit{price\_per\_ccf} + \beta_3 * \textit{people\_per\_household} + \beta_4 * \textit{people\_per\_household\_square} + \mu_0 \;\ldots\ldots\ldots\text{Eq. (3)}$$

5. Results and Analysis

First, we conduct the Durbin-Watson Test for serial correlation that tests the null hypothesis H_0: that the errors are uncorrelated, against the alternative hypothesis $H_{1:}$ that the errors are AR (1). Based on the Durbin-Watson test statistic we reject the null hypothesis that the errors are uncorrelated and thus concluding that there is serial correlation in the data. To correct the model for serial correlation we include 'lag of water use per person' as one of the regressors in Eq. (1). Estimation result for the regression is displayed in Appendix B, Table 3. According to results, the 'lag water use per person', 'price per ccf' and 'people per household' were found to be significant variables. Therefore, equation (4) may be used for estimation purposes.

$$water\_use\_per\_capita = \beta_0 + \beta_1 * lag\_water\_use\_per\_capita + \beta_2 * price\_per\_ccf + \beta_3 * people\_per\_household + \mu_0 \quad \ldots\ldots\ldots..Eq.\ (4)$$

Other than that, we also included variable 'people per household square' variable in Eq. (3). For the log–log model, the 'people per household' elasticity of water demand can be calculated as $\beta_3 + 2\beta_4 people\_per\_household\_square$. This means if β_3 is positive (negative), the 'people per household elasticity' elasticity is higher (lower) for higher 'people per household' levels and the 'people per household' elasticity would become positive only if the number of people per household were to go beyond 4.67 persons (exp ($\frac{\beta_{people\_per\_household}}{\beta_{people\_per\_household\_square}}$)). Table 6 in Appendix B displays the result for the model that contains the variable 'people per household square'. This result makes intuitive sense because as the number of people goes beyond a certain limit the per person savings obtained from having more people in a household will go away and a more linear relationship between people per household and per person water use will be observed. Also, the elasticity of water use with respect to people per household is negative (positive) for smaller (larger) values.

Regression results in Table 3 (Appendix B) show that 'people per household' is a significant explanatory variable, which represents the total number of people living in a house. The parameter estimate associated with 'people per household' is negative and significant (p-value < 1%). This means, as the number of people in a household increases, per person water usage decreases because over 50% of the total domestic indoor water use is a shared resource in US (Figure 2) and several water uses such as laundry, housecleaning, lawn maintenance, cooking, etc. increase less than proportional to the increase in number of people in a household. Also, the elasticity value is greater than 1, meaning the change in quantity of water demanded is proportionally larger than the change in household size. We also included ‘people per household square’ as one of the explanatory variables and its elasticity came out to be negative.

The regression point estimate for the price elasticity is -0.2. The value of price elasticity is at the lower spectrum of those found in the literature. This can be justified by a relatively low share of water costs in total household expenditure. Moreover, an Independent Comprehensive Budget Review in 2008 (DCWASA, 2008), commissioned by WASA Board of Directors, observed that percentage increases in rates at DCWASA were somewhat lower than the average percentage increases experienced by other large utilities. The lower rate of increase in water prices coupled with an increasing per person income of Washington DC explains lower price elasticity for this region. Also, US has one of the lowest mean water tariffs ($2.72 per 1,000 gallons 2000) in the world (EPA, 2002). Across the literature there is a wide variation in price specification, but the lack of variation in price elasticity estimates, which belies the substantial variation in price specification (Worthington and Hoffman, 2008). Almost all studies find estimated price elasticities to be negative and less than one, which means the percentage reduction amount of water demanded is less than proportionate to the percentage increase in price. Price elasticities also vary in magnitude across the literature.

Parameter estimates for summer temperature show a positive sign but it is not statistically significant in our model (p-value > 0.5). The ‘temperature’ variable represents extreme maximum temperature per month averaged over a year. We tried including a threshold over which the temperature starts to impact water use but it was not as significant as the average summer temperature. The reason could be the weather characteristics of the Washington DC region. Washington DC is not a dry or excessively hot region, therefore people don’t frequently experience heat waves that will propel them to fill up their pools or water their gardens more frequently, so they react to average temperature rather than spikes in temperature. Similarly, the parameter estimate for precipitation also showed the expected sign (i.e. negative), but the estimate is also not significant. To conclude, climate variables are not significant for our region for two reasons: first, it does not suffer from water scarcity; second, Washington DC has mostly multi-family type housing which reduces the impact of weather further because apartments do not have lawns and gardens where the impact of weather will be mostly felt. Finally, the parameter estimate for ‘impact of energy policy act’ came out to be negative as expected, meaning per capita water use decreases with the increase in the impact of Energy Policy Act. Energy Policy Act is measured by its penetration and the penetration is measured by the number of houses with low flow appliances each year. The estimation results show this variable to be insignificant. The reason for this could be the already saturated housing market of Washington DC. Since not many new houses are being constructed and only 2% of older stock are being remodeled, the penetration of this act in Washington DC is too low to impact demand.

The Instrument Variables (IV) technique account for “endogeneity” in water prices. The IV technique is a two stage OLS regression. The first stage of the IV procedure predicts water prices based on a set of instruments as seen in Eq. (2). In the second stage, Eq. (1) is estimated using OLS, but now the predicted prices from the first stage are used in place of the price variable. Besides the remaining explanatory variables in Eq. (1), the set of instruments for the first stage also contains the natural logarithm of ‘operating expenses’ and ‘operating revenues’ as additional instruments. The results of the first and second stage of IV procedure are displayed in Table 4 and Table 3 (Appendix C) respectively. The parameter estimates for the additional instrument variable ‘operating expenses’ and ‘operating revenues’ in the first stage have the expected positive and negative sign, respectively. Then we proceed to test the exogeneity of prices in Eq. (1). We do so by comparing the estimates obtained from IV second stage with the ones obtained from OLS technique, which can be tested by Hausmann test. This test checks for the exogeneity of the regressors and not for the exogeneity of the instruments. The Hausman test checks for the Null hypothesis (H_0) of exogeneity, which means that the difference in coefficients of second stage IV and OLS is not systematic (Hausman, 1978) or that endogeneity does not affect the OLS estimator. This test compares β_{IV} and β_{OLS}. Under H_0, β_{OLS} is both consistent and efficient and β_{OLS} is consistent but inefficient and since both are consistent under the null hypothesis, the difference between them should vanish as sample size approaches infinity. Under the H_1, β_{OLS} is inconsistent but β_{IV} remains consistent[3].

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[3] The Hausmans test statistic H is equal to $(\beta_{IV} - \beta_{OLS})^T [Var(\beta_{IV}) - Var(\beta_{OLS})]^{-1} (\beta_{IV} - \beta_{OLS})$.

To begin with, we expected prices to be endogenous because the fixed cost component of DCWASA is lower than other bigger utilities. But the test statistic can reveal that there is no significant difference between OLS and IV estimates, meaning prices are not endogenous. We explored the DCWASA financial reports to figure out the cause. It was found that DCWASA actually has very resilient prices. The DCWASA system assessment report (DCWASA, 2008) reveals that recent percentage increases in rates at WASA were lower than the average percentage increases of those experienced by other large cities. This can be attributed to WASA's aggressive bill collection strategies that, coupled with enhanced billing techniques, have significantly improved cash collections and reduced outstanding receivables to relatively low levels. Due to system wide improvements, WASA has been able to keep its rates more stable, which explains the exogeneity of prices.

Per capita water use in Washington DC decreases with an increase in water prices and decreases with an increase in the penetration of Energy Policy Act. Per capita water use also decreases with an increase in household up to a certain level, over which economies of scale vanish. Water use decreases with an increase in temperature as people tend to use more water if the weather is warm. Water use also decreases if rainfall increases. Estimation results suggest that price and 'people per household' are significant determinants for water demand in Washington DC and could possibly explain the drop in per capita water use in Washington DC over the last 20 years. This essay laid foundation for the modeling undertaken in the third essay as it is important to understand the relationships between water use and variables that determine water use before structuring the system that represents various facets of a water demand and supply system for a region.

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Chapter 4: Performance Assessment of Washington Metropolitan Area's Water Supply System under the Impact of Climate Change and Droughts

Abstract: Fresh water demand is rising due to multiple factors such as, population growth, economic development and land use changes. Climate change is rendering water even more uncertain for the future. Moreover, due to the recurring water restrictions and increasing water related taxes triggered by droughts and water shortages, there is a growing discomfort among people regarding future water availability. This has led to an increased interest in modeling the availability of water resources among stakeholders and local policy makers, with the aim of developing and implementing appropriate water resources infrastructure and management strategies. This paper attempts to examine the WMA water supply system to assess the adequacy of our study area's water supply system to meet the future water demand under the influence of historical droughts and climate change. The study found that our study area is self-sufficient under normal conditions during the entire planning horizon but will be strained under moderately severe droughts. Climate change will positively impact water supply system reliability, provided climate parameters move as anticipated (move towards the higher end of their ranges). However, climate change has uncertainty associated with it. Climate Change parameters may move towards the lower end of their ranges, which will decrease system's reliability. Regulating price and system losses can be valuable tools that can be leveraged. But these policy interventions require stakeholder participation (price regulation) and capital investments (curbing distribution losses). Finally, system reliability can also be improved by increasing supplies.

1. Introduction

Fresh water demand is rising due to multiple factors such as, population growth, economic development and land use changes. Moreover, climate change is rendering water even more uncertain for the future (Evan and Davies, 2011). Relentlessly rising demand and climate uncertainty are not the only factors affecting future water availability; the third World Water Forum held in Kyoto concluded that water scarcity is often an outcome of mismanagement (WWF, 2003). Moreover, there is a growing discomfort among stakeholders regarding recurring water restrictions and increasing water related taxes triggered by droughts and water shortages.

This has led to an increased interest in modeling the availability of water resources among stakeholders and local policy makers, in terms of supply and demand, with the aim of developing and implementing appropriate water resources infrastructure and management strategies (Evan and Davies, 2011). But modeling the water supply system is challenging due to its complexity in terms of number of sub-systems involved, which makes it difficult to develop a comprehensive mitigation and adaptation strategy that potentially can lead stakeholders and policy makers to come to an agreement regarding mitigation strategies. The complexity also makes it difficult to educate the public about the elements that may cause a water supply system to lose reliability such as droughts, population increase, crumbling water infrastructure, climate change, etc. Thus, simulation and modeling tools that can represent a water supply system with all or most of its components and demonstrate the effects of management policy interventions can be extremely valuable (Chung, Kim and Kim 2008).

Therefore, this paper models and examines the WMA water supply system to achieve two major objectives. The first objective is to assess the adequacy of the current Washington Metropolitan Area (WMA) water supply system to meet the future water demand under the influence of historical droughts and climate change. The second objective is more philosophical. We hope this interactive model, developed as a result of this comprehensive research, will be instrumental in facilitating a dialogue and provoking water managers, policy makers and stakeholders into developing potential policy scenarios directed towards mitigation of potential climate impacts on water availability rather than giving precise numerical prediction of the volume of water stored in a reservoir, which is the purview of hydrological models (Sušnik, 2012).

The objectives of this research were accomplished by creating a water demand-supply model to assist in water resource planning and decision making for the WMA region that spans over 15 counties and 6 county-equivalent cities, plus Washington DC. The 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) to analyze the impact of historical droughts and low flows on water availability; and 3) to assess the sensitivity of the region’s water supply system under various climate change scenarios and policy intervention scenarios.

The System Dynamic (SD) methodology is used for this research to build and assess the impact of climate change and policy interventions quantitatively. SD affords the engineering team the ability to: a) isolate key causal relationships between the system elements; and b) to graphically represent the constellation of subsystems for lay policy-maker. Moreover, system dynamics is a continuous modeling process that allows for an examination of the effects of multi-year droughts on different reservoirs.

The main advantage of the approach taken in this paper is to provide an integrated assessment (IA) of a water demand and supply system. The model is developed in an object-oriented system dynamics simulation environment. The generality of system dynamics simulation allows for the representation of multiple resources and stakeholders. It allows for an investigation of the feedback-effects of various water resources policies (Evan and Davies 2011). Finally, policy makers and stakeholders are able to look inside the model and understand the relationships that constitute the structure of the model. Unlike the mathematical programming approaches, system dynamics models are flexible and have a transparent structure (Chung et al., 2008).

This paper is organized as follows: Section (2) articulates the problem context. Section (3) provides an overview of the study area and its water resources. Section (4) examines the climate change variables for the study area. Section (5) covers the System Dynamics methodology and previous research. Section (6) provides the quantitative demand supply model; Section (7) discusses the results of the study and finally section (8) discusses the conclusions.

2. Problem Context

The Washington Metropolitan Area is the seventh largest U.S. metropolitan area and according to MWCOG Round 7.2 Cooperative Forecast for the year 2040, it is expected to grow from the 2010 levels by approximately 24 percent (MWCOG, 2009; ICPRB, 2010). Consequently, such high growth will place a tremendous additional burden on WMA’s resources such as water, power and land.

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. 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 (ICPRB, 2010; ICPRB, 2013). Moreover, climate change is expected to challenge the assumption of stationarity, "….the idea that natural systems fluctuate within an unchanging envelope of variability" (Milly, Betancourt, Falkenmark, Hirsch, Kundzewicz, Lettenmaier and Stouffer, 2008, page 573), which is the foundation of water resource engineering and planning. Researchers argue that climate change is altering means and extremes of precipitation, evapotranspiration, and streamflows (Milly et al. 2008). Frequent droughts have already prompted pricy withdrawals from reserve water supplies of the region and associated water studies confirm that the further taxing of reserve supplies is not a viable longer-term strategy (Van Dyne 2007). The WMA water supply system has made releases in three drought seasons since completion of the Jennings Randolph Reservoir (JRR). In 1999, 2002 and 2010, low precipitation and streamflow levels resulted in a water supply that proved to be insufficient to fulfill the region's demand projections during the summer months of these years. Episodes like this, prompted authorities to pay premium prices for additional water resources from the Jennings Randolph and Little Seneca reservoirs (LSR), which are the reserve water supplies for the WMA. The first release 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 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 in 1999, Maryland declared a drought emergency and imposed mandatory water restrictions, which were inconvenient for the residents (Wilson, 1999).

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 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 create an interactive and integrated model of the area's water supply system as a complete entity and to gauge its performance under different climate change, policy, drought and low flow scenarios.

3. Overview of the Study Area and its Water Resources

Our study area, shown in Figure 1, is comprised of 15 counties, 6 county equivalent cities and the District of Columbia. The main source of water in the WMA is the Potomac River. Around twenty water utilities operate in the region. The three main suppliers are: the Fairfax County Water Authority (FCWA), the Washington Suburban Sanitary Commission (WSSC), and the Washington Aqueduct. Approximately ninety percent of the WMA's population relies on water provided by these three main agencies.

The three major regional water suppliers have collectively invested for water storage in the Jennings Randolph and Little Seneca Reservoirs. Jennings Randolph holds 50 million cubic meters of water (USACE, 1997). It is located 322 kilometers 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 14 million cubic meters (Hagen and Steiner, 1999) of water. It is used to "fine tune" the larger releases from the Jennings Randolph.

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 reserves is about 38.6 million cubic meters (Hagen, Steiner and Ducnuigeen, 1998). 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 30 million cubic meters (Hagen and Steiner, 1998). 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).

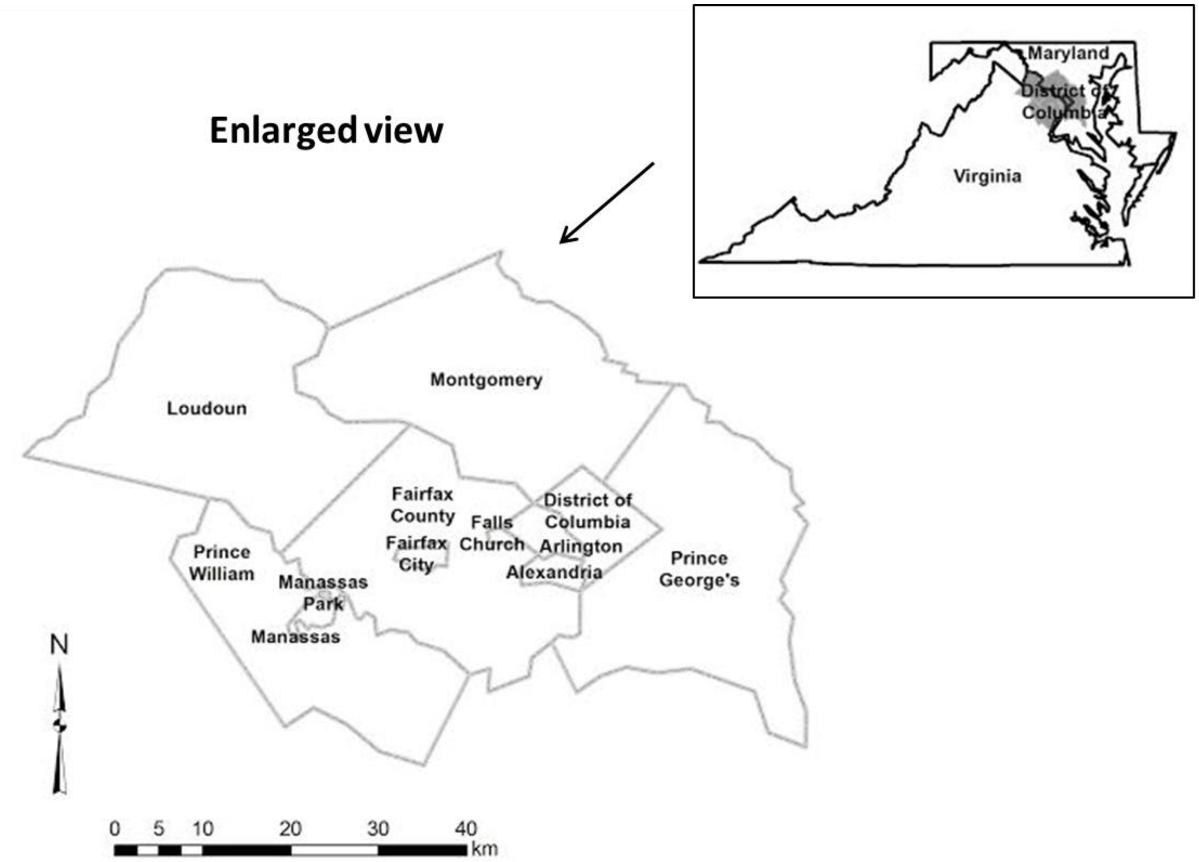

Figure 1: Study Area (Washington Metropolitan Area)

4. Climate change and the Washington Metropolitan Area

The United Nations' Intergovernmental Panel on Climate Change attempted to evaluate and quantify the impact of human activity and its development and progress on climate change. In order to do so they developed a set of four socioeconomic scenarios. These scenarios allowed for varying degrees of population change, development, technological improvements and consumption for the next 100 years and were labeled A1, A2, B1, and B2. These scenarios range from the most optimistic scenario B1 in which human population peaks around mid-century and declines thereafter, which shifts the focus of economies world over from production to service and information sectors, with significant reductions in material intensity and the introduction of clean and resource-efficient technologies, to A2, in which population continues to rise with regionally-oriented economies, fossil fuel usage continues unabated, and technological change is more fragmented and slower than other scenarios (Meehl, Stocker, Collins, Friedlingstein, Gaye, Gregory, Kitoh, Knutti, Murphy, Noda, Raper, Watterson, Weaver and Zhao, 2007; IPCC, 1996; IPCC, 2000).

Najjar, Patterson, and Graham (2009) applied the four scenarios to General Circulation Models (GCMs) in order to get a more detailed assessment of the impact of climate change on the Chesapeake Bay watershed and, more specifically, the Potomac River basin, which is within the Chesapeake Bay watershed. Climate studies conducted for the entire Mid-Atlantic region show an upward trend in temperature, precipitation and streamflow (Neff, Chang, Knight, Najjar, Yarnal, and Walker, 2000). Table 1 depicts the results of the study for the Potomac watershed.

Table 1: Climate Change Impacts in The Potomac River Basin (Najjar et al. 2009)

Year →	**2030**	
Parameter ↓	Mean	Range
Temperature (°C)	+1.25	+1 to +1.5
Precipitation (%)	+4	-1 to +8
Streamflow (%)	+2	-2 to +6

The four climate change scenarios when applied to the Chesapeake Bay watershed GCM, suggest an increase in annual mean temperature by 1.25°C by 2030. Mean annual precipitation is also expected to increase by 4% by 2030 (Najjar et al. 2009). Similarly, streamflow is also expected to increase by 2%. Predictions about streamflow in the Potomac watershed have much greater variability than temperature or precipitation (Neff et al., 2000; Wolock and McCabe, 1999; Meehl et al,. 2007; Najjar et al., 2009). Streamflow prediction is more challenging than temperature and precipitation because it requires assessing water balance equations including temperature, precipitation and groundwater levels. Consequently, we observe less reliability in the streamflow results. In Table 1, temperature predictions have the least variability, followed by precipitation and streamflow. Streamflow predictions have the most variability due to the offsetting effects of increased temperature and precipitation. Other than precipitation, streamflows may increase due to decreased evapotranspiration caused by elevated CO2 in atmosphere. Wigley and Jones (1985) estimated that a doubling of CO2 could increase streamflow as much as 20% for watersheds in which half of the precipitation runs off (Neff et al., 2000). Moreover, urbanization also causes an increase in impervious land, resulting in increased streamflow.

Although high uncertainty and variability in climate change models poses problems for policy makers, information from such models can be incorporated into various plausible scenarios in simulation studies to assess system performance under the influence of climate change. For this study, temperature, precipitation and streamflow range projections made by Neff et al. (2000) and Najjar et al. (2000) were used for our model simulation. Multiple scenarios were created using the ranges provided in Table 1.

5. Water System Modeling in Literature

Water resources are modeled at many scales. 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 and Trowsdale, 2009). So, local models are developed to facilitate decision making by local and regional governments since local governments have the 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 the overall development of human civilization. Various global water scarcity studies have been conducted (Saysel and Barlas, 2001; Alcamo and Henrichs, 2002; Chung et al., 2008). One such study conducted by Kojiri (2008) predicts that overall civilization development will be retarded if there is a deficit in water resources.

With respect to local water modeling efforts, many have focused on managing water for droughts for heavily populated regions. One such study investigated the impact of population growth and climate change on water demand and supply in the Okanagan Basin in Canada. The study projected the increase in frequency of water deficit in the future in an otherwise water abundant region, which would trigger conservation policies that would come into play to balance the deficit (Langsdale, Beall, Carmichael, Cohen and Forster, 2007). Similar projections were made by a study conducted for the Middle Rio Grande river basin, where water deficits have become more frequent (Tidwell, Passell, Conrad and Thomas, 2004). A Las Vegas study concluded that reducing outdoor water consumption can reduce the vulnerability of the water supply system and increase its robustness (Stave, 2003). An Iranian study reached similar conclusions regarding the current state of water policies for the Zayandeh-Rud river basin in Central Iran (Madani and Marino, 2009). Many studies explored the dynamics of the region where climate change and population growth were key variables that affected supply and demand, respectively (Saysel, Barlas and Yenigun, 2000; Simonovic, 2002; Barlas, 1996; Ahmad and Simonovic, 2004; Ewers, 2005; Sahlke and Jacobson, 2005; Madani and Marino, 2009; Winz et al., 2009; Gastélum, Valdes and Stewart, 2009; Simonovic, 2003).

Researchers have used different methodologies to understand and model the processes responsible for spatial and temporal distribution of water resources. Van Oel, Krol, Hoekstra and Taddei (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 a combination of optimization and simulation techniques for improving water resource efficiency and effective reservoir management (Sheer, 1977; Palmer, Smith, Cohon and ReVelle, 1982; Palmer, Wright, Smith, JCohon and ReVelle, 1979). Many specialized modeling tools have also been developed to simulate water supply systems (Ocanas and Mays, 1981; Huang and Loucks, 2000; Ejeta, McGuckin and Mays, 2004; Cohen, Shamir and Sinai, 2004; Chung et al., 2008). These tools are often specific to a system and inflexible to adapt to other systems. Some of them do not even have user friendly interface (Chung et al., 2008).

This paper uses a system dynamics (SD) modeling approach to develop a dynamic simulation model that evaluates the performance of WMA water supply system over a time horizon of 24 years (2016–2040). The main difference between SD and other modeling approaches is the study of a system in terms of stocks and flows over time (Ahmad and Prasha, 2010). SD modeling also has an ability to capture time delays that influence the behavior of the system (Sterman, 2000). SD helps capturing important feedbacks existing in our system such as the feedback going from water shortage to population growth rate. The water use restrictions also cause discomfort to people which has a negative impact on region’s growth rate. Feedbacks govern dynamics of a system and SD provides an ideal platform to capture these feedbacks. System dynamics framework also makes it very easy to connect various sub-systems together to formulate the structure of the whole system. Our system is comprised of multiple subsystems like water demand system involving factors that impact water demand such as socio-economic variables like price and population and water supply that involves rivers and reservoirs. SD affords us the platform to link all our sub-systems together with much ease. SD has a very user friendly graphic interface that enables lay people to visualize the system with all its components and linkages. Since our study involves water managers, civil engineers, public policy makers, environmentalists as stakeholders, a tool with an ability to graphically represent an entire water supply system with all its components and connections is a huge asset. Finally, SD has an ability to capture delays existing in the system. Our system also involves delays such as delay between the time of imposition of water use restrictions and the time it impacts the growth rate of the region. SD is able to capture such delays.

6. Study Area Modeling

The WMA water supply system has two main components: Demand and Supply. Total water demand is affected by population, price, regulation policies, and weather. The difference between water demand and supply is termed as supply gap that determines the reliability (Eq. 14) of the system. The supply gap results in restrictions and/or water shortages for the region. The water shortages and restrictions lead to discomfort among residents causing the growth rate to go down, eventually causing the population to decrease. The population in turn affects total water demand, thus closing the loop (Figure 2).

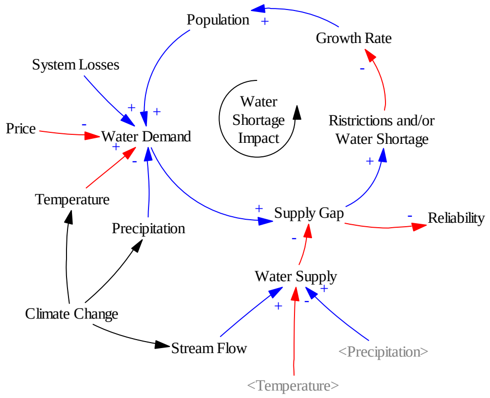

Figure 2: Causal Loop Diagram of the WMA Water Supply System.[4]

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[4] The figure describes the links and direction of relationship between different components of the WMA water. supply system (+/- describes a positive/negative relationship, meaning increase in causer will lead to an increase/decrease in the causee)

The causal loop diagram in Figure 2 is converted into a working model using SD framework for the purpose of characterizing complex, non-linear systems through capturing interrelations, feedbacks and delays. Moreover, system dynamics software packages are ideal for use with participants with varying degree of proficiency in modeling. SD models can capture both the physics (hydrology) and management (policies and human responses) of an urban water supply system (Langsdale et al., 2007). The famous World II model (Forrester, 1971) and “Limits to Growth” (Meadows, Meadows, Randers and Behrens, 1972) has shown SD to be an ideal tool for resource modeling. Mathematically, the basic structure of an SD simulation model is a system of coupled, nonlinear, first-order differential (or integral) equations (Equation 1),

$$\frac{d}{dt}x(f) = f(x, p) \tag{1}$$

where x is a stock or a state variable, p is a set of parameters, and f is a nonlinear vector-valued function (SDS 2016). Stocks and flows are basic components of an object-oriented system dynamics model (Figure 2). Stocks represent an entity that accumulates (example of a stock is a reservoir) and flows (rates) represent activities that fill and drain stocks such as natural inflows to reservoirs and water supply releases. Arrows are used to connect variables in the model and the direction of the arrow indicates the dependency relationships (Figure 3) (Elmahdi, Malano, Etchells and Khan, 2005).

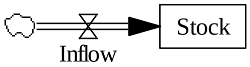

Figure 3: System Dynamics Basic Structure

Water Demand

Price and population are key determinants of water use. ‘Temperature’ and ‘precipitation’ are included to impart seasonality to the average annual water demand. The model estimates water demand per person (*Estimated Per Capita Water Demand*) is as follows:

$$Estimated\ Per\ Capita\ Water\ Demand = Average\ water\ Demand * Price^{Elasticity\ (Price)} \tag{2}$$

where, *price* is in the units of (dollars per cubic meters), *price(elasticit*y) is dimensionless and *estimated per capita water demand* and *average water demand* have units of cmd (cubic meters per day) /person. Per capita water demand is a function of price and price elasticity of demand.

Equation 2 is a popularly used water demand estimation form, which involves direct estimates of elasticities[5]. It assumes elasticitiy to be constant over the range of values for water use determining variable (Schleich and Hillenbrand, 2009; Arbu´es, Barberan and Villanua, 2003; Dandy, Nguyen and Davies, 1997; Williams, 1985).

For the WMA, per capita water demand is also impacted by the Energy Policy Act (EPA) of 1992 (Vickers, 1993). Once per capita water demand is estimated, it is multiplied by *demand reduction factor* (dimensionless) to calculate reductions resulting from conservation policies as regulated by law. The *demand reduction factor* (dimensionless) is calculated as

$$Demand\ Reduction\ Factor\ = \frac{per\ capita\ water\ demand\ of\ people\ affected\ by\ EPA}{per\ capita\ water\ demand\ of\ people\ not\ affected\ by\ the\ EPA} \qquad (3)$$

This separates the per capita demand into two categories; per capita demand with EPA and per capita demand without EPA. The two demand categories are then multiplied by their respective populations to calculate the simulated total water demand (equation 4). There are two population stocks in the model (Figure 4); Stock1: population that lives in households that have EPA regulated low flow appliances and Stock 2: population that lives in households that do not have EPA regulated low flow appliances.

$$\begin{aligned}
&Total\ WAter\ Demand\ = \\
&Population\ (Stock\ 1)\ With\ EPA * Per\ capita\ water\ demand\ of\ people\ affected\ by\ EPA\ + \\
&Population\ (Stock\ 2)\ Without\ EPA * per\ capita\ water\ demand\ of\ people\ affected\ by\ EPA \qquad (4)
\end{aligned}$$

There is a flow from Stock 2 to Stock 1 based on the cumulative rate of new housing stock and old stock that gets renovated as per new regulations. *EPA population growth rate* is the rate at which the people move from the stock of *Population without EPA,* into the stock of *Population with EPA.* Finally, the population of the region is affected by its *growth rate*. Since there are two population stocks, the new people getting added to the region are divided into the two stocks based on the volume of the stock. The growth rates of the two population stocks are proportional to their volumes.

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[5] Equation 2 is derived from exponentially transforming log-log water estimation equation from Schleich and Hillenbrand (2009)

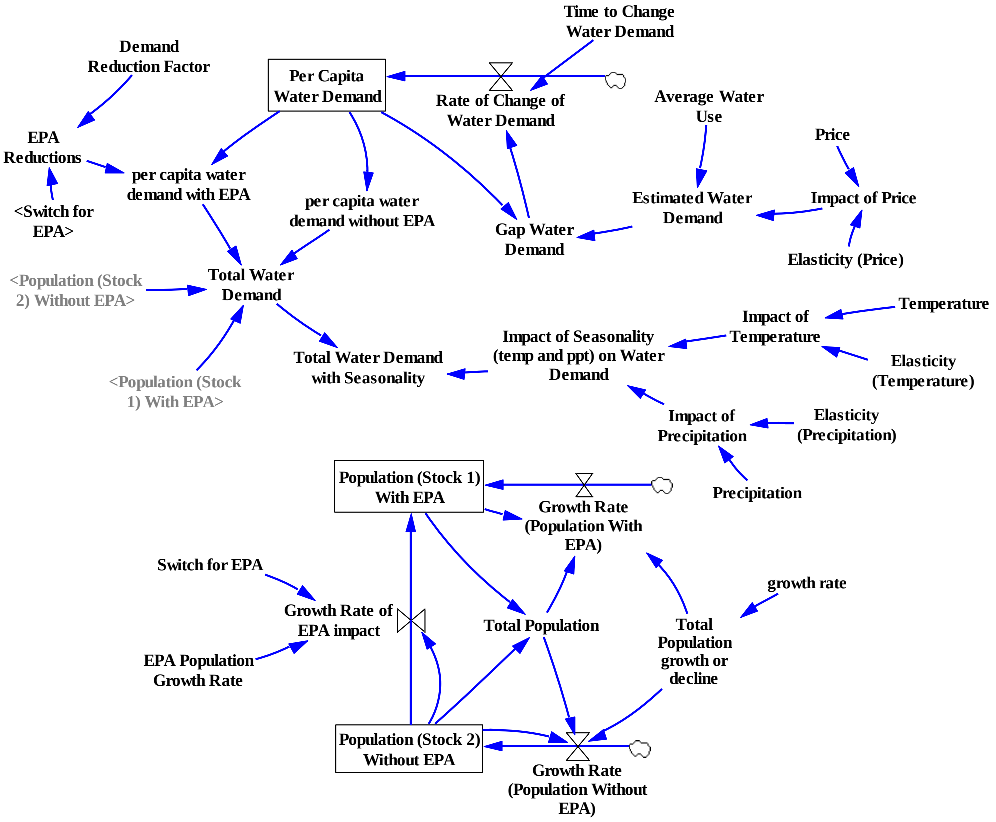

Figure 4: Demand Modeling[6]

Once the demand side modeling is complete, we require five parameters to calculate the total water demand. One of the five parameters, *Demand Reduction Factor* (dimensionless) is available in the literature. Vickers (1993) calculates the per capita residential water savings accruing due to the impact of the Energy Policy Act, which put restrictions on the flow rate of the plumbing fixtures. The second parameter that needs estimation is *Time to Change Water Demand* (months). Based on sensitivity analysis, varying *Time to Change Water Demand* has little influence on the Simulated *'Total Water Demand'*. Therefore, this parameter is not included in the calibration. This leaves three parameters to be calibrated; (a) *Elasticity (Price)* (dimensionless) (b) *EPA Population Growth Rate* (persons/month), and (c) *Average Water Use* (cmd/person).

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[6] This figure represents a simplified version of the more detailed stock and flow diagram given in Figure 20 and 21 in Appendix C

‘Elasticity (Price)’ is a measure of responsiveness of water demand to changes in its price, more precisely, price elasticity of demand gives the percentage change in quantity of water demanded in response to a one percent change in its price. For calibration, we compared the simulated water demand (cmd) with the actual water demand (cmd) (ICPRB, 2010) for the WMA region. The objective function is minimized at each iteration. The objective function is the sum of the difference between the actual water demand and its simulated value, multiplied by a weight (w) and then squared (equation 5) (Sabounchi, Triantis, Sarangi and Liu, 2011; Vensim, 2010). The weight is the inverse of the standard deviation of the error term (difference between actual and simulated values). In doing so estimated parameters converge to their maximum likelihood estimator (Dogan, 2007).

$$Minimize\left(\int_{t=Jan,1975}^{t=Dec,2008}\left(\left(w\left(Water\ Demand_{simulated}(t)-Water\ Demand_{simulated}(t)\right)\right)^{2}\right)\right) \quad (5)$$

Water demand is also impacted by weather, hereon referred to as seasonality. This affect is incorporated into the total water demand by including average extreme maximum temperature (Celsius/month) and total monthly precipitation (millimeters/month) impact. The impact of weather variables in calculated as (equation 6 and 7):

$$Impact\ of\ Seasonality\ on\ Water\ Demand =$$

$$temperature^{Elasticity(temperature)} * precipitation^{elasticity(precipitation)} \quad (6)$$

$$Total\ Water\ Demand\ with\ Seasonality =$$

$$Total\ Water\ Demand * Impact\ of\ Seasonality\ on\ Water\ Demand \quad (7)$$

where, *elasticity(temperature)* and *elasticity(precipitation)* are dimensionless quantities and *total water demand* and *total water demand with seasonality* have the units of cmd. Equation 3 is similar to Equation1 and is a popularly used water demand estimation, which involves use of elasticities (Schleich and Hillenbrand, 2009; Williams, 1985; Dandy et al., 1997).

In order to calculate *Total Water Demand with Seasonality*, we need temperature and precipitation elasticity values. Calibration was again conducted for the time period of 1990 to 2008, comparing simulated seasonal water demand to actual seasonal water demand data (see Table 5 in Appendix C for calibration results). Figure 5 shows the simulated and actual water demand curves. The water demand for the WMA region increases until the Energy Policy Act of 1992 comes into effect from year 1994.

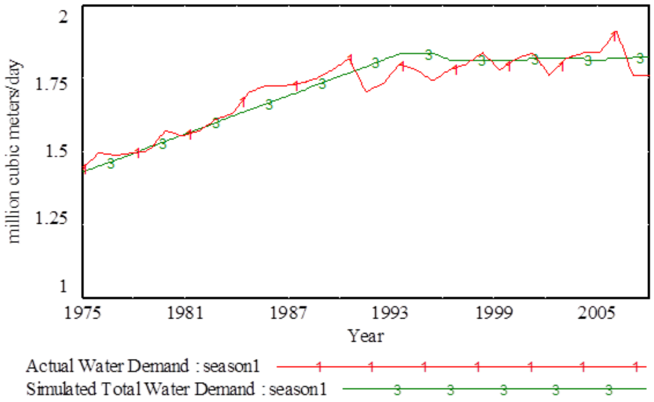


Figure 5: Actual vs. Simulated Total Water Demand in the WMA from 1975 to 2008

Water Supply

The main source of water drinking supply for the majority of people in the WMA is the Potomac River. Other than the Potomac River, there are few shared resources. The region's water suppliers jointly collaborate to pay for storage in Jennings Randolph and Little Seneca reservoirs. Additional resources include the Occoquan and Patuxent Reservoirs.

The Supply Side Model: Potomac River System

The average annual streamflow for the Potomac River is around 26.4 million cubic meter per day, with higher flows typically occurring in the winter months and lower flows in the summer months. 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 the WMA suppliers is approximately 1.9 million cubic meters per day (ICPRB 2010). This may give a false sense of water availability for the region. The critical aspect here is the streamflow variability. Potomac streamflows may even fall below 1.9 million cubic meters per day. The lowest observed flow was 1.3 million cubic meter per day (summer of 1966, the flow was less than projected demand). Streamflow discharges can vary from a typical high of 24.6 million cubic meters per day to a typical low of 4.9 million cubic meters per day. Due to such large flow variability, the inability of a water supply system that relies solely on Potomac flow to not meet 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 the environmental flow requirements.

The total available Potomac water is further constrained by minimum environmental flow-by requirements. Changes to the ‘Minimum flow-by Requirements’ will influence water availability in the system. This requirement is necessary for protecting aquatic life forms (Kiang and Hagen, 2003). The water management agencies must ensure that streamflows do not fall below the minimum mandated flow-by requirements and ensure that natural flows in Potomac River are augmented with water releases from various reservoirs. Additionally, there have been persistent pressures from environmental agencies and environmental advocacy groups to increase the minimum flow requirements (Pegg 1999). Therefore, utilities withdrawing water from the Potomac River through their various water treatment plants (WTPs) (e.g., intakes like FCWA’s James J. Corbalis, Jr. WTP) should make sure that the discharge does not fall below the mandated level.

Supply Side Model: Additional Reservoir Systems

Other than the free flowing Potomac River, there are two separate reservoirs that are operated by the WMA utilities. WSSC operates the Patuxent Reservoirs in the neighboring Patuxent River watershed. 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. Other than that, WSSC, Washington Aqueduct, and FCWA collaborate to pay for storage in Jennings Randolph Reservoir (JRR) and Little Seneca Reservoir (LSR). Both these reservoirs are used together to augment the Potomac flow at times of drought. LSR flows are only used to “fine tune” (ICPRB, 2010) the larger releases from Jennings Randolph Reservoir because it takes time for JRR water releases to reach supplier intakes. Another reservoir called Savage River Reservoir (SRR) is also part of the Potomac River system. It also lies in the North Branch Potomac River watershed just like the JRR and the LSR. But we do not consider it while modeling the WMA water demand and supply because SRR is primarily used for water quality improvement to dilute relatively acidic flows in the North Branch of the Potomac. The SRR does not contribute towards the water supply (Prelewicz, Hagen and Kame’enui, 2004).

The model depicts three reservoir systems: a) The Occoquan Reservoir, b) The Patuxent Reservoir, and c) The Jennings Randolph Reservoir (JRR) system. Figure 6 depicts modeling of a reservoir as a stock. The model calculates daily storage available in the reservoir using the water balance approach that calculates the reservoir storage at each time. The Reservoir can be understood as a stock having a fixed capacity that accumulates the difference between its inflow and outflow (equation 8).

$$Stock(t) = \int_{t_0}^{t_n}[Inflow(t) - Outflow(t)]dt + Stock(t_0) \tag{8}$$

where: *Stock(t)* is the amount of stock at time *t*, *Inflow(t)* is the inflow at time *t*, and *Outflow(t)* is 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). There are two inflows and three outflows to the reservoir (Figure 6).

Inflow 1: Reservoir Inflow

Inflow 2: Direct Precipitation

Outflow 1: Reservoir Evaporation

Outflow 2: Reservoir Spill

Outflow 3: Reservoir Outflow

The Reservoir Inflow (million cubic meters/month) is a time series of direct inflows to the reservoir. The time series for these inflows is obtained from ICPRB records (Cherie Schultz, e-mail communication, 2015). Another inflow to the reservoir is direct precipitation (million cubic meters/month) that pours directly over the reservoir. The inflow due to direct precipitation is calculated as precipitation rate (NCDC 2015) multiplied by the area of the reservoir (USACE, 1997).

The physical reservoir system has to be transformed into a mathematical representation reflecting real physical conditions. Therefore, while modeling outflow, we have to make sure that the stock of the reservoir doesn't become negative. For example, outflow due to evaporation should drop to zero when the reservoir is empty. This condition is modeled using equation 9.

$$Reservoir\ Evaporation =$$

$$Min\ of\ \ (Reservoir\ Area * Evaporation\ Rate, Reservoir\ Volume/Minimum\ Reservoir\ Evaporation\ Time)$$

(9)

where, *Reservoir Evaporation* has units of million cubic meters/month, *Reservoir Area* has the units of million square meters, *Evaporation Rate* has units of meter/month, *Reservoir Volume* has units of million cubic meters and *Minimum Reservoir Evaporation Time* has units of month. As per equation 9, the outflow due to evaporation will drop to zero as reservoir volume drops to zero. Similarly, the reservoir volume cannot exceed its capacity. Any flow over and above the capacity goes out in form of 'reservoir spill'. Reservoir spill is calculated using equation 10.

$$Reservoir\ Spill = \frac{Maximum\ of\ [0,(Volume-Capacity)]}{Reservoir\ Spill\ Time} \tag{10}$$

where, *Reservoir Spill* has units of million cubic meters/month, *Reservoir Capacity* has the units of million cubic meters *and Reservoir spill Time* has units of month.

Finally reservoir outflow (million cubic meters/month) is the outflow occurs only when there is a need for flow augmentation for the Potomac River. Reservoir storage capacities decrease with time due to the deposition of sediments. Sedimentation is assumed to be linear, meaning reservoir capacity decreases linearly over time due to sediment deposition, Reservoir rates are acquired from ICPRB (2010) reliability study.

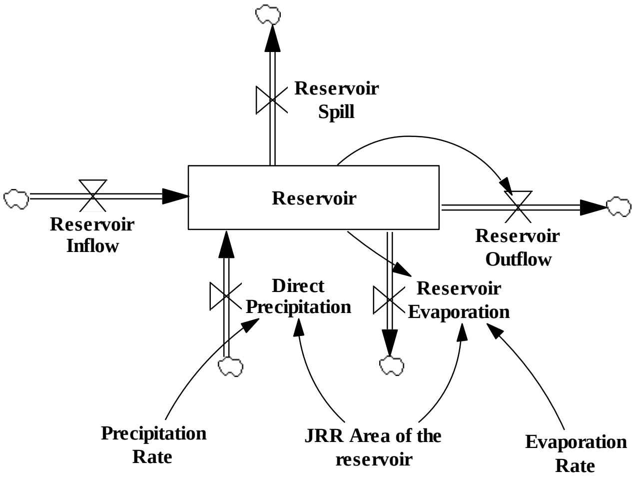


Figure 6: Supply Side Model: Reservoir System

Balancing Demand and Supply

The simulated demand is connected to the WMA supply side to complete the model. The model is first used for the period of 1990 to 2013. This time period is chosen because all WMA reservoirs were operative during this time period and data is available to validate the model. The simulated water demand (Figure 4) is the aggregate demand for the whole WMA region. The aggregate demand has to be disaggregated into four major sub categories for each different service area (FCWA, WSSC, WA, and City of Rockville), based on the proportionality of each utility service area demand. The ratios 'rA, 'rW', 'rF', and 'rR' are based on historical data (Cherie Schultz, e-mail communication, 2015) (see Table 3 Appendix C for demand ratios).

The water suppliers have to produce more water than the actual demand to account for distribution and production losses. The difference between total water produced and total water billed to customers is termed as 'system losses'. This parameter is an average of the recent years' water losses for all water utilities (see Table 4 in Appendix C for system losses calculations). System losses can be varied in the future to study its impact on the performance of the water management system. It is an important policy tool that has a huge impact on water supply reliability. Currently it is fifteen percent, meaning 15 percent of water produced is counted as distribution and production losses (ICPRB, 2010). FCWA and WSSC demand is further divided into Potomac service area and non-Potomac service area using ratios (rFO, rWP) based on historical data (Cherie Schultz, e-mail communication, 2015) (Figure 19 and 20 in Appendix C).

After demand disaggregation, the Potomac service area demand is summed to calculate total Potomac demand. This demand is satisfied by water produced by water treatment plants that utilities operate on the Potomac River such as, the Corbalis Water Treatment Plant operated by FCWA. Similarly, demand for the Occoquan and Patuxent service area is satisfied by the respective reservoirs. The three demands a) total Potomac demand, b) FCWA Occoquan Service Area Demand, and c) WSSC Patuxent Service Area Demand are assigned to Potomac River, Occoquan Reservoir and Patuxent Reservoir respectively (Figures 17 and 18 in Appendix C).

Generally, water in the Potomac River is sufficient to satisfy the daily water needs of WMA customers except during prolonged drought conditions. The water utilities in the area not only have to fulfill the region's water demand but they also have to maintain the environmentally mandated minimum flow in the Potomac River at all times. Potomac River flows are augmented by releases from the Jennings Randolph Reservoir during times of severe drought. There have been three summers in history when such releases have been made. These historical instances are used to validate our model. The first ever release was made in the year 1999 during summer months. Since then, similar releases were made during the droughts of 2002, and 2010 (Hagen and Kiang, 2002; Ahmed et al., 2011; Bencala et al., 2013). Figure 7 shows that our model is able to approximate the time of the releases from the JRR.

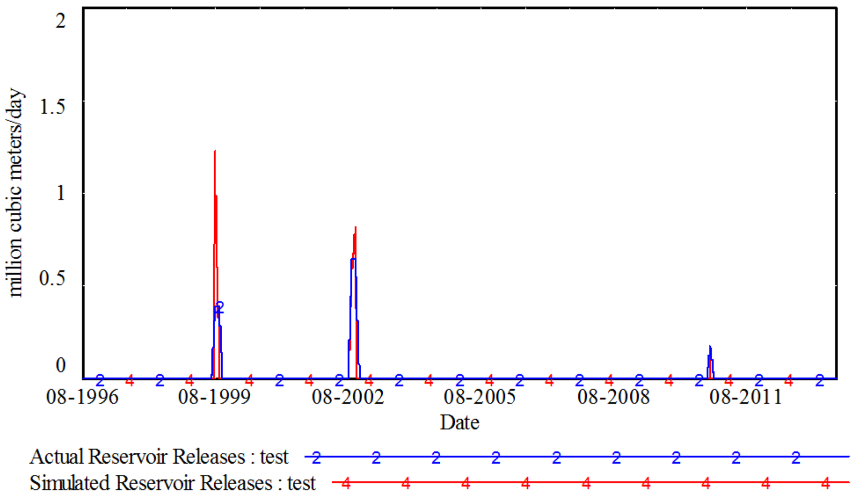


Figure 7: Instances Requiring Releases from the Reservoir

Connecting Water Shortages to Population Growth (closing the loop)

Water releases from JRR are a cause of concern for the WMA region because firstly: 1) these releases deplete the only “savings account” of the region (Jennings Randolph Reservoir) (ICPRB, 2010) and 2) the JRR releases are often accompanied by water use restriction (Wilson, 1999) like regulations on sprinkling lawns, topping off swimming pools, washing cars and hosing down driveways (LeDuc and Wilson, 1999). Water restrictions ultimately reduce the attractiveness of the region for the existing and future population (Mirchi, 2013).

If demand for water increases unchecked, it puts a strain on the existing water resources. Increasing demand and limited supplies may cause water shortages. Water shortages make people uncomfortable, which ultimately impact the population growth rate. Meadows et al. (1972) demonstrate how a region’s population is limited by its resources. We put similar limits on growth for the WMA population in our model (Figure 9). The *base fraction growth rate* (bgr) in persons/month, is the growth rate of the WMA region without taking into account water shortages. The Metropolitan Washington Council of Governments (MWCOG) forecast is used to obtain the base growth for the region (MWCOG, 2009; ICPRB, 2010)). MWCOG creates population projections based on past trends and current information on population, employment, school enrollment, land use, and zoning.

We define two types of impacts that are imposed on the system due to water shortage, impact(1) is the stress caused to people when water use restrictions are enforced and impact(2) is the stress caused to people by the water shortage (see Figure 9). In the first instance, although our region is able to fulfill demand, it uses its ‘savings account’ to make withdrawals accompanied by water use restrictions. In the second instance, the region fails to meet demand and there not enough water supply to fulfill demand.

These two types of stresses can have variable impact on the base growth rate of the WMA. The *net fraction growth rate* (ngr) in persons per month is calculated by using equation (11).

$$ngr = bgr * (w_1 * Impact1 + w_2 * Impact2) \tag{11}$$

$$w_1 + w_2 = 1 \tag{12}$$

Where, impact1 and impact2 are dimensionless variables as defined by equation 13 and 14 and w_1 and w_2 are weights associated with them (equation 12). Impact1 is a function of perceived discomfort (*perceieved_discomfort_R)* (dimensionless) caused by water use restrictions and impact2 is a function of perceived discomfort (*perceieved_discomfort_R*) (dimensionless) caused by water shortage. The weights can vary depending upon the severity of one impact over the other. Intuitively, people will be more stressed if the region suffers water shortage as opposed to restrictions, thus assuming w_2 to be greater than w_1 (we assume w_1=0.25 and w_2=0.75).

$$Impact1\ (restrictions) = f(perceieved\_discomfort\_R) \tag{13}$$

$$Impact2\ (shortage) = f(perceieved\_discomfort\_S) \tag{14}$$

The graph in Figure 8 demonstrates that when there is no restrictions and water shortages (*perceieved_discomfort_R and perceieved_discomfort_S* = 0), impact1 and impact2 are both 1. When discomfort and water shortage increase (e.g., *perceieved_discomfort_S and perceieved_discomfort_R* = 1), stress becomes negative, thus making *the net growth rate* negative.

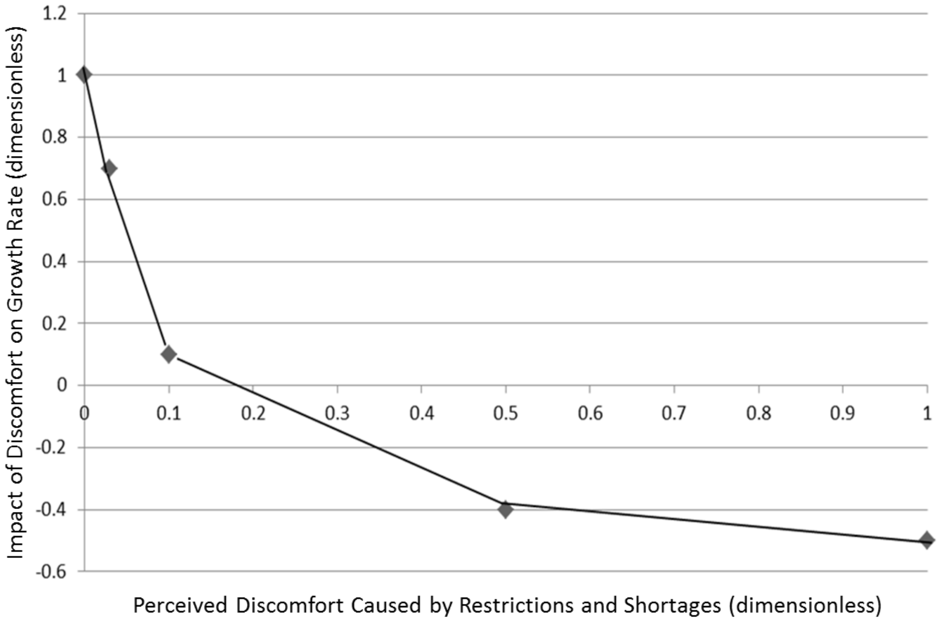


Figure 8: Connecting Perceived Discomfort to Population Growth Rate

Sterman (2000) explains that people take time to gather information that is required to form beliefs and judgments. People also don't immediately change their minds on receiving new information. Thus, there is a time delay from a change in the physical world to the time people start realizing it. Exponential smoothing or adaptive expectations is most widely used to model such information delays involving humans, meaning that human perception gradually adjusts to the actual value of the variable. In our model, we assume that the discomfort and water shortage is a human perception that builds over time. If droughts occur in successive years and water restrictions are levied more frequently, people's perception regarding restrictions will eventually build up.

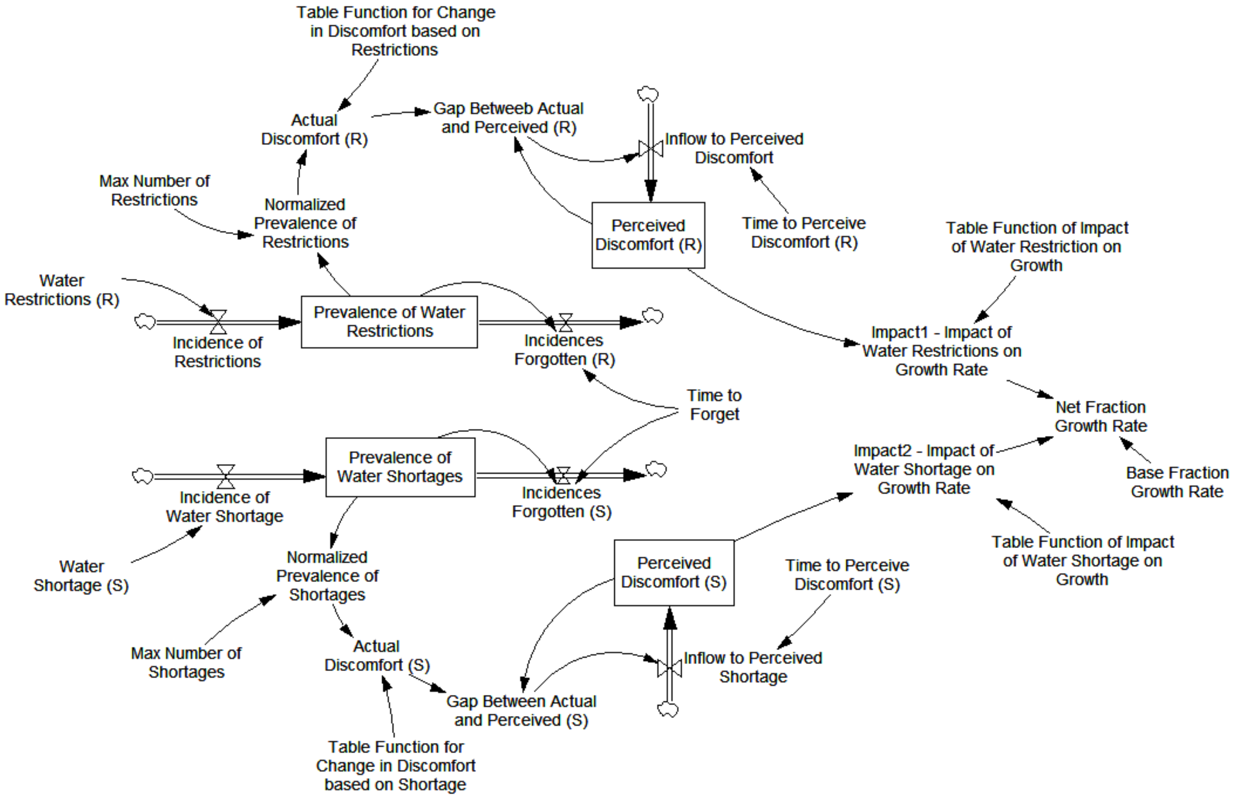


Figure 9: Closing the Loop

In adaptive expectations (Figure 9) the perceived value of the input, *perceieved_discomfort_S and perceieved_discomfort_R*, is modeled as a stock, defined by equation 15 and 16,

$$perceieved\_discomfort(t) =$$

$$\int Change\ in\ perceived\ discomfort, perceieved\_discomfort(0) \tag{15}$$

$$Inflow\ to\ perceived\ discomfort\ = \frac{Actual\ Discomfort - Perceived\ Discomfort}{Time\ to\ Perceive\ Discomfort} \tag{16}$$

where, *time to perceive discomfort* (in months) is the time required by human beings to perceive natural resource scarcity. WMA has never experienced any region wide imposition of water use restrictions. Hence, the model could not be calibrated to calculate the *time to perceive discomfort* parameter. However, there are studies that calibrate similar parameters such 'resource shortage perception delay' (Meadows et al., 1972), 'energy shortage perception' (Wright, 1975), feedback delay (Honda, Hagura, Yoshioka and Imamizu, 2013), 'perception delay' (Juhn, 1999; Mehmet and Yasarcan, 2015; Dutta, Lee and Yasai-Ardekani, 2014), 'response delay' (Meadows, 2008), etc. This study uses ‘resource shortage perception delay’, as used by Meadows et al. (1972). We assume both stocks (*perceieved_discomfort_S and perceieved_discomfort_R*) to have the same time delay associated with them, which is 24 months.

Actual discomfort (S) and *actual discomfort (R),* on the other hand is the function of *normalized prevalence of shortages or restrictions,* which is defined as the ratio of incidences of water use restrictions to the maximum number of incidences (Figure 9). The graph in Figure 10 demonstrates how *actual discomfort,* varies with *normalized prevalence of shortages or restrictions.* When *normalized prevalence of shortages or restrictions* is low, *actual discomfort* is also low. But *actual discomfort* rises faster as at higher values of *normalized prevalence of shortages or restrictions.* The intuition behind this curve is that people may begin to feel much more discomfort if restrictions or shortages happen in multiple years. To close the loop, the *net fraction growth rate* is connected to the population stock (Figure 4 and Figure 9).

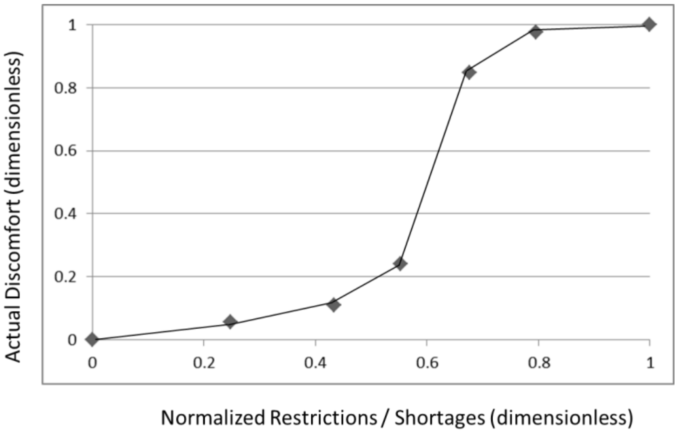


Figure 10: Connecting Actual Discomfort to Normalized Prevalence of Shortages or Restrictions

Modeling Climate Change

Climate change affects our system through temperature, precipitation and streamflow. Temperature influences water use and reservoir volume through evaporation, thus affecting both water demand and water supply. Similarly, precipitation also impacts both demand and supply by affecting water demand and reservoir volume through precipitation directly pouring over the area of the reservoir. Lastly streamflow only affects water supply (Figure 2).

Temperature, precipitation and streamflow monthly means are varied by the range projections made by Neff et al. (2000) and Najjar et al. (2000). Sensitivity analysis is conducted to examine the impact of climate variability on performance metrics, water availability and water use restrictions. Sensitivity analysis involves changing the parameter values from one extreme to another according to range provided in Table 1.

7. Simulation Results and Discussion

The objective of this study is to analyze the impact of historical droughts and low flows on water availability and to examine the impact of climate change and policy variables on system performance. To achieve these objectives, the model is used for a 24 year simulation period (2016-2040) under two scenarios: Normal and Drought. This simulation period is chosen because 20 to 30 year is a reasonable forecast horizon for water supply reliability studies (ICPRB, 2010; Langsdale et al., 2007; Madani and Mariño, 2009; Stave, 2003). Other agreements signed by the WMA's water suppliers and MWCOG are the Water Supply Coordination Agreement (WSCA) and Low Flow Allocation Agreement (LFAA). These agreements also call for periodic water demand and resource availability studies with a 20 to 30 year time horizon.

There have been many instances when Potomac flows have fallen below the historical mean discharge (Figure 11). During the five drought years (1932, 1966, 1999. 2002, and 2010) Potomac flow was below the monthly mean discharge from July to September. Of the five drought periods, 1999, 2002 were moderately severe droughts, whereas, the drought of 1930 is the drought of record for the region and the drought of 1966, although relatively brief saw the Potomac River flow dropped to its lowest ever recorded value (ICPRB, 2013).

The historical instances of droughts are imposed on the water supply system to create future scenarios. For instance, historical data for temperature, precipitation and streamflows for drought years are imposed on the system to create future droughts.

Climate change will affect low flows during droughts. For example during the summer of 1966, streamflow in the Potomac fell below 30 cubic meters per second. If similar conditions happen again in 2035, the climate change considerations suggest streamflow will vary anywhere from 29.4 cubic meters per second to 31.8 cubic meters per second (as the streamflows are expected to vary from -2% to 6% around the mean as depicted in Table 1).

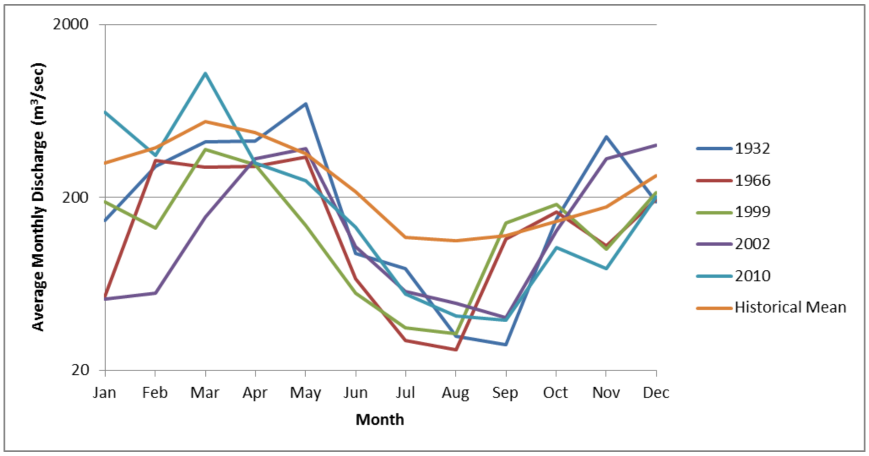


Figure 11: Average Monthly Discharges for Historical Drought Years compared to Historical Mean Monthly Discharge.

Other than climate change, this research also examines the impact of policy variables such as price and system losses on the WMA water supply system. Finally, to gauge whether the system is performing as intended, it is necessary to assess its performance under a wide range of conditions expected during their operating life. Hence, the performance of the current WMA water supply system was evaluated under various climate change and drought scenarios. The system performance metric that we use to compare scenarios is volumetric reliability (R_v). R_v is based on the volume of water demand met by the current water supplies (Potomac River and reservoirs) divided by the total target demand during the simulation period. Mathematically, it is expressed as (McMahon, Adeloye and Zhou, 2006):

$$\mathrm{Reliability_v}\ (R_v) = 1 - \frac{\sum_{\mathrm{i=1}}^{\mathrm{N}} (\mathrm{D_i} - \mathrm{D_i'})}{\sum_{\mathrm{i=1}}^{\mathrm{N}} \mathrm{D_i}}; \quad 0 < \mathrm{Reliability_v} \leq 1 \qquad (16)$$

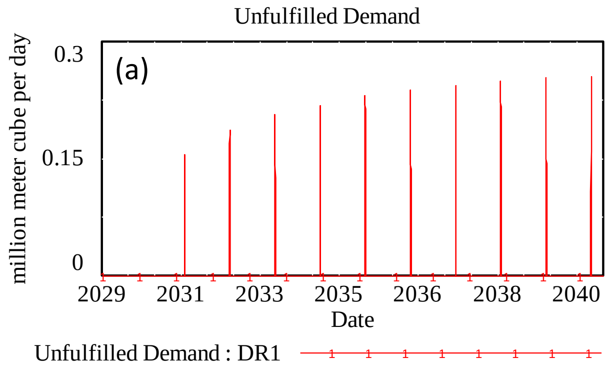
where R_v is the volumetric reliability, D_i is the simulated target demand during the i^{th} period, D_i' is the simulated volume supplied during the i^{th} period and N is the number of intervals in the simulation. For reliability calculations we only include those time periods where the water supply system is not able to meet the demand in order to analyze the extent to which the demand is not met, meaning $\mathrm{D_i} - \mathrm{D_i'}$ would be treated as zero, for cases when demand is met.

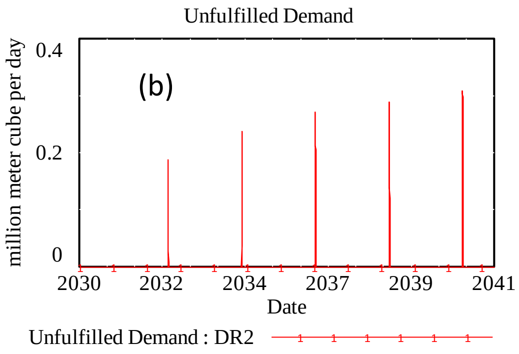
Drought Scenarios

Varying Drought Imposition Frequency

Next, in order to see the effect of prolong droughts on WMA water availability, five drought scenarios were imposed on the WMA water supply system (Figure 12a, 12b, 12c, 12d, 12e). A moderately severe drought of 1999 was imposed on the simulation period of 2031 to 2040 with varying frequency. Drought Scenario X (DRx) was created by imposing temperature, precipitation and streamflow data of 1999 at intervals of X (x= 1, 2, 3, 4 and 5) years. To create impression of a normal year in the simulation period of 2031-2040, we impose temperature, precipitation and streamflow data for a non-drought year (2004). Such scenarios are created to examine the reliability of the water supply system under extreme conditions of decade long droughts, similar to ones occurring on the west coast of the USA (Rogers, 2014). The normal scenario (NS) is defined in this paper as repetition of historical weather conditions for normal years. See Figure 23 in Appendix C for difference between 1999 and 2004 conditions.

The simulation was run for both droughts (DRx) and normal (NS) scenarios. The system response to drought scenarios is shown in Figure 12. As it is clear from Figure 12, WMA's supplies will not be sufficient to meet the demand if a moderately severe drought was enforced on the system every X years (x= 1, 2, 3, 4 and 5) (Figure 12a, 12b, 12c, 12d, 12e). The model also predicts that the region has sufficient water resources to fulfill demand for the entire simulation period (2016-2040) under normal scenario (Figure 12f).





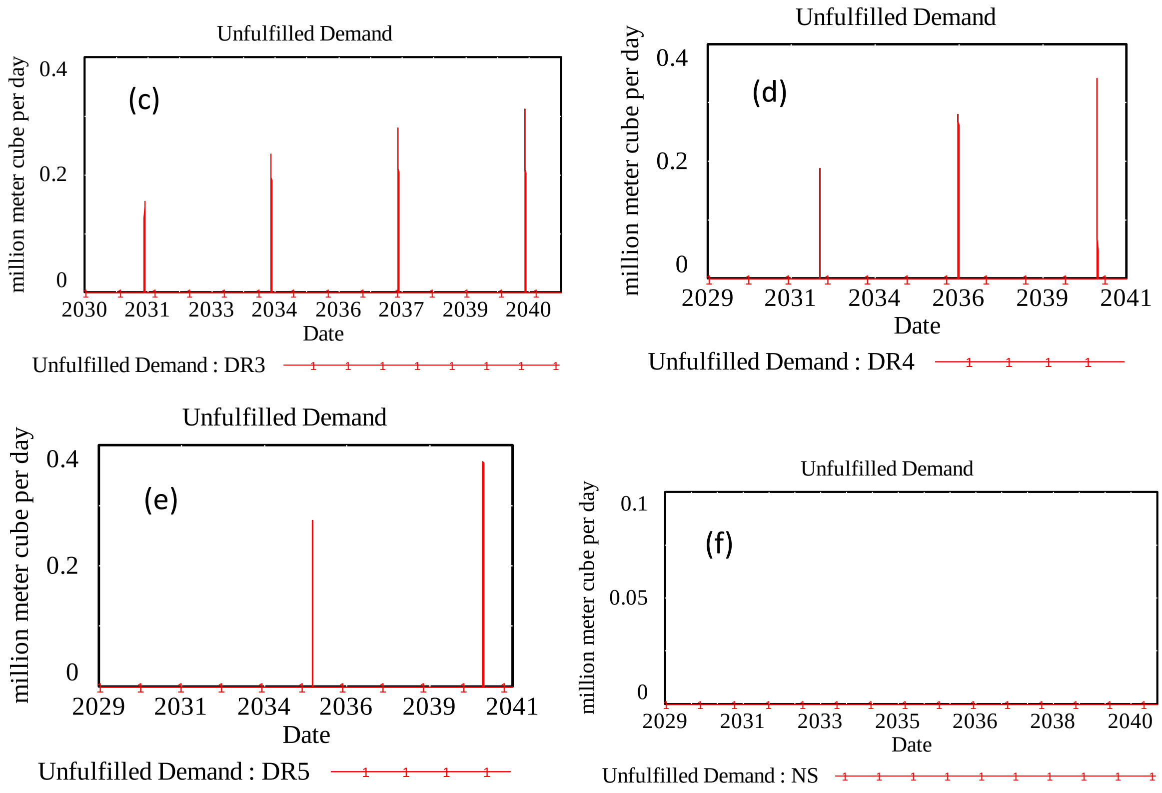
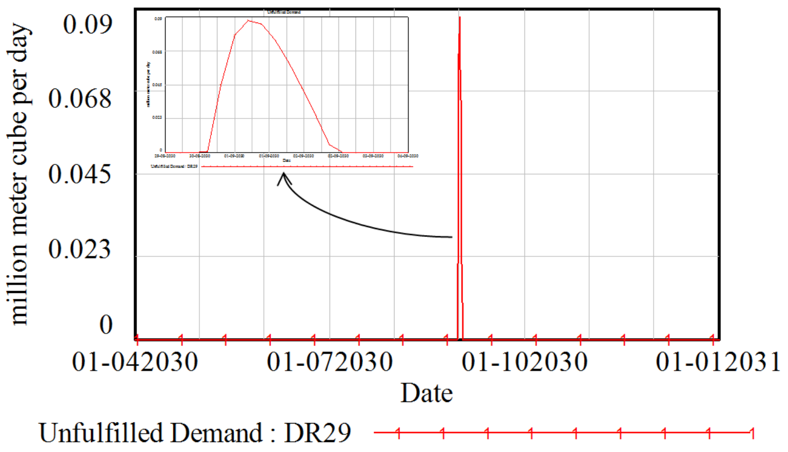


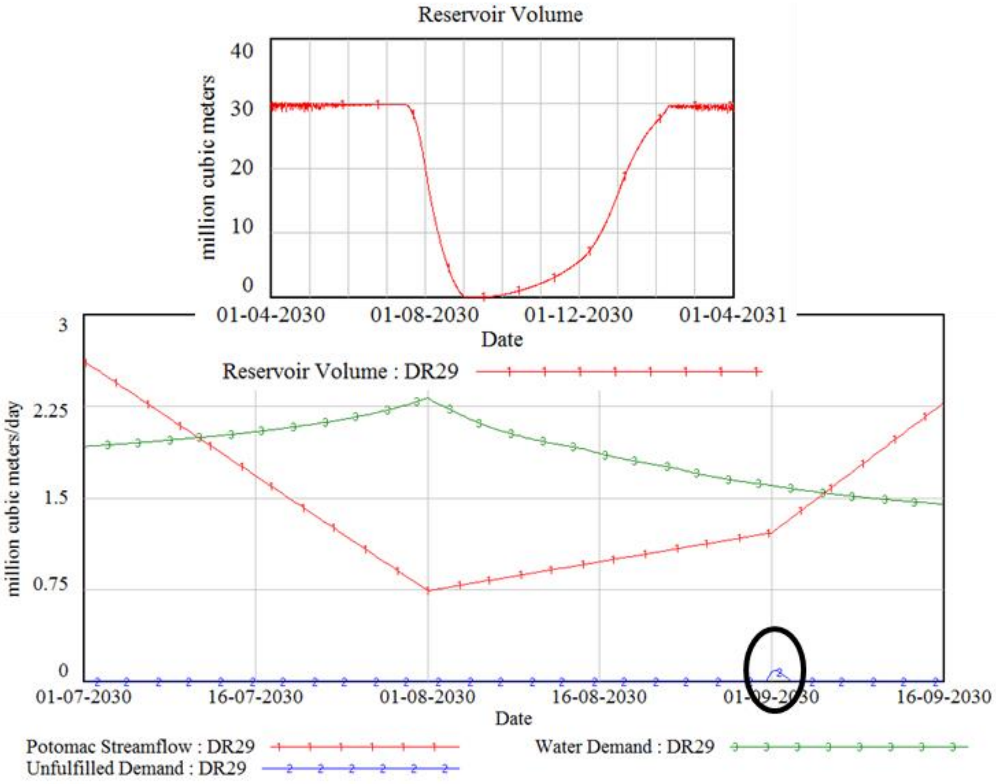
Figure 12: Water Unavailability under Normal Scenario (NS) and Drought Scenarios (DRx)

(DR1 - (a), DR2 - (b), DR3 - (b), DR4 - (d), DR5 - (e). NS – (f))

Next, in order to identify the year from which the region will start experiencing water shortfall, we impose drought conditions from 2025 onwards, one year at a time. It was observed that WMA will start experiencing water shortfall from 2030 onwards (Figure 13). Figure 13a shows that in the year 2030, there will be few days of when the WMA supplies will not be sufficient enough to fulfill demand. Figure 13b illustrates the cause behind the shortfall. The graph shows that not only WMA region’s water demand it more than Natural Potomac streamflows, the available reservoir volume also drops to near zero.



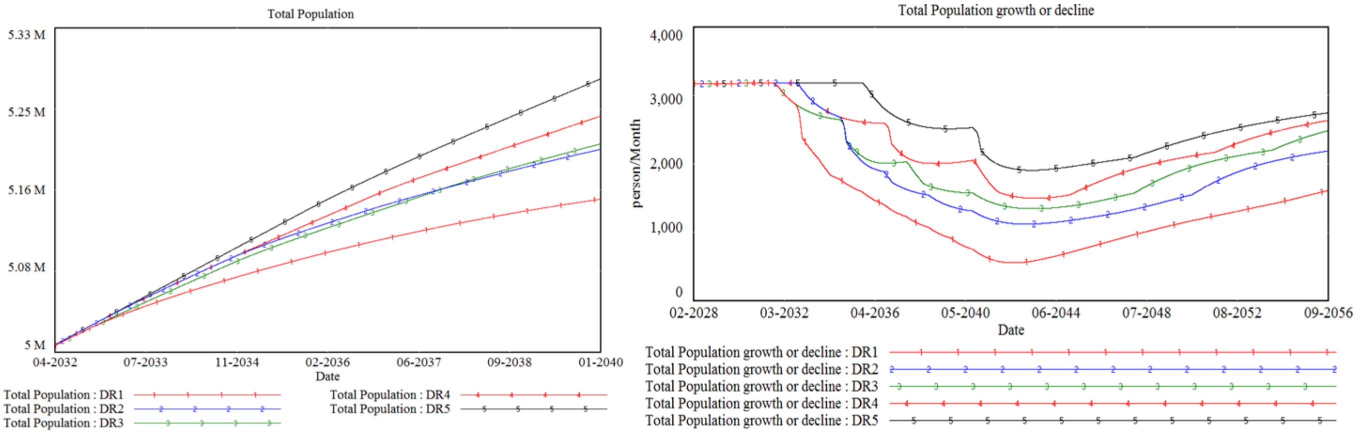
13a



13b

Figure 13: Water Availability for year 2030, under moderately severe drought

Another surprising observation was that the reliability of the system for the simulation period of 10 years (2031-2040) dropped as the frequency of drought decreased from every year (DR1) to every five year (DR5). Volumetric reliability drops from 90.5% to 86.9% for drought scenario 1 to 5. The reason behind this drop lies in the feedback that connects water unavailability and people's discomfort to growth rate. Since drought scenario DR1 is the harshest because it imposes drought on the system every year from 1931 to 1940, it reduces the growth rate of the region (Figure 14a). This causes the population to grow at a slower rate (Figure 14b). Therefore, the total water demand is less under DR1 scenario than in DRx (x=2, 3, 4 and 5).



(a) **(b)**

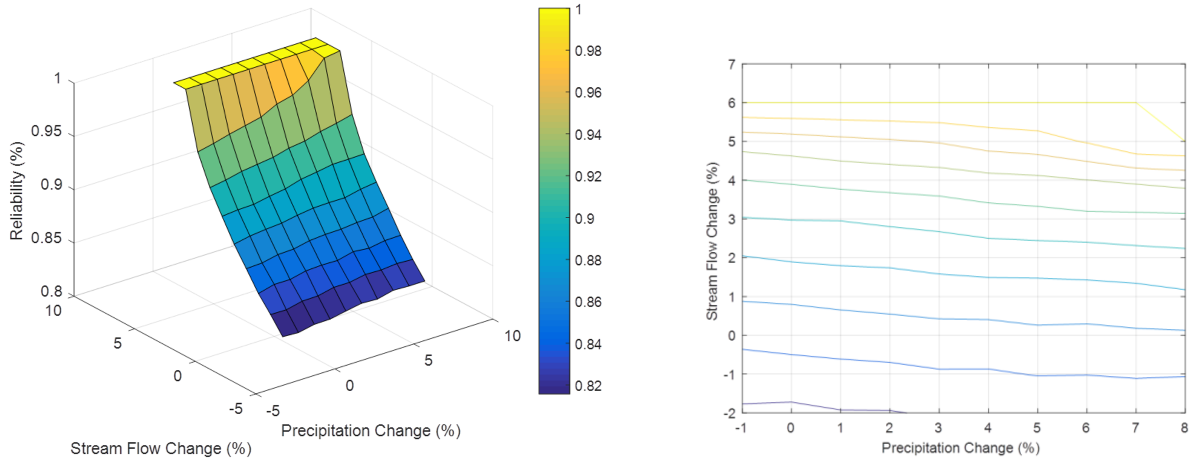
Figure 14: Impact of Drought Scenarios DRx (x= 1, 2, 3, 4 and 5) on the Growth rate (b) and Population (a)

Climate Change

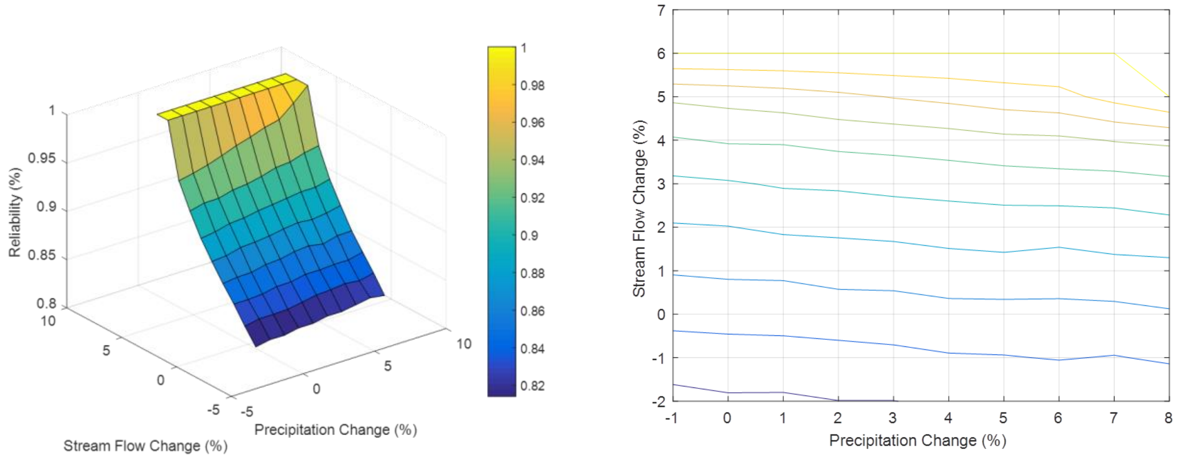
Based on the ranges provided in Table 1, 990 climate change sub-scenarios (11 increments of 0.05^{O}C for temperature, 10 increments of 1% for precipitation and 9 increments of 1% for streamflow) were constructed. Climate change was imposed upon the system from 2031 onwards. In order to examine the impact of both climate change and drought on reliability of the system, we impose a moderately severe drought in the year 2040 and ran all 990 climate change sub-scenarios. Reliability R_v was estimated for each climate change sub-scenario and plotted on a surface and contour graph (Figure 15).

- **Reliability**

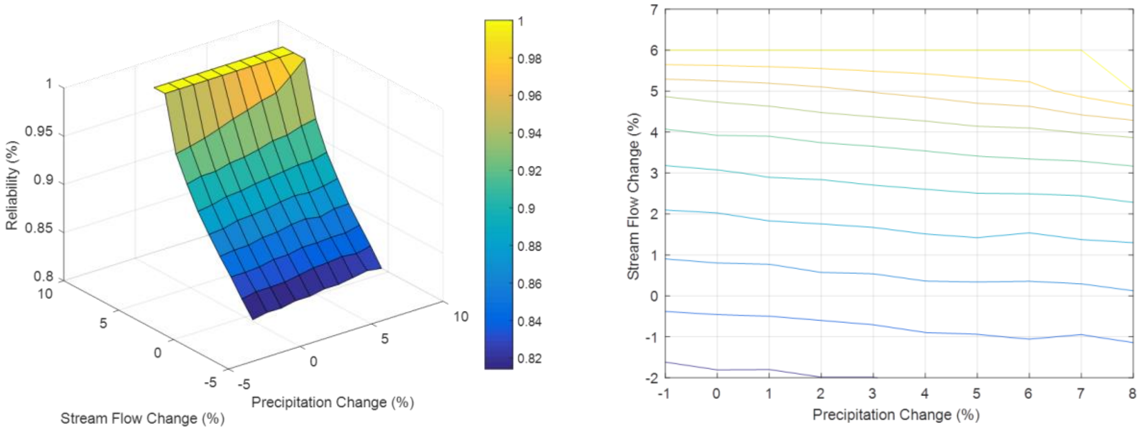
Figure 15 depicts the reliability R_v as a function of precipitation and streamflow keeping temperature fixed at ΔT= 1, 1.25 and 1.5^{O}C (Figure 15a, 15b and 15c). The reliability of the system increases with an increase in streamflow and precipitation, whereas reliability of the system decreases as temperature increases. Climate studies conducted for the entire Mid-Atlantic region show an upward trend in temperature, precipitation and streamflow (Neff et al., 2000), which means the WMA water supply system is likely to have more water due to climate change in the future. Table 2 shows that the WMA water supply system will become more reliable (R_v = 0.89) under a mean climate change scenario (where temperature increases by 1.25^{O}C, and precipitation and streamflow increase by 4% and 2% respectively) as compared to 0.85, when there is no climate change and the system is stressed due to imposition of a moderately severe drought in 2040. The reliability will fall only if climate variables move towards the lower end of the range (0.81). The WMA becomes more reliable if climate change variables, streamflow and precipitation moves towards the higher end of the range.



15a



15b



15c

Figure 15: System Reliability under Multiple Climate Change Scenarios.

13a, ΔT= 1 °C, 13b, ΔT= 1.25 °C and 13c, ΔT= 1.5 °C

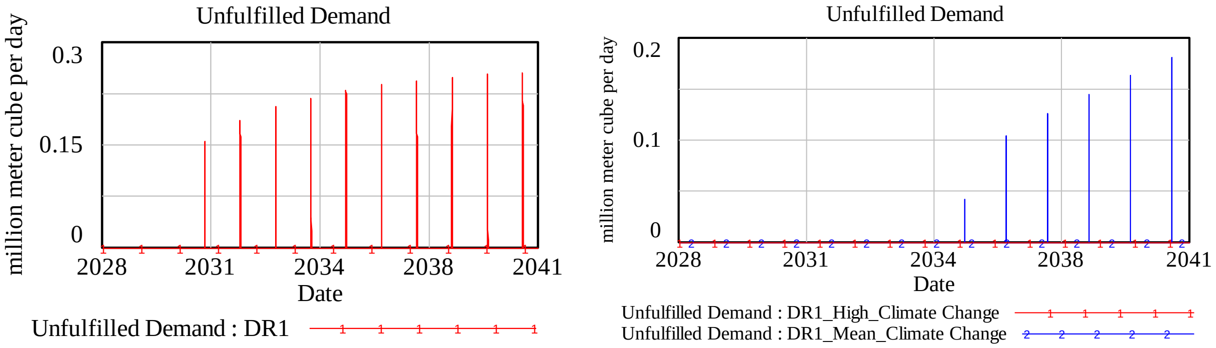
Table 2: System Reliability under Low, Mean and High Climate Change Scenario

Climate Change Scenarios	Change in Temperature (°C)	Change in Precipitation (%)	Change in Streamflow (%)	Reliability
low →	1.5	-1	-2	0.81
Mean →	1.25	4	2	0.89
high →	1	8	6	1
No Change				0.85

The climate change sensitivity results reflect that our region is very sensitive to small changes in the mean of weather variables. Six and eight percent change in monthly mean streamflow and precipitation respectively can make the drought disappear (R_v=1).

- **Availability**

Figure 16, show that if climate change comes into effect by 2030, a 10 year continuous moderately severe drought will be reduced to a 6 year drought for mean climate change conditions and completely disappears for high climate change conditions. This also proves that WMA water supply system is very vulnerable to small changes in streamflow brought about by climate change or natural variability in streamflows. We also impose a 2004 drought on the system to examine its response. The 2004 drought is also categorized as a moderately severe drought like 1999, but the streamflows occurring in 2004 are much greater than occurring in 1999.



(a) **(b)**

Figure 16: Water Availability. (a) Drought without Climate Change (b) Drought with Climate Change

Due to the sensitivity of the system to changes in weather variables, we observe a difference between the system's response to DR99 and DR02. There is a 15% difference between the total streamflow for the month of July and August between 1999 and 2002 (Figure 23, Appendix C). Both these droughts were imposed onto the system from 2025 onwards on a yearly basis. Figure 17a shows that the WMA will start experiencing water shortages from 2033 under drought year 1999. Figure 17b shows that under 2002 drought condition the system will only experience water shortages from 2041 onwards. This is similar to the impact of climate change. Thus, both climate change and naturally occurring variability in weather variables may provide respite or strain the system more, depending on which direction they move.

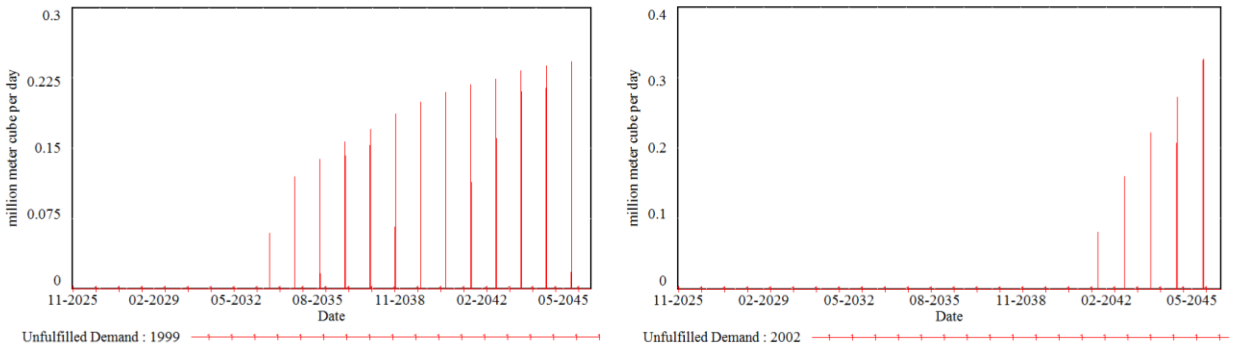


Figure 17: Water Availability. (a) 1999 Drought (b) 2002 Drought

Policy Interventions

We tested two policy alternatives and examine their impact on the WMA water supply system; *system losses* and *price*. One of the alternatives, *System Losses* is calculated by taking the difference between the amount of water produced by water suppliers and the amount of water billed to customers (ICPRB 2010). More specifically, system losses are calculated using equation 17.

$$System\ Losses\ (SL) = \frac{Total\ Water\ Produced - Total\ Water\ Billed\ to\ Customers}{Total\ Water\ Billed\ to\ Customers} \qquad (17)$$

It is an important parameter that is considered while making planning-level estimates of future water demand. Generally, losses may increase as water infrastructure ages but we assume that they stay constant unless attempts are made to reduce losses with the intension of improving water availability. *System Losses* directly impact water availability as it is a direct multiplier (Appendix A, Figure 20) that yields total water demand. This parameter is assumed constant at 15% over the entire simulation period. For the purpose of analysis, this parameter is varied over small increments to see if the variation will lead to any change in the system. System Losses is reduced from 15% to 0% in increments of 1.

Price is another parameter that is altered to examine its impact on water availability. Price has been one of the tools to regulate demand. Water use is inversely related to water price. Water price, unlike system losses is not constant over the simulation period. Water price for the future years is projected based on historical prices and is termed as base price. Base price is increased by 100% in increments of 10%. We used 176 (11 values for price and 16 values for system losses) sub scenarios involving price and system losses.

To examine whether policy variables can make a difference in water availability, a moderately severe drought was imposed on the WMA water supply system for the year 2028. The model was run for 176 policy scenarios to see if the outcome is affected. Under normal scenario (no policy intervention) the system will experience imposition of mandatory water use restrictions such as a ban on outside water use. Although, policy intervention scenarios were not able to completely alleviate the problem of restrictions, it was observed that few policy intervention scenarios were able to reduce the severity of the restrictions. Figure 18 shows that reducing system losses is a more effective policy alternative than increasing price. Figure 18 also shows that if system losses are capped at 11%, the system will not experience mandatory restrictions under moderately severe drought, in year 2028. A mix of two policies can also be adopted to achieve the same results. For instance, if system losses cannot be reduced below 13%, a 50% hike or more hike in price and 2% reduction in system losses (from 15%) will have the same effect on restrictions.

Water is a public good. Water price hike is not an easy. Water utilities have to take into account stakeholders before setting prices for next fiscal year. For instance, the DC Water Board of Directors recently held its annual public hearing on the proposed rate increases for Fiscal Year 2017 and Fiscal Year 2018 on May 11, 2016 at District Department of Employment Service (DCWASA, 2016). Price hike impacts low-income residents and often sends the wrong message to many people who actively conserve water (Garrick, 2015). Plugging system losses require huge investments. Hence a simultaneous tweaking of both policy interventions can provide an optimum solution that is both cheap and acceptable to all.

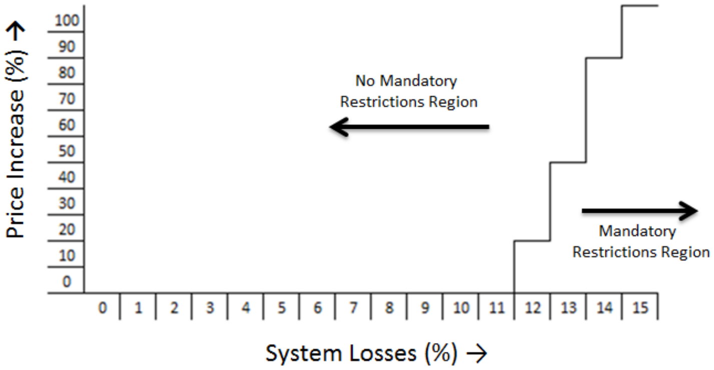


Figure 18: Impact on System Losses and Price on Restrictions (System under Moderately Severe Drought in 2025)

8. Conclusions

To conclude, the WMA water supply system complexity makes it difficult for policy makers to predict the systemic and coalesced impact of droughts, climate change and management policies. An interactive modeling approach that can involve multiple stakeholders and has an easy user interface along with strong dynamic and spatial modeling capabilities can be a useful tool for planners. The creation of multiple policy, climate and drought scenarios helps planners and laypeople to examine “what if” scenarios while looking into the future.

The study concludes that the WMA is self-sufficient under normal conditions during the entire planning horizon but will be strained under moderately severe droughts. Climate change will positively impact water supply system reliability, provided climate parameters move as anticipated (move towards the higher end of their ranges). However, climate change has uncertainty associated with it. Climate Change parameters may move towards the lower end of their ranges. Reliability will suffer when this happens. Reliability of the system under a moderately severe drought in year 2040 decreases from 80% to 75%, if climate change parameters were to move towards the lower end of their ranges. Thus, planners should look for management strategies to offset growing water demand fueled by rapid growth. Regulating price and system losses can be valuable tools that can be leveraged. But these policy interventions require stakeholder participation (price regulation) and capital investments (curbing distribution losses). Finally, system reliability can also be improved by increasing supplies.

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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

Chapter 5: Synthesis

1. Research Synthesis and Future Direction

This dissertation explored the impact of climate change and extreme weather events on critical infrastructure as defined by US Department of Homeland Security. The focus is on two important critical infrastructure systems – Water and Transportation.

Chapter 2 focused on the portfolio of bridges in our region (Washington Metropolitan Area) and examined the consequences of bridge design for flooding under the influence of climate change. The study looked at the freeboard design criteria for bridges of different road classifications. Climate change may necessitate different design criteria because of changes to flood frequency behavior. Hence, the margin of safety associated with a designed freeboard may change under future climate conditions. Chapter 2 uses systems thinking to connect multiple sub-systems that define and feed into our problem of finding appropriate design criteria. The climate sub-system is included in the analysis in form of IDF (Intensity-duration-frequency) curves of future climate models for direct comparison to current IDF curves. Climate change impacts the environmental variable (precipitation) by changing the frequency associated with a given flood event. Flood discharges for varying frequencies for current conditions are estimated using US Geological Survey regression equations and Natural Resources Conservation Service methods to inversely calculate the causal precipitation for floods of varying frequencies. Finally, the return frequency for this causal precipitation is determined from both NOAA Atlas 14 and future climate intensity-duration-frequency curves.

The results indicated that the transportation network is vulnerable to climate change, irrespective of the category of the roadways under analysis. The magnitude of bridge vulnerability to future climate change is variable depending on which climate model projection is used. Climate change models have varying projections based on socioeconomic conditions they assume for the future. The results also pointed out that the local roads are more vulnerable to flooding under the influence of climate change. The failure of bridges also has a systemic effect. The flooding of bridges causes upstream backwater effects, thus increasing the likelihood of flooding other areas in addition to the road itself. This may further lead to an increase in the risks associated with mapped flood inundation zones. Finally, the research also demonstrated that imperviousness, which is a function of land use and urbanization; increases the susceptibility of the bridge to failure. This enabled the conclusion that regulating the development in a watershed can bolster resilience of bridge infrastructure to climate change.

This research can be expanded further to include hydraulic structures other than bridges such as culverts, drains, detention ponds, etc. to examine the impact of climate change induced flooding on these structures. Similar to bridges, other transportation related hydraulic structures are also vulnerable to climate change (Mayers, 2006). One such example is provided in Appendix C (Exercise A). Another direction possible for this research is to analyze the impact of bridge or road failure on the performance of a transportation network. The transportation network can be inundated with floods of varying frequencies (for both current and future climate scenarios) and performance indicators such as number of links flooded, total trip travel time, total trip distance, average trip time between few critical origin-destination pairs can be measured. By comparing the performance of the road network for the current climate scenarios and future climate change scenarios, we can assess the impact of climate change on road network performance. As a next step, we can also validate the research by exploring the local roads further as storm frequencies associated with local roads are smaller as compared to highways.

Like the transportation infrastructure, water infrastructure is also vulnerable to the impact of extreme weather conditions and climate change. A reliable water supply is an important determinant of health and wellbeing of individuals and of whole communities. Chapter 3 and 4 analyzed the performance of the WMA water supply system using the system dynamics paradigm. Similar to the research conducted in Chapter 2, this research also involved multiple subsystems, such as the water demand subsystem, the reservoir subsystem, the free flowing river subsystem, climate and policy considerations.

The study concludes that the WMA is self-sufficient under normal conditions during the entire planning horizon (2016-2040) but will be strained under moderately severe droughts. Climate change will positively impact water supply system reliability, provided climate parameters (temperature, precipitation and streamflow) move as anticipated. However, climate change has uncertainty associated with it. Climate Change parameters may move towards the lower end of their ranges. Reliability will suffer when this happens. Reliability of the system under a moderately severe drought in year 2040 decreases if climate change parameters were to move towards the lower end of their ranges. Regulating price and system losses can be valuable tools that can be leveraged. But these policy interventions require stakeholder participation (price regulation) and capital investments (curbing distribution losses).

Since the research did not include the water supplies that are under development and planning for the WMA region such as the use of Lorton and Loudoun quarries as supplemental water supplies (ICPRB, 2010), due to the uncertainty in the volume and the timeline of these new water sources, the next step could be to include them as potential new supplies and re-examine the WMA water supply system reliability under drought and climate change.

The research can be taken further to model, simulate and examine other metropolitan cities like San Diago, Las Vegas, etc., which are relatively water scarce regions to evaluate the difference between dryer and wetter regions. It could be insightful to study the difference in performance between the two regions' future water reliability under climate change scenarios and drought conditions.

Climate change also impacts population growth by impacting land use patterns especially in regions which are more vulnerable to extreme events like coastal or low lying areas. More direct impact of climate change on population can also be included while modeling population growth. Other than that, impact of resource scarcity and depletion on population growth can be modeled more accurately by calibrating model with data from regions where resource scarcity had occurred in history.

Finally, this research can be made accessible to public and policy makers so that they can experiment with different climate change, population growth and policy scenarios just like the World 3 model (Meadows et al., 1972). Due to its user friendly graphic interface, this research can also be made available as an educational tool for public awareness. This research can be used as a public policy tool for collaborative decision making that involves diverse stakeholders. For example, policy decisions regarding changes in environmental flow regulations are often riddled with persistent pressures from environmental agencies and environmental advocacy groups (Pegg 1999). Often the complexity of water supply systems can make it difficult to develop a comprehensive mitigation and adaptation strategy that potentially can lead stakeholders and policy makers to come to an agreement regarding mitigation strategies. In such cases, a tool with an ability to graphically represent an entire water supply system with all its components and connections is an important asset.

To conclude, this dissertation provides an insight into the impact of climate change and extreme weather events on the water and transportation infrastructures. The results of this research can be used by policy makers and stakeholders as an input to planning and decision making.

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Appendix A

Table 7: List of bridges and their watershed characteristics.

Bridge ID	Road Classification	Drainage Area (km^2)	Impervious Area (%)	Watershed Slope (dimensionless)	Channel Slope (dimensionless)	Curve Number	Time of Concentration (hours)
1	A1	2.7	41.1	0.087	0.027	76	1.30
2	A1	142.0	31.0	0.059	0.003	75	11.01
3	A1	0.9	44.5	0.057	0.024	79	0.86
4	A1	8.2	40.6	0.054	0.008	77	2.75
5	A1	1.8	40.0	0.085	0.031	76	1.08
6	A1	1.0	60.3	0.036	0.018	85	0.96
7	A1	8.7	42.6	0.054	0.009	78	2.75
8	A1	6.1	37.2	0.062	0.010	76	2.30
9	A1	6.5	47.0	0.052	0.013	80	2.29
10	A1	1.1	43.8	0.056	0.014	78	1.00
11	A2	70.7	24.6	0.067	0.003	72	8.04
12	A2	29.5	26.3	0.063	0.007	73	5.28
13	A3	0.8	50.4	0.061	0.029	80	0.75
14	A3	1.7	47.9	0.054	0.017	79	1.22
15	A3	0.9	52.8	0.070	0.026	82	0.72
16	A3	1.1	46.9	0.066	0.020	79	0.90
17	A3	11.3	35.3	0.062	0.011	75	3.19
18	A3	1.5	41.0	0.079	0.034	76	1.05
19	A3	1.6	48.0	0.054	0.019	81	1.10
20	A3	0.9	59.1	0.055	0.020	84	0.77
21	A3	5.9	34.2	0.057	0.011	74	2.49
22	A3	10.3	35.5	0.059	0.013	75	3.12
23	A4	4.5	43.6	0.069	0.014	78	1.76
24	A4	1.1	43.9	0.056	0.014	78	1.00
25	A4	3.9	51.7	0.058	0.014	81	1.64
26	A4	120.4	28.6	0.058	0.003	75	10.21
27	A4	0.9	37.2	0.074	0.030	76	0.85
28	A4	2.9	36.8	0.054	0.016	75	1.78
29	A4	126.9	29.7	0.059	0.003	75	10.46
30	A4	132.6	30.3	0.059	0.003	75	10.67

Appendix B

Table 3 – Estimation Results For Water Demand For The Log–Log Model

	OLS Regression			**IV Regression (Second Stage)**		
Variable	**Estimate**	**Std. Error**	**p-value**	**Estimate**	**Std. Error**	**p-value**
people_per_household	-1.32	0.184	< 1%	-1.29	0.235	< 1%
price_per_ccf	-0.20	0.050	< 1%	-0.18	0.075	< 5%
lag_water_use_per_capita	0.41	0.077	< 1%	0.43	0.102	< 1%
impact_energy_policy_act	-0.01	0.022		-0.02	0.030	
temperature	0.18	0.117		0.17	0.148	
precipitation	-0.03	0.030		-0.03	0.038	
Adjusted R2	0.99			0.98		
F-value	276			174		
Sample size	19			19		

Table 4 – Estimation Results For The First Stage Of The IV Approach

Variable	**Estimate**	**Std. Error**	**p-value**
precipitation	-0.09	0.098	
temperature	0.13	0.383	
impact_energy_policy_act	-0.06	0.088	
operating_expenses	0.57	0.355	
operating_revenues	0.49	0.263	< 10%
people_per_household	0.79	0.702	
lag_water_use_per_capita	0.04	0.274	
Adjusted R2	0.95		
F-value	54		
Sample size	19		

Table 5 – Estimation Model			
Variable	**Estimate**	**Std. Error**	**p-value**
water_use_per_capita_lag	0.43	0.078	< 1%
price_per_ccf	-0.19	0.043	< 1%
people_per_household	-1.51	0.164	< 1%
Adjusted R2	0.98		
F-value	483		
Sample size	19		

Table 6 – Model With 'People Per Household Square' Variable			
Variable	**Estimate**	**Std. Error**	**p-value**
people_per_household	-14.83	6.595	< 5%
people_per_household_square	9.65	4.781	< 10%
water_use_per_capita_lag	0.45	0.072	< 1%
price_per_ccf	-0.19	0.039	< 1%
Adjusted R2	0.98		
F-value	438		
Sample size	19		

Appendix C

Table 3: WMA Demand Ratio

WMA Demand Ratio	
Ratio of Aqueduct demand to total WMA demand (rA)	0.29
Ratio of Rockville demand to total WMA demand (rR)	0.01
Ratio of FCWA demand to total WMA demand (rF)	0.36
Ratio of WSSC demand to total WMA demand (rW)	0.33
Ratio of FCWA Potomac demand to FCWA Occoquan demand (rFO)	0.30
Ratio of WSSC Potomac demand to WSSC Patuxent demand (rWP)	0.54

Table 4: System Losses Calculations (ICPRB 2010)

Ratios	WMA Demand Ratio		Average System Losses
Ratio of Aqueduct demand to total WMA demand (rA)	0.29	*	24.77
Ratio of Rockville demand to total WMA demand (rR)	0.01	*	3.90
Ratio of FCWA demand to total WMA demand (rF)	0.36	*	6.25
Ratio of WSSC demand to total WMA demand (rW)	0.33	*	15.50
Average System Losses for WMA	**15**		

Table 5: Calibration Results

Parameters	Value
Elasticity (Price) (dimensionless)	-0.037*
EPA Population Growth Rate (people/month)	0.0025*
Average Water Use (m^3/day)	0.5*
Elasticity (Precipitation) (dimensionless)	-0.115**
Elasticity (Temperature) (dimensionless) *-4.53e+015 (payoff) ** -6.94e+017 (payoff)	0.15**

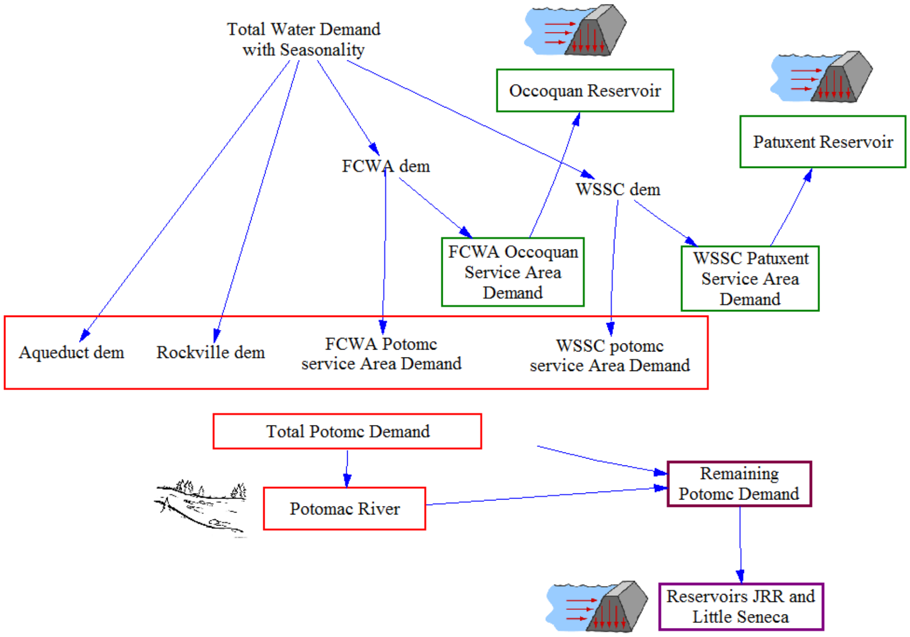

Figure 19: Balancing Demand and Supply - Schematic

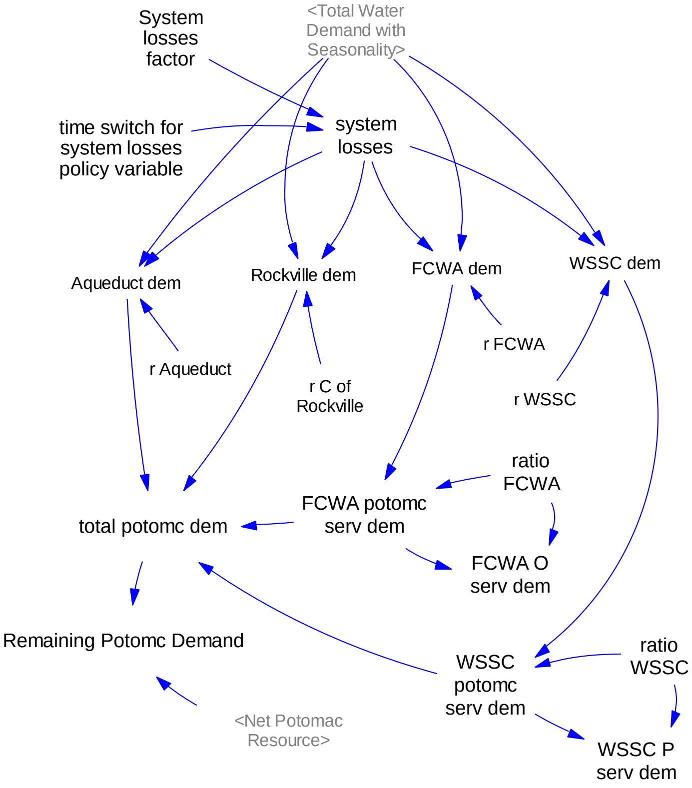

Figure 20: Balancing Demand and Supply - Modeled

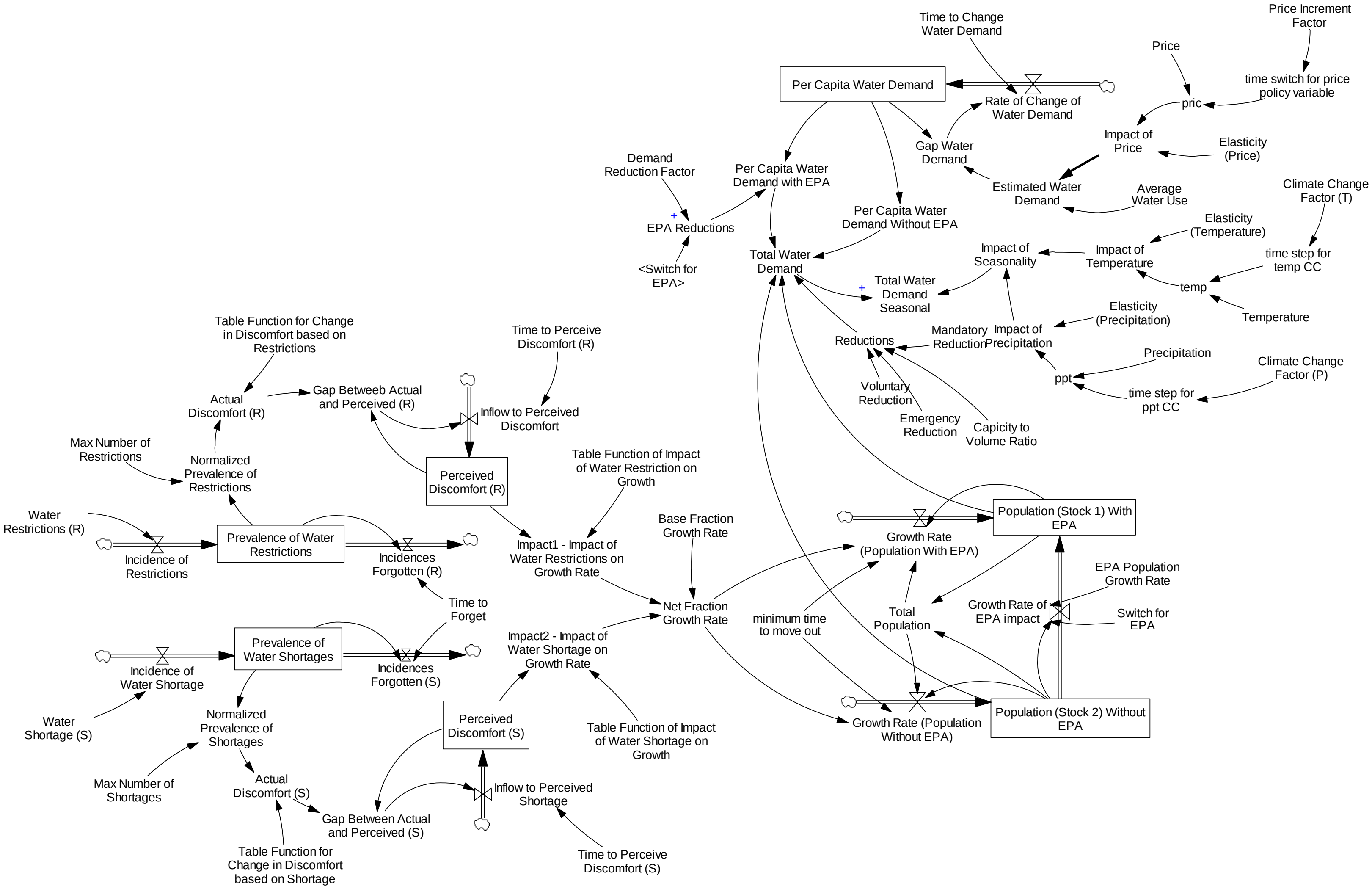

Figure 21: Stock and Flow Part 1

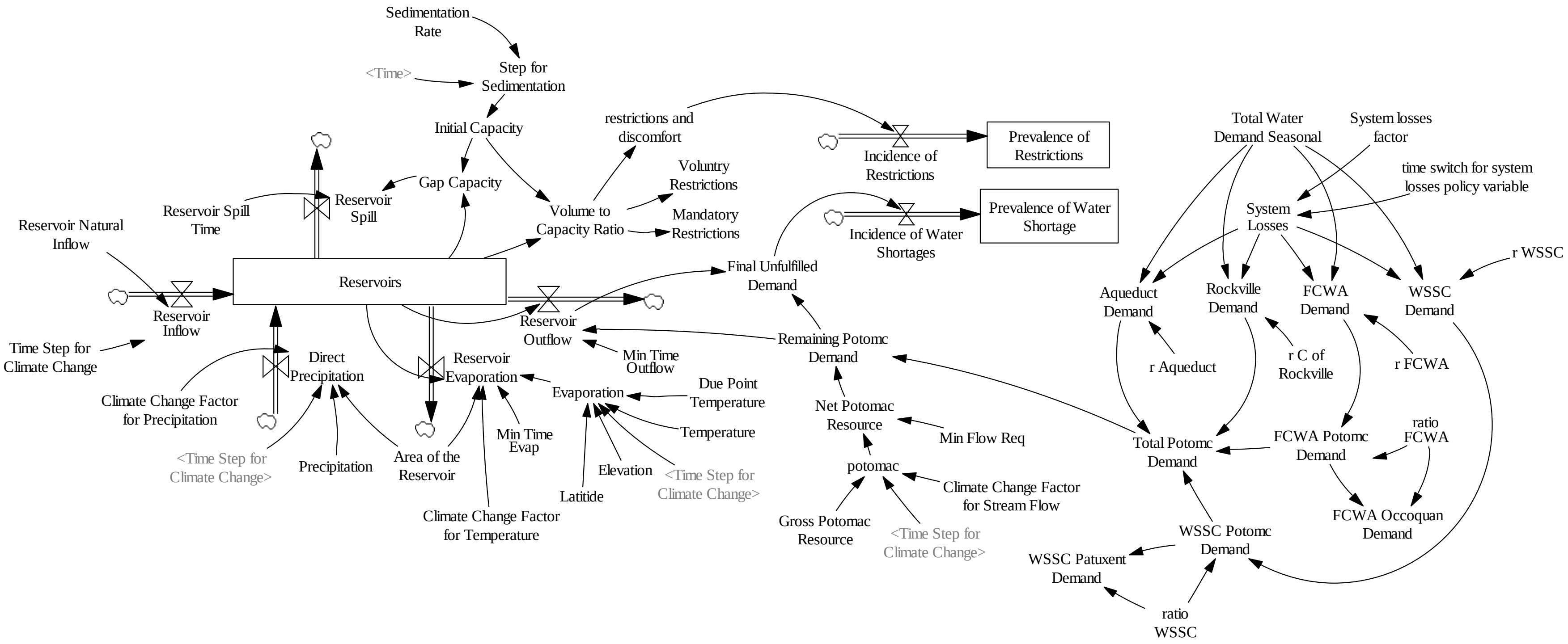

Figure 22: Stock and Flow Part 2

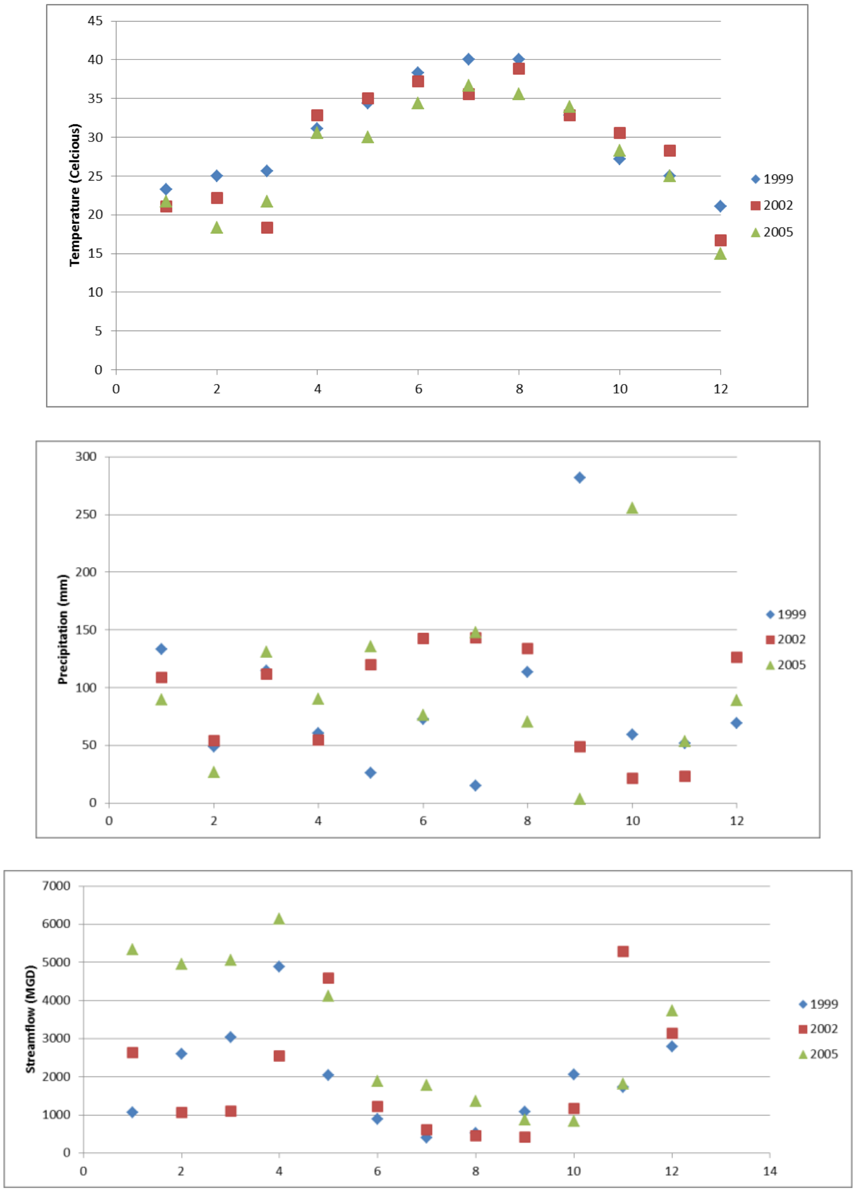

Figure 23: Difference Between (drought year) 2004 and 1999 and (non-drought/normal year) 2005[7]

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[7] Due to missing data from NCDC (national arboretum at Washington DC gauge), random substitution was made in place of missing values.

Appendix D

Exercise A

Optimizing Detention Ponds in lieu of Uncertainties in Climate Change and Urbanization: Problem Statement

Objective: The Objective is to optimize the cost associated with design, construction and maintenance of detention ponds which are considered as the most robust storm water control practices available.

Introduction: A detention basin is a stormwater management facility installed on, or adjacent to, tributaries of rivers, streams, lakes or bays that is designed to protect against flooding and, in some cases, downstream erosion by storing water for a limited period of a time. They are considered as Best management practices (BMPs) that provide general flood protection to an area and can also control extreme floods such as a 1 in 100-year storm event. Such basins are built during the time of construction of new land development projects like residential houses, stadiums or shopping centers. These ponds help manage the excess runoff generated by newly-constructed impervious surfaces such as roads, parking lots and rooftops. They allow large amounts of water to flow into them during a rain event and release that water gradually by having a small opening at the lowest point of the structure (Detention Basin, 2016).

Detention ponds are basically designed to mitigate the detrimental effects of land development. The objective is to limit the peak flow rates of the developed areas to that which occurred before development took place; meaning that the flood frequency curve after development coincides with the flood frequency curve after development of the area (this is one of the many storm water management policy considerations). It is usually designed for lower return periods like 5, 10 to 50 years return period discharges.

Costly damages are incurred if we don't build them. The damage can be in form of erosion, flood damage to homes, loss of trips due to flooding of roads, increase in travel time, etc.

Climate Change: Climate change has impacted the frequency of peak discharges for example, a 5 year rain event is no longer a 5 year event, it has now become a 2 year event. This will have an implication on the infrastructures built to accommodate a 5 year precipitation event. Since detention ponds design criteria include flood return period, therefore any changes to it will impact the design of the structure. There is need to optimize the design of such structures by incorporating uncertainties in climate change.

Objective Function: Minimize the cost of making such basins while answering three questions in lieu of uncertainties posed by climate change:

- Should we build it (Detention Ponds)?
- When do we build it (Time Horizon)?
- How big should we build it (Volume)?

Costs involved:

- Cost building the Structure (Cost of land, Manufacturing Cost)
- Cost of maintaining the structure over a period of time
- Cost of damage associated with inappropriate structure.