ABSTRACT

Title of Thesis: URBAN WATER SUPPLY PLANNING UNDER CLIMATE AND DEMAND GROWTH UNCERTAINTIES: A FRAMEWORK FOR IMPROVING SYSTEM RESILIENCE

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Urban areas around the world are facing increased challenges in consistently and reliably providing water services. Rapid urbanization, climate change, and the disjointed management of water distribution systems reveal the need for the creation of holistic management solutions. San Francisco Public Utilities Commission (SFPUC) is considering alternative water supply options to improve the reliability of San Francisco’s water resource, which provided a case study for this research. This research proposes an alternative planning tool used for systematic urban water supply planning and demand management. This approach compares water supply options using the Water Evaluation and Planning tool (WEAP) and a drought resilience matrix. Future implications of modeled climate change, extreme drought, and population increase effects on the natural and urban water system are explored in this study. The effectiveness of water supply portfolios is compared through the creation and use of a drought resilience matrix.

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by

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Thesis submitted to the Faculty of the Graduate School of the
University of Maryland, College Park, in partial fulfillment
of the requirements for the degree of
Master of Science
2018

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Dedication

I would like to dedicate this thesis to God, my family, my fiancé, and Chiko the bunny. Their foundational love and support were instrumental in this process.

Acknowledgements

I would like to thank my advisor, Dr. Negahban-Azar, for providing me with the opportunity to complete my graduate studies under his thoughtful guidance, encouragement, and support. I also appreciate the feedback, instruction and assistance from my committee members Dr. Pavao-Zuckerman and Dr. Tilley. This work would not have been possible without the support, consultations and encouragement from my lab mates and fellow graduate students. Finally, I would like to thank Matt Moses at the San Francisco Public Utilities Commission for his wisdom, expertise and provision of information about Hetch Hetchy Reservoir and the Regional Water System.

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List of Abbreviations

BAWSCA	Bay Area Water Supply Conservation Agency
SFPUC	San Francisco Public Utilities Commission
WEAP	Water Evaluation and Planning Tool
IWRM	Integrated Water Resource Management
IWCM	Integrated Water Cycle Management
EPA	Environmental Protection Agency
GHG	Green House Gases
IPCC	Intergovernmental Panel on Climate Change
WSIP	Water System Improvement Program
BMP	Best Management Practice
SWAT	Soil and Water Assessment Tool
IWFM	Integrated Water Flow Model
MGD	Million Gallons per Day
RWS	Regional Water System
USGS	United States Geological Survey
NOAA	National Oceanic and Atmospheric Administration
WCRP	World Climate Research Programme
CMIP3	Coupled Model Intercomparison Project 3
PDSI	Palmer Drought Severity Index
RWTP	Recycled Water Treatment Plant
WPCP	Water Pollution Control Plant
PEIR	Programmatic Environmental Impact Report
GCM	Global Climate Model

Chapter 1: Introduction and Literature Review

1.1 Overview

Managing the urban water sector in the 21st century comes with a variety of challenges. Protecting the urban water systems, the natural source water, and water needs of humanity has become critically important. Both conservation and alternative water sources are being used to address the shortcomings of the development of traditional water sources. In the face of increased urbanization, degraded water quality, and dwindling water supply it is becoming increasingly difficult to manage the current system and create effective solutions to help the urban water system combat these issues in a resilient manner. The dramatic increase of the world's population over the past century has increased the water use more than six-fold, with irrigation accounting for 70% of the water global water withdrawals (Gourbesville, 2008). It is estimated that, by the year 2025, 4 billion people will be subjected to living under conditions of severe water stress (Gourbesville, 2008). The rapid increase in urbanization in recent years has contributed to the development of water stress. According to the United States Census Bureau, from 2000 to 2010 the urban population increased by 12.1% in the United States, surpassing the overall growth rate of the nation at 9.7% for the same period (United States Census Bureau, 2012). This unprecedented increase in urbanization only continues as urban areas now account for 80.7% of the U.S. population (United States Census Bureau, 2012). Increased competition for water allocations among agriculture, industry, and domestic sectors only add a larger strain on the finite amount of freshwater resources available from the natural environment (Anderson, 2003). These factors not only affect the urban water systems, but the natural bodies of water they depend on, causing changes in the water quality, hydrology, and ecological processes embedded in the natural water system.

1.1.1 Urban Water Management Challenges

The three major systems that comprise the urban water sector are wastewater, stormwater, and drinking water. Traditionally, these large engineered centralized systems have been studied separately with the use of tools like life cycle assessment, footprints, and risk assessment to improve their function and management (Xue et al., 2015). Depleting water resources, increased water demand, and aging infrastructure has placed a strain on the affordability of water and service costs associated with water systems. It has been hypothesized that large cities around the world, by 2025, will have an annual demand for municipal water increased by 80 billion cubic meters per year and helping to expand the infrastructure needed will cost 480 billion dollars (Jagerskog et al., 2015). The increase in urbanization adds additional complications to the management of increasing service costs for these water systems (Xue et al., 2015). Water resource governance also suffers from a lack of communication and collaboration between different sectors. Current water governance and management measures are not proving effective under varying circumstances and uncertain climatic conditions. From jurisdictional issues associated with source water and its various stakeholders to generalizing solutions that work in one place will also suffice in another are just some of the water governance issues present in many countries around the world (Pahl-Wostl et al., 2012). Creation of innovative water management solutions has proved effective only for a period of time due to the lack of long-term monitoring put into place to measure the sustainability and efficiency of these solutions over time (Pahl-Wostl et al., 2012). Economic and institutional considerations prevail over those of an environmental nature. But the problems with current water resource management regimes do not just stem from governance and socio-economic issues. As mentioned earlier, traditional water management approaches characterize the water sector into four separate parts: water source, drinking water, wastewater, and stormwater. Each of these parts are managed differently with part-specific techniques and tools used to assess each with aims to reach different goals (Ma et al., 2015). Integrated Water Resource Management (IWRM) is a concept being used by water managers to begin to move cities to a place of developing and monitoring water systems in a holistic way that incorporates environmental, social and economic considerations. This approach seeks to manage water more holistically, focusing on four key dimensions of including water resources, water users, the spatial distribution of resources, and temporal variation of demand for water resources (Savenije & Van der Zaag, 2008). While IWRM has sought to provide improvements to the way water resource planning is handled, some researchers argue that the concept of IWRM has not addressed the parameters that need to be monitored that indicate whether a water resources system is functioning in an integrated manner or a measure for when a system has flipped from integrated to fragmented (Biswas, 2008). There are concerns when it comes to how IWRM is addressing problems of how a system can maintain integration on a long-term basis.

Integrated Water Cycle Management (IWCM) is a strategy that has tried to address some of the issues with IWRM in accounting for the complexities of the urban water cycle over a longer period of time. But even with IWCM, there is still a need for a framework that can be more universally used that includes the concepts of quantifiable resilience.

Traditional management of urban water systems has depended more heavily on supply-oriented management strategies rather than demand-side management strategies. There is a need for an increase in the use of demand-side management strategies in conjunction with supply-oriented strategies to add increased efficiency to the distribution of water and to reduce peak water use and short-term costs (Beal et al., 2016). Large centralized structures are still the common layout/format for most water systems in urban areas. But studies have been done that have concluded that a more decentralized approach to the organization of water systems and infrastructure promotes a more closed-loop system and prevail in performance when studied against centralized systems (Hiessl et al., 2001). The urban water sector and its challenges are studied by scientist and researchers in a very fragmented manner, with managers and planners of different parts of the water sector lacking communication, each sector individually seeking to help develop more sustainable water solutions, regulations, and practices. However, studying these water systems in such a fragmented way can lead to an oversimplification of the complex interactions between and coupling of the human- made urban water systems and the natural environment (Yang et al., 2016). Studying one system in isolation, like stormwater or wastewater, can cause problems to be missed entirely or shifted to other parts of the water sector, missing optimal solutions that could only surface if the urban water sector is studied holistically with the natural environment (Xue et al., 2015). For example, wastewater is viewed as strictly waste with little consideration for the potential value of the constituents in wastewater or water recycling and reuse. With the amount of capital, time, and energy invested in wastewater treatment, ignoring the multiple use potential of the water more comes at a high price. In cities around the world all domestic water is treated to drinking water standards, sometimes including the water used by fire departments, and this water is typically used once and discarded (Ma et al., 2015). Instead of using water that has been treated to drinking water quality standards for fire hydrants, the use or grey water could be employed. Through this one change precious high-quality water, monetary resources, and materials used in the processing of water could be saved. This is just one example of solutions fragmented management fails to recognize for concerning components of the urban water system. To move towards sustainable development in urban water systems, the development and use of a framework that can holistically evaluate the urban water sector with the natural water systems in the environment is needed.

1.2 Resilience and Urban Water Systems

Resilience has been used and coupled with frameworks that seek to holistically evaluate the urban water sector and help generate sustainable solutions. A widely accepted general definition many studies have used for resilience was one developed by the National Academy of Sciences that says resilience is “the ability to prepare and plan for, absorb, recover from, and more successfully adapt to adverse events" (National Research Council, 2012; Connelly et al., 2017). But how is resilience defined in relation to the urban water sector? When the term was first introduced, it came out of the area of mechanics and was used to show the ability of a system or object to bounce back to its original state after an external force was applied (Blackmore & Plant, 2008). Resilience in the urban water sector defined in this manner could refer to the ability of the infrastructure, used to treat and distribute water, to bounce back after a disturbance (i.e., floods, hurricanes, earthquakes. Etc.). This can also be viewed as engineering resilience, where the focus is on the return time or the amount of time it takes for a system to return to a stable equilibrium after disturbance (Folke, 2006). The focus of this type of resilience is characterized by attempting to preserve the system that is already in place and the system's ability to resist change. Another way of viewing and understanding the urban water sector holistically is understanding the natural water systems that the urban water sector depends on and the complex interactions that go on between the two systems. The system would then be referred to as a coupled human and natural system or a social-ecological system. A coupled human and natural system is a system that contains human and natural components that have complex interactions that form feedback loops (Liu et al., 2007). In simplistic terms, water is taken from the natural environment and treated at a drinking water treatment plant where it is then distributed throughout the urban environment for use and some of that water, in one form or another, ends up at a wastewater treatment plant where the effluent from the treatment is then dumped back into the natural water body. This process creates a feedback loop between the human and natural water systems. The processes that go on in a coupled urban and natural water system can be affected by factors like the built infrastructure, location and rate/type of consumption in given area, changes in land cover, type of urban form present, infrastructure material and businesses consumption or resources (Liu et al., 2007). Resilience can and has traditionally been built into a system using structured scenarios and adaptive management (Folke, 2002). Generating different scenarios allows alternative future events and their outcomes to be assessed and allows a determination of what is a desirable outcome vs. an undesirable outcome (Folke, 2002). Resilience can be decreased by trying to have a system reach its optimal reliability and efficiency when this very action could increase the system's vulnerability to fiscally degrading failure should a failure ever occur (Hashimoto et al., 1982). While the concept of resilience is not without its faults, resilience thinking still has great potential for strengths to bring to a framework if incorporated with WEAP. Resilience can also be used as a sustainability indicator, which would aid WEAP in further validating the sustainability of water resource management strategies. Current indicators of sustainability are only able to truly measure the current condition of the system, without considering the probability of the system’s state being preserved and improved over time (Milman & Short, 2008). A new indicator has been developed called the Water Provision Resilience indicator that adds new layers and dimensions to traditionally sustainability indicators regarding the provision of safe water access (Milman & Short, 2008). This new indicator could be incorporated into the potential framework.

Social-ecological systems are like the definition of coupled human and natural systems in that it is viewed as a coupled system of nature and people (Liu et al., 2007). When studying the coupled urban and natural water system and the complex interactions and dynamics that go on in and outside the system, the definition of resilience for such a coupling must incorporate both the social and ecological aspects of the system. Social resilience has been defined as "the ability of communities to withstand external shocks to their social infrastructure" (Adger, 2000). A social-ecological system can then be understood through resilience by defining resilience as being able to cope with shocks and disturbances to a system, keeping factors in mind like ecosystem services and social institutions and economic/ market structures that are affected directly by disturbances. In the case of urban water systems, resilience can be based on the infrastructure being studied, taking on the definition of infrastructural resilience-the ability to reduce the magnitude and duration of disturbance (EPA, 2015). The resilience definition can also be looked at from the point of view of how water systems in the urban water sector are performing concerning efficiency (i.e., is the water system performing its intended purpose efficiently and consistently?). However, other definitions of resilience have come along reimagining the concept of change and how to approach becoming more resilient. For some urban water systems, resilience can be characterized by persistence, change, and unpredictability-allowing for less resistance to change and more of an understanding change as an inevitable factor that systems should be able to adapt to. Change and disturbance begin to be viewed as an opportunity for systems to not only maintain their function but potentially diversify their functionality and learn, developing different interactions and connections that allow the system to increase its adaptability and resilience. With the introduction of new concepts like adaptive capacity, vulnerability, transformability, adaptive management/governance, the definitions and methods of achieving resilience have evolved (Folke, 2006). Resilience does not simply focus on bouncing back from disturbance, but rather opportunities that disturbance can present to a system regarding reorganization or evolved interactions, structures, and processes-creating a continuous feedback loop between sustaining and developing in the face of change (Folke, 2006). Keeping all these definitions in mind, it is easy to see how the urban water sector can relate to different definitions of resilience. The best definition of resilience that can capture all the different concepts from the other definitions is the definition of urban resilience given by (Meerow et al., 2016):

> “*Urban resilience refers to the ability of an urban system-and all its constituent socio-ecological and socio—technical networks across temporal and spatial scales—to maintain or rapidly return to desired functions in the face of a disturbance, to adapt to change, and to quickly transform systems that limit current or future adaptive capacity.”*

This definition can include many of the definitions previously mentioned and some outside the scope of this study. It should be noted that resilience is a concept that has been developed, used, and defined differently across disciplines. This causes major challenges in operationalizing and understanding resilience. For the purposes of this study, the National Academy of Sciences definition of resilience will be the one that governs the term ‘resilience’. Since various aspects of resilience for the urban water sector will be studied, concepts from the definition of ‘urban resilience’ will also be used. With the increasing need for the enhancement and protection of water distribution systems against drought, the term drought resilience will also be used in this study. Drought resilience, as defined by University of California, Davis Sustainability Group, is the maximum severity of drought during which core water demands can still be met, including social and environmental minimum requirements. Drought resilience offers one aspect of resilience that is threatened in San Francisco, CA and is of one of the main concerns for the future of the Hetch Hetchy Regional Water System.

1.3 Effects of Climate Uncertainty on Urban Water Systems

Climate change is a pressing challenge that many cities are facing. A wide variety of predictions have been made that anticipate significant temperature increases and concentrations of Green House Gases (GHGs), which makes managing these expectations difficult (Hoornweg et al., 2011). Observable changes in the variability and frequency of extreme weather events are expected to increase in both the distant and immediate future. Historically dry areas are expected to experience dryer periods (potentially drought), and historically wet areas are expected to experience more wet periods (potentially floods). These changes in temperature and precipitation will have significant impacts on the urban environment and its water distribution system. In many cities around the world, climate change is expected to increase water demand, and in some cases, decrease the natural water supply (EPA, 2014). Both The quantity and quality of water resources are predicted to be significantly impacted by climate change with changes in ice and snowmelt as well as changes in hydrological processes in many regions (IPCC, 2014). According to the Intergovernmental Panel on Climate Change (IPCC), the consequences of 1-degree Celsius warming caused by the increased occurrence of extreme weather events and sea level rise and diminishing snowmelt levels are already being observed currently (IPCC, 2018). Climate change models predict that the warming trend will persist past 2100, so both long-term and short-term climate mitigations strategies are needed to reduce the impact of the predictions. Studies also show that scientists should seek to reduce global warming to 1.5 degrees Celsius as opposed to 2 degrees Celsius that would help to limit climate change impacts and provide affected areas with a better capacity to adapt and function within their acknowledged risk thresholds (IPCC, 2018). But the necessary measures and reductions needed to achieve that global warming limit are severe and would have to be implemented more quickly, which presents challenges when working on such a large scale.

Climate change impacts urban areas both directly and indirectly. The expected direct impacts to cities are extreme events like storms, heat waves, and typhoons while expected indirect impacts consist of widespread capacity effects on the ability of systems in the urban environment to adapt to stresses that leave holes in the social-ecological connects in the environment (Silva et al., 2012). Climate change will, directly and indirectly, affect the pathways and networks in the urban environment and different water agencies abilities to communicate and effectively manage these systems. Studies show that coastal infrastructure will be affected by sea level rise, groundwater extraction will increase land subsidence, and floods and droughts will have far-reaching effects on the water distribution networks performance (Silva et al., 2012).

1.4 Urbanization and Population Growth

Cities around the world are experiencing rapid urbanization impacting land use cover and the water distribution system. Urban landscapes across the globe are occupied by more than 3.5 billion people, with the expectation that this number will increase close to 70% by the year 2050 (Silva et al., 2012). This growth in the urban population have drivers associated with population demographics, job opportunities, and cost of living in cities. Recent studies have shown that North America alone has 82% of its population living in urban areas, in contrast to the much slower growth noticed in rural areas (United Nations, 2018). However, the growth that can be seen in urban populations mainly are connected to the overall increase in population, with a noticeable shift in the percentage of people becoming urban dwellers. The global population in 2012 doubled in less than 50 years breaking 7 billion people with an estimated 394 of the world's city-dweller population breaking 1 million residents (McGrane, 2016). Both the increase in urbanization and the overall increase in population are expected to have dramatic effects on industrial growth, especially along important waterways (Cheng & Wang, 2002). Urbanization has a multifaceted effect on land cover and the increase in infrastructure from schools, apartment buildings, and grocery stores to shopping outlets, industrial, and commercial buildings. The increase of infrastructure in urban environments also brings an increase in impervious surfaces. These new structures and impervious surfaces aid in the increased prevalence of the urban heat island effect as well as severely altering the natural landscapes water storage capacity (Cheng &Wang, 2002).

The effects on hydrology in the urban environment are characterized by increased flow rates, reduced infiltration and recharge, increased yield and frequency of surface water runoff, vegetation and natural drainage loss, and changes to peak flows of rivers and nearby waterways. These dynamics result from the interaction between increased urbanization, impervious landscape, and meteorological/or hydrological processes. The introduction of artificial drainage networks, canals, and culverts change the timing, magnitude and frequency of the distribution of water and any chemicals, trash or pollutants that water is carrying (McGrane, 2016). Particulate matter from urban environments has an impact on the generation of rainfall and the frequency and intensity of summer thunderstorms (McGrane, 2016). Moreover, urban areas situated upstream versus downstream experience different hydrologic and water quality effects. The wastewater, drinking water, stormwater, and sewage distribution systems transfer large amounts of water and its constituents throughout the urban environment. The rate, frequency and magnitude of the water flow conveyed from these systems can severely degrade and natural water bodies and aquatic species (McGrane, 2016). Runoff on urban surfaces can collect pollutants, trash, heavy metals and nutrients (i.e., phosphorus, nitrogen, etc.) that are then transferred to streams and rivers that only further degrade the quality and habitats of the water. Recent studies have explored different fluxes of more complex microbial pollutants bodies (Tetzlaff et al., 2010, McGrane et al., 2014), man-made pharmaceuticals (Buckholder et al., 2007) and chemicals and sought to identify the sources to understand their prevalence in urban areas and conveyance to natural water bodies (McGrane, 2016). Water, sediment, and temperature dynamics are a part of what determines the health and functionality of aquatic ecosystems and these dynamics are impacted by urbanization (Cosgrove & Loucks, 2015). Increased urbanization puts further stress on the natural environment through the withdrawals that are taken from natural water bodies to meet the urban water supply demand. As urban demand grows, more withdrawals of water are taken out of the natural system and will be treated and used for water supply, food production, industrial processes, and to produce energy (Cosgrove & Loucks, 2015). These withdrawals adversely affect the flow and recharge of natural water bodies and decrease their adaptability to flooding and drought cycles. Thus, urbanization and population increase put a considerable strain on both the built environment water systems and the natural environment water systems. Understanding the connection between the two environments is imperative in order to move towards sustainable urbanization and development. New tools and holistic frameworks are needed to support better management decisions to protect, evaluate and maximize the benefits of these water systems efficiently.

1.5 Literature Review Conclusions

The impacts of climate change and increased occurrence and magnitude of natural disaster events combined with changing population dynamics continue to create difficulties for the urban water sector. Urban water treatment and conveyance systems (i.e., drinking water, wastewater, stormwater drainage, etc.) water services are especially vulnerable and in need of moving towards more sustainable water service provision (Johannessen & Wamsler, 2017). Incorporating resilience into management and the sustainable development of urban water service provision will help urban water systems be able to absorb and adapt to the hazards and disturbances. One way in which resilience is built into urban water systems is through improving water management. Management could focus more on managing urban water systems consistently and holistically, using similar planning, monitoring, and operation and maintenance standards (Savenije & Van Der Zaag, 2008). The traditional large centralized urban water systems that govern much of the water sector are proving to be less resilient, with many in need of infrastructure repair. Different frameworks and decision-making tools have been used to assess sustainable solutions to these problems but, few of these frameworks evaluate urban water systems holistically and in an integrated manner. With the complex interconnected nature of the coupled human and natural water systems, holistic assessment and evaluation of urban water systems are necessary and crucial to achieve sustainable alternative water resource solutions.

1.6 Research Questions and Objectives

This research seeks to answer the question: Can an integrated water planning and management approach be used in conjunction with resilience thinking to form an alternative planning tool for systematic urban water supply and demand management?

The primary objective of this research is to develop an alternative planning tool for systematic urban water supply and demand planning and management. City of San Francisco, CA has been selected as the study area for this research. Considering the proposed method, this study aims at addressing the following questions in the study area:

1. Which alternative water supply options (i.e., water recycling plants, desalination, reservoirs, etc.) will consistently and reliably meet the water demand of San Francisco under various climate change and population growth scenarios?

2. What is the best way of combining both centralized and decentralized water supply options to increase the Regional Water System's drought resilience? Which alternative water system provides the Regional Water System with the most resilience in terms of cost, the quantity of water, and reliability of delivery?

1.7 Research Approach

To answer these research questions, a modeling-based scenario approach for integrated urban water resource management will be used to model the existing Regional Water System in San Francisco, California. The scenarios will be created to simulate future water system improvement projects under the effects of present and future climate change and high population growth projections. The results of these scenarios will be analyzed regarding cost, yield, the timing of implementation, project requirements, unmet demand, and drought resilience. The modeled water supply alternatives will then be used to create an urban water resource development options portfolio for the San Francisco Public Utilities Commission (SFPUC). We have used the Water Evaluation and Planning tool (WEAP) for the modeling of an urban water system. This research will help to highlight new ways WEAP and resilience thinking can be used to improve the current fragmented analysis of water sustainability and approach to the management of the urban water sector. The results of this research will advance prior work on integrated water resource/water cycle management solutions by presenting a flexible and holistic solution to the water resource longevity problems. Understanding the integrated modeling system and resilience thinking (in relation to drought conditions) could lead to more cities around the United States with similar problem progressing to achieving water sensitivity. This research also has the potential to advance the understanding of climate change and its impacts on San Francisco's water sector. The WEAP model resulting portfolios should establish a simpler and more effective way for managers and policymakers to make decisions and organize water supply options. The results will also expose more information about the interactions between/interconnected nature of the urban water systems and the natural water systems (i.e., reservoirs and oceans vs. wastewater, stormwater and drinking water). Finally, this research should compare the benefits and disadvantages of using different alternative water resource systems like desalination and recycled wastewater.

1.7.1 Study Area

We have selected San Francisco as the study area for this research. SFPUC urban water management is moving towards the increased incorporation of resilience thinking into their practices. This research would help them develop and test out the performance of different supply/demand enhancing options to develop a more efficient and successful Water Management Action Plan. They are looking for the ultimate water supply yielding projects while trying to help increase the resiliency of SFPUC's water supply to ensure future needs and obligations are met in the future. SFPUC must develop a water supply program for the 2019-2040 planning horizon and this research could help influence what projects are included.

Cities like San Francisco, California are facing similar issues including increased drought, strained water supply, and increased degradation of water quality in the Bay area. To date, some of California's most significant historical droughts range from the six-year drought of 1929-34 to the more recent five-year drought (2012-2016) that was one of the driest periods on record (Jones et al., 2015). The hilly city of San Francisco is in northern California with a population of 864,816 people, surrounded by the Pacific Ocean and San Francisco Bay. The San Francisco area is serviced by the SFPUC, with ~85% of its water needs being met by the Hetch Hetchy reservoir and ~15% by local sources (SFPUC, 2017). San Francisco, and many other cities like it, have used traditional lifecycle assessment tools, emergy, modeling and footprints effectively to understand parts of the urban water system but, little to no research has been done on system-based tools that can assess the urban water sector holistically (Xue et.al, 2015). This gap in the literature is one that could be filled with the use of WEAP and resilience thinking. WEAP is a computer modeling tool that uses an integrated approach to model water systems and policy, with attention on both supply and demand side management. This tool is flexible, comprehensive and user friendly, making it the best framework to help combat integrated water resource management issues. A case study of using WEAP and resilience thinking to create ten future scenarios will be constructed as a part of this research on San Francisco, California to test the validity and efficiency of this framework.

The adoption of resilience theory and resilience thinking to develop sustainable practices and technologies to combat water scarcity and security issues are used across the United States. Green infrastructure, alternative frameworks of study, incorporation of decentralized systems, a combination of assessment tools, and water reuse are just some of the advancements being used around the world to combat water quality and quantity issues. Water reuse has gained much attention in recent years, helping to meet the rising human demand for water using less freshwater, reducing water diversions, and impacts of wastewater and stormwater discharge on environmental water quality (Anderson, 2003). Much of the United States, especially in places that suffer from droughts and floods, are employing the use of water reuse facilities. SFPUC has created a $4.8 billion-dollar program called the Water System Improvement Program (WSIP) that seeks to improve regional and local water systems and create sustainable, reliable and affordable alternative water systems (Anon, 2017). To incorporate more water reuse systems into San Francisco’s portfolio, SFPUC is considering two recycled water projects (Westside and Eastside) and a desalination project (Mallard Slough). Water Scarcity, climate change, and population growth have severely affected urban areas water supply. These issues have led to the development of urban water reuse/recycling due to shortcomings of traditional water resource expansion to meet growing demand (Behzadian et al., 2014). Water reuse is mostly used for non-potable water uses due to public perceptions and concern, along with other environmental factors (Behzadian et al., 2014). Water reuse is an alternative system that benefits the entire urban water sector. Using other alternative water systems like rainwater harvesting and greywater recycling reduces stormwater runoff and sanitary sewage discharge respectively but does not cover the entire urban water sector, so choosing the appropriate alternative system to match the need is important (Behzadian et al., 2014). Alternative water systems, like water reuse, are employed to not only meet a human need but to increase the sustainability of natural and urban water systems functions. Resilience is a concept that has been used in association with the topic of alternative water systems as these systems are seen to add resilience to the urban water sector when employed. Resilience theory and the concept of integrated water cycle management are viewed as the means to achieving water sustainability and the desired environmental and societal outcomes in the urban environment. Unlike other theories and concepts, Resilience theory and integrated water cycle management can holistically address the different behaviors and interactions happening in the system and the external factors that may seek to alter the system (Blackmore & Plant, 2008). But what is the best tool that can be incorporated into a framework with resilience theory to assess supply and demand side management options in the urban water sector? How can the concept of resilience be defined and used in relation to the urban water sector in San Francisco, California? This research seeks to determine if the combination of WEAP and resilience thinking can be used to make a comprehensive framework to aid in systematic water supply and demand planning. But how has WEAP been used and what qualifications or special features does it possess that makes it a competitive tool compared to traditional water service assessment tools? It is important to answer this question as well as understand what comprises the urban water sector, its current condition, and different definitions of resilience in the context of the urban water sector.

1.7.1.1 Climate Change Impact on the Study Area

California is a unique case as its climatic conditions are normally more wet in the north and dry in the south, and the state is characterized by some precipitation variability. Global climate models do predict that northern California will get wetter and southern California drier with cities like San Francisco characterized by increased droughts and precipitation variability (California Department of Water Resources, 2017). Some significant decreases were noted in the precipitation for southern California since 1990 (California Department of Water Resources, 2017). The San Francisco Bay area is expected to be characterized by 0.2-meter increases in sea level rise rising temperatures (0.6-1.1 degrees Celsius) in the Sierra Nevada, creating earlier snowmelt and decreased snowpack (California Department of Water Resources, 2017). This has a significant impact on many of California’s water supply systems as they depend on the Sacramento-San Joaquin Delta or the Tuolumne River. Because urban areas are so complex and interconnected with the natural environment, understanding how these dynamic challenges will influence feedbacks across temporal and spatial scales is important. Places that rely heavily on only one water supply source are in danger of undergoing complex issues with feedbacks and its ability to reorganize when facing the challenges of climate change.

1.7.2 The Water Evaluation and Planning Tool (WEAP)

As mentioned before, we have used WEAP to do modeling for the integrated water resources planning. WEAP is a user-friendly framework that takes an integrated water resource planning approach to the management and modeling of water supply and demand projects with policy orientation (Stockholm Environment Institute, 2016). With WEAP a user can perform more complex and holistic modeling of water systems in a scenario format and create alternative water systems/projects more readily in a comprehensible format. The benefit to using WEAP as a framework to study urban water systems is that WEAP can be used in addition to other tools, software’s, and databases already being used to help as an extra aid, while it can also be used alone. Conventional models used in water resource management focus on creating “supply-oriented simulation models” that can lack full representation of what’s going on in the system or potentially miss solutions (Stockholm Environment Institute, 2016). WEAP incorporates the demand side (i.e., water reuse, equipment, use patterns) and supply side (reservoirs, water transitions, streamflow) water issues into its modeling structure. (Stockholm Environment Institute, 2016). Alternative water management and development strategies are easy to simulate and study using this tool. WEAP the basic principles of water balance, which allows it to be a versatile system that can model the agricultural water resource issues as well as municipal water resource issues. Projects can be studied to scale in WEAP as well, whether it be an entire watershed or a small Best Management Practice (BMP) water feature. WEAP allows the user to model multiple competing scenarios, combine scenarios, and weigh policy along with the water resource management options under forecasted conditions. This framework would be unique in that it can engage multiple stakeholders because of its open structure, calculates water balance information, assesses a full range of water development options, and it can work with other modeling systems (Sieber, 2017). WEAP has been used across the globe, from California to Korea for various types of water resource projects. Other articles detailing WEAP and its use in different situations as an assessment and forecasting tool will be discussed in more detail and added to this section. As well as a section that goes more in-depth into the various disadvantages of using traditional tools in water resource management vs. WEAP.

WEAP has been used in numerous studies across the globe to assess and combat specific problems within the water sector. In other areas of California, it has been used to assess potential bottom-up and top-down adaptation strategies used to combat climate change effects on the water sector. A study of the Tuolumne and Merced River Basins was conducted in California using WEAP to determine climate changes potential impacts on the hydrology of the basins and the water supply for agricultural and urban uses (Kiparsky, Joyce, & Purkey, 2014). Another study done on the Kangsabati River catchment in India used WEAP to forecast the effect of three different adaptation options on the streamflow of the river under climate change (Bhave, Mishra, & Raghuwanshi, 2014). This study compared a dam check, increase in forest cover, and a combination of dam checks and increase in forest cover under climate change conditions using WEAP and the study concluded that the combined option was able to address the adaptions requirements for the given study area (Bhave, Mishra, & Raghuwanshi, 2014). These studies show how WEAP can be used on both a large and small scale as a decision-making tool. WEAP's capabilities stretch to use as a tool for environmental assessment analyzing economic advantages and disadvantages. WEAP comes with water quality simulations and analysis as well, providing a platform that can simulate multiple scenarios with water sustainability, quality, quantity, and cost in mind. A study in China used WEAP to test and produce sustainable management strategies for coastal zones, specifically the Binhai New Area which is facing significant water supply shortages (Li et al., 2015). This study not only had a focus on water quantity but the socio-economic effects of water challenges, which WEAP can model. WEAP's versatility allows it to be used in conjunction with other well-known modeling systems as well. The Soil and Water Assessment Tool (SWAT) is a well know modeling tool that some studies have used in conjunction with WEAP. A study was done in South Phuthiatsana catchment, Lesotho where WEAP and SWAT were used to assess the water quantities that could be made available for competing uses such as industrial and irrigation demands (Maliehe & Mulungu, 2017). These are just some examples of the many ways in which WEAP has been successfully used. WEAP studies have been conducted all over the United States, and in parts of Africa, South America, and Asia. WEAP possesses the necessary capabilities to be useful as the universal modeling system and tool in water resource management and beyond.

There is a push and a great need to move towards sustainable water resource management and integrated urban water systems. Frameworks are being developed, like the "urban water transitions framework” that are used as conceptual tools that can help with the transitions of policies about urban water and the creation of benchmark for sustainable development (Brown et al., 2009). The framework considers temporal, ideological, and technological aspects that cities change through when new management paradigms are introduced and when a city is trying to transition from any of the five different city types (i.e., “water supply city”, “sewered city”, “drained city”, “waterways city”, and “water cycle city”) to a “water sensitive city” (Brown et al., 2009). This framework introduces a management framework that evaluates cities as systems that go through various transitions and how these transitions can be navigated through management allowing the city to become more sustainable and resilient. This tool could act as a benchmark for urban water management and other institutions to assess a city’s growth (or lack thereof) towards sustainable urban water management and be able to compare this progress to other cities (Brown et al., 2009). Resilience tools like this and WEAP could work together to produce favorable holistic resilient development options. This study of San Francisco seeks to be an example of what potential there is for the future of the supply and demand of the water sector in California and its implications for other regions of the world. WEAP will allow for the creation of a clear and coherent framework for studying ecological processes, relationships (social and political), technical aspects, and other services/actors involved in the urban water system. These aspects may influence the system’s management and function. Frameworks like risk assessment and life cycle analysis have been used to evaluate the sustainability and function of urban water systems, but minimal research is available on the sustainability of the water sector (i.e., wastewater, stormwater, and drinking water). However, WEAP, with its flexible and comprehensive approach to integrated water resource management, can be used to compare systems and understand the complexities of the coupled human and natural urban water system. It accomplishes this by using both qualitative and quantitative inputs to model the historical, current, and future conditions of urban water systems and scenarios displaying projects and natural phenomenon that may affect those systems. WEAP allows the user to evaluate and analyze the behavior of the parts of the urban water system in a holistic manner. WEAP, therefore, uniquely presents the means to holistically evaluate the water sector and future management decisions for sustainable development. This research focuses on a case study in San Francisco, California (i.e., the Westside Water Reuse Project). In the future, WEAP can be used to more effectively create realistic potential Supply and Demand scenarios that display different projects and uncertainties potential effects on the water sector in San Francisco, California, accurately assess the sustainability of the urban water systems.

1.7.3 Measuring Resilience

Climate change continues to pose grave threats to the functionality of our cities. The expected increase in temperatures, heatwaves, and droughts are just some of the expected effects that will alter aspects of the environment. Particularly in urban areas, water distribution systems and other infrastructure are predicted to suffer transportation disruptions, higher stresses on equipment and materials, and increased use of emergency management protocols (Jabareen, 2013). In order to increase the security and reliability of water supply distribution to residents in urban areas, it is important to consider the water supply options that help build resilience into the existing water supply network. In an effort to increase urban water distribution systems functionality and manage resilience to drought, we created a drought resilience matrix. The drought resilience matrix, discussed in chapter 3, applies the four main features of resilience (i.e., plan, adapt, absorb, recover), to water supply alternatives to evaluate which additional projects will increase the drought resilience of the existing water distribution system. These four features of resilience were redefined to incorporate more characteristics intrinsic of the functionality and management of urban water systems. Each feature has an associated score that correlates to the level of importance the feature holds in increasing drought resilience. The plan metric focused assessing institutional aspects, yield, cost, implementation time, and location of the projects involved in each portfolio. The absorb metric assessed thresholds intrinsic to the water supply options and its ability to endure stress when exposed to drought variables. The adapt metric evaluates the water supply options abilities to help the water system persist through drought and reduce its impact on consistently meeting urban water supply demands. Finally, the recover metric focused on evaluating the water supply options ability to increase the return time of the urban water system. After each portfolio of water supply alternatives is judged and scored based on its ability to fulfill the components associated with the four resilience feature definitions, the total score is added up with a possible 55 points. The Regional Water system and associated water supply improvement projects in San Francisco, California were used as the case study to test the use of this matrix. Three portfolios (Portfolio's A, B, and C), discussed in both chapters 2 and 3, were created and tested using the drought resilience matrix.

Chapter 2: Comparing and Selecting Urban Water Supply Alternatives Under Climate and Demand Growth Uncertainties: A Case Study of San Francisco, CA

2.1 Abstract

Increased population growth, climate change, failing infrastructure, and water scarcity are a few challenges affecting many large cities today. Water is a key resource for sustainable development, but urban areas around the world are facing challenges in reliably and efficiently providing water services. Strained water resources and the fragmented management of large centralized urban water systems reveal the need to search for holistic management solutions. San Francisco faces increased drought and formidable freshwater constraints. San Francisco Public Utilities Commission's (SFPUC) exploration of alternative water supply options, to improve San Francisco's water sustainability and reliability provided a case study for this project. The objective of this study is to develop an alternative planning tool used for systematic urban water supply planning and demand management. This framework will compare water supply options using the Water Evaluation and Planning tool. We developed a model to compare a range of alternative water systems and their combinations (e.g., recycled water, desalination, etc.) under future climate change and population growth scenarios. The results show that the inflows for the years 2020-2060 are characterized by increased variability and frequency of low inflow than prior years. Under a 2% population growth rate the projected annual water use rate increased with notable changes from the year 2042-2060. The annual water use rate increases more rapidly after the year 2042 for both San Francisco

residential and wholesale customers. Conservation techniques, Tuolumne River diversions, and in-city desalination offer the most benefits when considering the cost and yield of the projects. The most cost-effective portfolio is portfolio A, which contains the Los Vaqueros reservoir expansion, Tuolumne River diversions, and conservation technique projects. The high population growth scenario had the highest unmet demand, increasing at a rapid rate from the year 2022-2060. The amount of unmet demand for the high population growth scenario from the year 2022-2060 was higher than that of the climate change scenario. Additional alternative water supply options were added to the model. Results from this study demonstrate the use of an integrated modeling tool, within a framework, and its capability to holistically compare urban water development options under uncertainty.

2.2 Introduction

2.2.1 California's Changing Climate

Evidence of climate change is apparent in western states of North America, like California. The effects of climate change on California has increased over the past decade, with records only furthering the narrative of the need for additional measures and management (California Air and Resources Board, 2017). As each decade displays warmer conditions, increased changes in the performance of natural systems and anthropogenic contributions to warming have increased (Intergovernmental Panel on Climate Change, 2014). Research indicates the human activities have advanced the temperature increases through actions like deforestation and the burning of fossil fuels. Climate change has intensified the prevalence of droughts, water supply distribution interruption, coastal erosion, and wildfires in California. Specifically, climate change has increased winter and spring temperatures, diminished spring snow levels, and has caused snowpack to melt one to four weeks earlier than historically seen (Luers et al., 2006). Many basins in the Sierra Nevada that contain rivers like Tuolumne and San Joaquin were studied and displayed signs of changes in streamflow and seasonal fraction of runoff (through snowmelt) from April to July was decreasing at statistically significant rates (Roos 1987, 1991; Wahl 1991; Aguado et al.,1992; Pupacko, 1993; Dettinger and Cayan, 1995; Shelton and Fridirici, 1997; Shelton, 1998; Freeman, 2002; Vicuna and Dracup, 2007). Streamflow may also be changing due to the increase in winter rainfall and the increase in spring temperatures. Throughout the state of California, previous observations have predicted that the hydro-climatology will be altered further in future years, impacting precipitation uncertainty, streamflow in rivers and reservoirs, source water, and water supply systems (California Department of Water Resources, 2017). This is of specific concern for the state of California since many water supply systems in the state depend on water bodies that are fed by the snowmelt process. Temperatures dramatically affect whether the portion of precipitation results in rainfall or snowfall and determines the timing of the snowmelt (Vicuna and Dracup, 2007). With increased temperatures California will see less snowmelt and a change in the timing of the snowmelt. The remaining snowmelt ultimately affects the amount of water that’s available to meet the demand and the timing in which that water demand can be met. The amount of water content in snowpack expected to be lost within this century is estimated to be up to 65%, with an expected increase in droughts and overall dry years (Liu, 2016). Overall, climate change threatens to further alter the hydrology of California with expectations of increased temperatures, shorter and earlier streamflow, and increased winter runoff.

It is becoming progressively important to study the regional, local, and statewide effects of climate change to understand how to manage water systems in the future better. The water system in California is far reaching, and water supply sites tend to be far in terms of distance (sometimes in other states) from urban sites, increasing the importance of understanding climate change effects on the water supply of nearby states rather than just focusing on with local rainfall (Carle, 2016). The most recent 2012-2016 drought in California set numerous records from diminished snowpack statewide, overuse of groundwater, to severe moisture deficits, and large economic losses in recreational and agricultural sectors (Ackerly et al., 2018). This drought event, specifically in years 2012-2014, was characterized as the “driest three-year period of statewide precipitation” coinciding with a period of record warmth in California (California Department of Water Resources, 2015). California receiving its normal winter precipitation, especially in the months December and January, are important for replenishing the water supply. During the 2012-2016 drought, many storms were forced away from the state causing during important winter months only increasing the dry conditions of the state (California Department of Water Resources, 2015). This drought was so taxing on California’s water supply that the Governor had to declare a state of emergency and ask the people of California to reduce their water use by 20%. A drought task force was created, and many state agencies had to work around the clock to ensure plans were being carried out to help those areas severely affected by the water shortage. The San Francisco Bay Area was one of the many regions impacted by decreased water allocations with residents asked to decrease their water use significantly. The Bay area depends on the Sierra Nevada and large reservoirs in that area to meet the water demands of the San Francisco Public Utility Commission customers (SFPUC). These customers include both wholesale and retail customers that encompass more than 2.6 million residents in San Francisco, but also three Bay Area counties (San Francisco Public Utilities Commission, 2016). San Francisco depends on the Regional Water System, specifically Hetch Hetchy reservoir located near the Sierra Nevada mountains, for 85% of its water needs (San Francisco Public Utilities Commission, 2016). The Regional Water System and its configuration are depicted in Figure 1. As mentioned earlier, the streamflow in the Sierra Nevada is being altered by climate change, which further alters the hydrology of several large reservoirs that places like San Francisco depend on. Not only will San Francisco need to plan for these regional effects of climate change but also the predicted local impacts. San Francisco and the Bay Area are expected to see rising temperatures and year-to-year precipitation variability with more intense winter rain storms (Ackerly et al., 2018). Sea level rise and increased urbanization are also concerns that may exacerbate the impacts of climate change in the Bay Area. The continued ability of SFPUC to meet San Francisco’s and wholesale customers growing water demand under local and regional climate change impacts depends upon the ability to recognize new water supply alternatives, advance climate adaptation, and increase the resiliency of the Regional Water System. In order to accomplish this, a framework is needed to be able to evaluate the current and future state of San Francisco’s urban water system holistically to determine how it will perform under climate change and growing water demand scenarios. Alternative water supply options need to be assessed as additions to the Regional Water System to understand which are the most advantageous in reliability and consistently meeting the needs of SPFUC customers. The creation of such a holistic framework would allow regions like the San Francisco Bay Area the ability to become more resilient and managers better prepared for planning and adapting to current and future water supply challenges.

2.2.2 California’s Water Use and Management

California’s natural water bodies and water supply system is one of the most extensive and complex in the world (Kallis, Kiparsky and Norgaard, 2009). Around the 1870s plans were first proposed about connecting large watersheds in California through large canals and aqueducts and importing water, then the proposed ideas were organized and extensively planned out from the 1920s-1950s, and finally created and managed between the 1930s and 1980s (Jenkins et al., 2004). In order to understand the management of California’s water supply, it is important to understand the general climate of the state. California is characterized by a semi-arid Mediterranean climate where you would expect very dry and warm summers accompanied by cool and wet winters (Fleskes, 2012; Matchett and Fleskes, 2018). The precipitation in this valley is variable, and the dry conditions only increase as you move southward. The Central Valley of California is a major component of water management in California because of the composition of natural water bodies, and human-made reservoirs that are present and used heavily by both the agricultural and urban water sectors. These reservoirs, rivers, and lakes mostly depend on snowmelt from mountains as a water source and surface runoff resulting from rainfall. The water supply in the valley is managed by various local, state, and federal agencies. The San Francisco Bay and the Sacramento-San Joaquin Delta supply 2/3 of California's drinking water and the management of these large areas have many implications on wildlife, water quality, and overall environmental protection (Kallis, Kiparsky and Norgaard, 2009). Many major pipelines, aqueducts, canals, and dams were put in place to ensure the safe delivery of water in the valley to urban developments. Currently, California's water use is divided into three main sections: urban, agricultural and environmental. Across California, on average, urban areas make up 10% of the water use, agricultural areas make up 40%, and environmental make up 50% of the water use (Mount and Hanak, 2016). It is important to note that these percentages and values can vary widely depending on whether it is a wet a dry year for the area and the location of the area within the state. The environmental section of water use is broken in four main categories including: the portion of water in rivers that is left by federal laws to be used as unimpaired flows, the water needed in order for stream communities to survive, water present in wildlife preserves that act as wetlands, and the water needed to keep the water body's water quality high enough for urban and agricultural use (Mount and Hanak, 2016). Water in this classification usually resides in northern California in areas that that are further from urban and agricultural activities allowing the water to remain pristine, unlike some water bodies in southern California. These water systems in California can stretch as far as 700 miles from upper watersheds in Northern California (i.e., Feather River) to branches that go for 1,400 miles reaching places like the Rocky Mountains (Carle, 2016). Many of the water delivery systems parts (i.e., reservoirs, aqueducts, pumping stations, etc.) help to collect and transition a large amount of surface water to different parts of California. Delivery systems in California like the California Aqueduct are highly integrated systems that are owned and sometimes collaboratively managed on the local, federal, and state levels. Among the delivery system connections, you have various hydropower, wastewater treatment plants, drinking water treatment plants, and underground storage facilities. These lengthy delivery systems in California present many challenges to the planning and management of these systems.

Over the years there has been mounting controversy over the management of California's water system because of the complexity of the system coupled with the increased effects of land cover change and human impacts. The extent of the California water system brings rise to questions about how the movement of water from the source across the landscape to people in urban and agricultural areas is affected and how the change in the dynamic of human consumption and pipe connections may foster consequences felt both regionally and locally. The availability of water for consumptive use in California is and will, therefore, be impacted by the development and growth of urban areas (Carle, 2016). The development and treatment of the land surrounding the freshwater sources have a significant effect on the immediate watershed (Lenat and Crawford, 1994; Gutman, 2007; Klausmeyer and Fitzgerald, 2012). Land changes like logging, mining, farming, and clearing land for building developments have effects on surrounding water bodies. In California, the drinking water supply system spans roughly 157 million acres and, of that land, only 16% is strictly regulated with proper protections against ecological degradation in the form of national parks and wilderness reserve areas (Klausmeyer and Fitzgerald, 2012). Some of the watersheds in California that service cities are well protected, while others need restoration and protection efforts. But even with the controversy, California's water system is one of the most studied and innovative systems that has been managed through collaborative policies and adaptive management (Kallis, Kiparsky, and Norgaard, 2009). Excellent communication and efficient collaboration are essential in order to manage and operate the water system properly. State and federal regulators will have to work more closely in the future in order to better prepare for balancing allocations of the water supply to urban areas to meet demands with allocations of water set aside for the environment during periods of extreme drought (Mount and Hanak, 2016). Water managers in California are continually trying to balance the perceived long-term and short-term economic, and environmental effects on water users in urban areas.

The California water system is heavily dependent on natural water sources, and the advancements in the aqueducts established for the transport of water in California has allowed water to be distributed to larger populations further away, increasing the stress and accessibility of the overall distribution system. Most Californians rely on water that is publicly supplied to meet their domestic needs by public water districts (Klausmeyer and Fitzgerald, 2012). Freshwater sources account for 82% of the water California's water distribution system withdrawals, with roughly

67% coming from surface water and 34% coming from groundwater (United States Geological Survey, 2010). Most of the freshwater sources are from a series of reservoirs, rivers, and lakes (Kenny et al., 2009; Klausmeyer and Fitzgerald, 2012). For many years, California was one of the only states to not have clear groundwater regulations in place until the Sustainable Groundwater Act was passed in 2014 with goals that locale agencies must meet by 2040 (Carle, 2016). This is an example of one area in California's water management that needed, and still needs, improvement to move towards a more holistic understanding and treatment of the water system. Groundwater is used largely around the state as a water supply resource. Without regulations, groundwater was easy to over pump and use at rates that were not sustainable leading to problems that persist in California today like land subsidence, deteriorated water quality, and increased costs associated with deepening wells and pumping (Borchers et al., 2014). Understanding the connections between groundwater, surface water, and their interconnections with the three major parts of the water sector (i.e., wastewater, stormwater, and drinking water) would produce more effective tactics for managing and protecting water resources in California. California historically sought to manage its water in the traditional capacity, with a centralized configuration that allowed for centralized control from either a regional or statewide government program (Blomquist, 1992). But California has always been innovative in the way that they progress their treatment and management of their water systems. In California's history, "self-governing institutional structures" were put into place to address basin and watershed specific water supply arrangements, building up a water resource governance system that factored in local users

(Blomquist, 1992). Eventually, California managers moved to more of a conjunctive use management of water, which looked at treating groundwater and surface water as one entity instead of focusing on simply conservation and surface water augmentation (Ashley, 2005). As the natural landscape was altered and water use increased, new challenges in water management were presented that led California officials to introduce new laws, projects, and agencies to undo damage that had been caused by altering historic landscapes and the natural hydrology to convey water along with the lack of understanding of how the built and natural water systems interact. The true beginning of a lot of changes in water management in California started in the 1930s with projects like the Central Valley Project that sought to create a series of dams and reservoirs for water storage, conveyance, flood management, and electricity production (Water Education Foundation, 2018). This project was later created into the Central Valley Project Improvement Act that stirred many scientific debates about how water should be allocated, especially water for agriculture/farmland vs. water for drinking and other human-specific uses. As more was discovered about the effects of water management on both the built and natural water system the management style moved towards integrated water resource management with considerations for more decentralized approaches to the configuration of the water sector in urban environments. Even though great strides have been made in the management of water in California, similar questions about water allocations, alternative supply sources, and innovative solutions to preserve natural water bodies need to be addressed. California water management and planning needs to develop more alternatives water supply options that can be combined with the current urban water systems in

California to act as buffers and catalysts to add resiliency to the overall water system. Formidable freshwater constraints in California need an exploration of combining both supply and demand side management measures with the concept of resilience and alternative water supplies that are decentralized and diversified to take the pressure off components of the water system like wastewater treatment plants and potable water use. Managing water resources in a way that allows it to be efficiently used in a fit-for-purpose method, from a variety of sources that takes pressure off the dwindling natural water supply, to help reliably and consistently meet the water demands of the future is imperative.

2.2.3 Modeling Future Water Supply and Security

Presently, management of water systems in and outside the urban environment usually incorporates a form of modeling into the planning and design updates of water resource systems. With the ability of models to factor in economic, hydrologic, institutional, political, and environmental parameters make it easier now more than ever to display the complex processes of water distribution systems and how they will develop over time under various conditions. Modeling water supply provides a way to forecast and predict how policy changes, additions to water infrastructure, economic or environmental changes may affect different components (i.e., reservoirs, instream flows, the effluent of treatment plants, etc.) of the water system (Loucks and Van Beek, 2005). Evaluating the potential impacts of climate change, demand growth, and human activities both presently and in the future can be done easily using modeling (Milly et al., 2008). In the case for California, integrated hydrologic modeling is used by the California Department of Water Resources to aid in the planning process for future development of their resources (California Department of Water Resources, 2016). The modeling system used the most to study California's water system in the Central Valley is the Integrated Water Flow Model (IWFM) that focuses on water resources planning and management. IWFM can simulate the interaction between groundwater and surface water, water reuse schemes, and calculate water demand using land use data (California Department of Water Resources, 2016). But often with models this complex, communication between stakeholders, policymakers, engineers, and politicians can become difficult in terms of communicating the functioning and results of the model. In order to have a better understanding of the performance of water resources under different conditions, it is important to have and employ the use of a modeling system that is user-friendly, flexible, and comprehensive in its parameters and projections. A model capable of testing the reliability and consistency of water resources in the wake of rapid climate change, will have implications for the planning and management of these systems facing increased water vapor fluxes, severity and occurrence of droughts, sea level rise, and contamination of natural water supplies (Milly et al., 2008). Having models that can be used on both small-scale and large-scale water supply projects is important. California has "simulation-based planning approaches" that are used to manage current water supply alterations and new managements suggestion, but in order to accurately capture large-scale and small-scale management changes these planning approaches should be combined with a model that has efficiency and optimization techniques to help with selection and complexity of changes of both scales (Jenkins et al., 2004). Using modeling in water supply management more would allow for better predictions and analysis of proposed future behaviors. Many models come with constraints and limitations on their abilities to accurately depict all the variables and interactions at play in the natural environment. However, even with these limitations' models can produce a variety of information that managers and planners can use to make informed decisions. Complex modeling systems that depend on mathematical modeling have been less helpful when there are data gaps and less clear goals and alternatives for projects (Loucks and Van Beek, 2005). There is a need for the creation of a framework that incorporates the complexities of mathematical modeling and the complexities of planning and management goals with the ability to capture the interdependencies between water resource components as a system and as individuals.

Urban water managers are paying more attention to the concept of water security in light of issues with the competition between the growing limitation of water resources and demand (Marlow et al., 2013). The growing interest in the topic of water security at the urban level stems from the fact that the term has acted as an umbrella for integrated or sustainable water resource management concepts, as well as being used interchangeably with these terms (Hoekstra, Buurman, and van Ginkel, 2018). The effective holistic management of water in the natural environment is critical for the success and sustainable development of urban areas. In order to foster holistic management, agencies have to acknowledge and incorporate all the facets of urban water management including: social, environmental, financial, institutional, infrastructural, and operational considerations. The concept of water security at the urban level incorporates different perspectives and approaches that look at assessing long-term and short-term water resource issues. Incorporating water security concepts into a holistic urban water planning tool and framework, like the one I am proposing, allows for the production of problem-oriented, environmental sustainability-oriented, and goal-oriented solutions. The present concerns for the inadequacy of the centralized urban water system’s ability to combat pressures from climate change and demand growth, complex social and institutional constraints, water service budgeting and delivery uncertainty can be combated and evaluated better through the use of water security concepts (Marlow et al., 2013). On the urban level, considering alternative water sources and systems that can address the environmental, financial, social, and demand requirements for the present and future urban population is paramount for increasing the reliability of the urban water systems. The use of water security concepts can help to evaluate to what extent alternative water resources would help to increase the reliability of the urban water system in San Francisco. Water security helps to identify weaknesses in urban water management and broader implications for decisions made to implement specific strategies. The concept of water security has been used in the development of water resources around the world. Water security over the past 20 years has increased in mention and relevancy across multiple disciplines, producing over 400 peer-reviewed publications, half of which were published within the last five years (Bakker, 2012). Many states across the U.S. have water security outlined as apart of goals and initiatives in water resource management plans for the future. But what is water security? The definition of water security according to (Grey and Sadoff, 2007) is:

> ‘The availability of an acceptable quantity and quality of water for health, livelihoods, ecosystems, and production, coupled with an acceptable level of water-related risks to people, environments, and economies.’

The broader definition of water security views the water from both a services perspective and as a potential threat. Trying to achieve a secure water environment means addressing potential tradeoffs and risks to different groups of people that depend on the resource. Defining this term in a way that can be operationalized needs to be done on a case by case basis as the assumptions you make about livelihoods, demographics, health, and what’s considered an acceptable allocation of water may change based on the case study components (Grey and Sadoff, 2007). For the sake of this study, water security will be tackled from an urban perspective and will be more focused on water allocations, demands, and their effect on the water supply and environment and less about waters potential threat to the more social aspects of water security. Looking at human versus environmental water needs is an important aspect of water security and one that will be important to California’s future. Water Security is related to California’s mounting water resource problems in that the term used to be view as akin to integrated water resource management or sustainable water management (Hoekstra, Buurman, and van Ginkel, 2018). But adding water security to a study of California’s water resources adds a layer to integrated water resource management as its definition seeks to approach water resources in a more holistic manner. Some of the linked resources, like stormwater and wastewater, are ignored or looked over, and new solutions to water system problems are missed by ignoring such linkages, or potential problems not incorporated into future planning. This study of a section of California's water system will look address the areas of water security that are most important to California's future: drought (water shortages) and environmental integrity and sustainability of the water supply source used. This study will focus on urban water security, which focuses on more of the concept of water security constrained to those aspects that affect a specific urban area and its relating natural water supply sources (Hoekstra, Buurman, and Ginkel, 2018). Urban water security factors in the unique municipality structures and active or proposed policies for the urban water setting. A combination of water supply projects San Francisco, California municipalities are looking at will be analyzed for the level of reliability they potentially add to the Regional Water System and the ability to help meet the water demand in the future.

2.2.4 Population and Demand Dynamics

Rapid urbanization and population growth are spreading across the Central Valley and are predicted to increase with climate change, affecting the water supply resources in the surrounding area (EPA, 2009; Radeloff et al., 2010, 2012; Matchett and Fleskes, 2018). The term "urbanization" refers to the process and development of a rural area socially and economically, encouraged by increasing job opportunities (Tucci, 2017). Increased development and spread of urban areas will add more strain to the inadequate water supply. As the urban areas become more concentrated, additional water supply infrastructure will have to be installed, and that may be accompanied by new instream flow requirements on the water source (Loucks and Van Beek, 2005). While the increase in instream flow requirements would help preserve the wildlife and hydrology of rivers and stream, it would leave less water available to domestic, industrial, and commercial use. Fights over the balance of land and water use, increasing water transfers and markets, are potential resulting issues that can arise from having inadequate water supplies to meet the demand (Loucks and Van Beek, 2005). Studies have also shown that many reservoirs have competing uses (i.e., hydropower, water supply, flood control, etc.) that lead to fights over water allocations and difficulties in managing and operating the system (Loucks and Van Beek, 2005). In order to help combat some of these issues, demand-side measures need to be used and the encouragement of the use of alternative water supplies in the forms of water reuse. The two urban areas in California that account for most of the urban water use are the San Francisco Bay area and South Coast regions and both areas depend on water to be imported from other parts of California (Mount and Hanak, 2016). In recent years, urban areas like these have made strides in reducing their overall use of water through programs, monetary incentives, and the increased use of water saving technologies in commercial buildings and households. Many of the projects California water agencies have collaborated on produced an overall reduction in the percentage of water supply used for landscaping areas like golf courses and parks. These urban areas new water reuse schemes and water conservation efforts have decreased water use from 1995 levels of 232 gallons per day to 2015 levels of 130 gallons per day (Mount and Hanak, 2016). Despite the strides urban areas in California have made to reduce water use, the future impacts of climate change and population growth together may begin to outweigh the efficiency in water use that cities can achieve now. Looking at California holistically, the water demand is exceeding the currently developed supply of water (Carle, 2016). With increased drought expected for areas like the San Francisco Bay in the future these water savings may not be able to persist as the future demand and urbanization increase.

2.2.5 Study Overview

As urban areas like San Francisco seek to explore resiliency and the addition of alternative water sources, it is important to understand how alternatives will compete with one another and how they will perform under these future conditions. A framework is needed that combines the concepts of resilience, the evaluation of water supply alternatives, and the modeling/forecasting of potential future challenges in order to inform management and policy decisions better. San Francisco's Regional Water System provides an opportunity to create a framework that can study their existing water supply system because they have proposed water supply alternatives SFPUC is currently considering adding and it is a growing area severely affected by drought.

Cities like San Francisco, California are facing similar issues including increased drought, strained water supply, and increased degradation of water quality in the Bay area. To date, some of California's most significant historical droughts range from the six-year drought of 1929-34 to the more recent five-year drought of 2012-2016 that was one of the driest periods on record (Jones et al., 2015). San Francisco, and many other cities like it, have used traditional lifecycle assessment tools, emergy, modeling, and footprints effectively to understand parts of the urban water system but, little to no research has been done on system-based tools that are able to assess the urban water sector holistically (Xue et al., 2015). This gap in the literature is one that could be filled with the use of the Water Evaluation and Planning tool (WEAP) paired with resilience thinking. WEAP is a computer modeling tool that uses an integrated approach to model water systems and policy, with attention on both supply and demand side management. This tool is flexible, comprehensive and user-friendly, making it the best framework to help combat integrated water resource management issues. A case study of using WEAP and resilience thinking to create 11 future scenarios were constructed as a part of this research on San Francisco, California to test the validity and efficiency of this framework.

The main objective of this research is to develop an alternative planning tool for systematic urban water supply and demand planning and management for the city of San Francisco, CA. The ultimate goal is to use an integrated water planning and management approach in conjunction with resilience thinking to form an alternative planning tool for systematic urban water supply and demand management.

The specific questions we evaluated in this research are:

1) Which alternative water supply options (i.e., water recycling, desalination, new reservoirs, etc.) will consistently and reliably meet

the water demand of San Francisco under various climate change and population growth scenarios?

2) What is the best way of combining both centralized and decentralized water supply options to increase the Regional Water System's drought resilience?

3) Which alternative water system provides the Regional Water System with the most resilience concerning cost, the quantity of water, and reliability of delivery?

To answer these questions, we modeled the SFPUC Regional Water System and several alternative water supply projects using the Water Evaluation and Planning tool (WEAP). We then created three scenarios based on climate change, extreme drought, and population growth projections to simulate the changes the water system and proposed projects may undergo in the future (from the historical year 2004 to the future year 2060). The performance of the Regional Water System under the three scenarios was evaluated and compared. Finally, the water supply projects were organized into three portfolios that were evaluated based on cost, yield, and implementation timeline.

2.3 Study Area

2.3.1 San Francisco and the Regional Water System

The diverse city and county of San Francisco houses 884,363 people, based on a 2017 population estimate (United States Census Bureau, 2018). San Francisco resides in northern California surrounded by the Pacific Ocean and San Francisco

Bay. The city of San Francisco is a part of the San Francisco Bay Area, also known as northern California's largest metropolitan area. San Francisco is a vibrant city that has been faced with numerous water challenges. However, unlike some cities around the world, it has a rich history in environmental advocacy and innovation. The SFPUC services the city and county of San Francisco for all its water needs. Roughly 85% of its water needs are being met by the Hetch Hetchy reservoir and with 15% by local reservoirs (SFPUC, 2016). The department of SFPUC also provides drinking water, wastewater, and power to San Francisco (its retail customers) and 28 water agencies (its wholesale customers) located in surrounded counties (Alameda, San Mateo, and Santa Clara) along the peninsula (Cooley, 2007). In total, SFPUC services close to 2.7 million people in the San Francisco Bay Area (SFPUC and Carollo Engineers Inc., 2018). Roughly 30% of the water from SFPUC goes to its retail customers while approximately 70% goes to the wholesale customers. Within the past fiscal year 2016-2017, the average amount of water delivered through the Regional Water System to SFPUC's customers was 181 MGD for wholesale customers and 62 MGD for retail customers, with the retail customers having a gross per capita use of water around 72 gallons per day and residential per capita use of 41 gallons per day (SFPUC, 2016a). The Regional Water System is the water delivery system composed of various channels, pipes, and aqueducts that supply water to SFPUC customers. The system typically delivers about 265 MGD across the extent of the systems 167 miles course from the Sierra Nevada to the city and county of San Francisco (San Francisco Planning Department, 2008). The Regional Water System is also composed of 11 reservoirs, two water treatment plants for filtrations, 5 or more pumping stations and over 340 of combined pipeline and tunnels. The Regional Water System mainly draws from the Tuolumne River, Alameda, and Peninsula watersheds and many components of the system have been in existence for over 100 years. Updates and monitoring of this system’s infrastructure and watersheds are critical in order to maintain the integrity of the system under stressors, but this can be a challenge.

Residents of San Francisco and wholesale customers depend on watersheds that are less than 2 million acres near the Central Valley for their drinking water supply (Klausemeyer and Fitzgerald, 2012). Water from the Hetch Hetchy, Tuolumne, and Alameda watersheds help to supply the Regional Water system where water is piped to the local reservoirs and directly to the city of San Francisco. San Francisco also has three active wastewater treatment plants including the Oceanside treatment plant, the Northpoint Wet Weather Facility, and the Southeast Treatment Plant. SFPUC also owns and operates these wastewater treatment facilities and the entire combined sewer system. So, both wastewater and stormwater are sent to the wastewater treatment plants for handling. The Southeast treatment plant has the largest capacity at 250 million gallons per day (MGD), with Oceanside having the second largest capacity at 175 MGD, and the Northpoint Wet Weather facility, which is only used when Southeast is near capacity, having a capacity of 150 MGD (SFPUC, 2014). Back in 2004 SFPUC sought to improve its urban water management by creating installing the multi-billion dollars Water System Improvement Program (WSIP) that aimed at improving the Regional Water System’s reliability addressing water quality, delivery, supply, and seismic safety into the year 2030 (Cooley, 2007; SFPUC, 2015; Bay Area Water Supply and Conservation Agency, 2018). SFPUC continues to seek to move towards increasing the efficiency and reliability of the Regional Water System with similar programs to the WSIP and the increased incorporation of resilience thinking into their practices. SFPUC continues to create and participate in numerous conservation projects. This research will help them develop and test out the performance of different supply/demand enhancing options to develop a more efficient and successful Water Management Action Plan. They are looking for the ultimate water supply yielding projects while trying to help increase the resiliency of SFPUC's water supply to ensure future needs and obligations are met in the future. SFPUC must develop a water supply program for the 2019-2040 planning horizon, and this research could help influence what projects are included.

2.3.2 Hetch Hetchy Reservoir, Local Reservoirs, and the Tuolumne River

Hetch Hetchy is the main reservoir source for meeting 85% of the water needs for SFPUC customers. Hetch Hetchy has a reservoir capacity of 360,360 acre-feet. The Hetch Hetchy system is composed of Hetch Hetchy Reservoir, Lake Lloyd (also known as Cherry Lake), and Lake Eleanor. Lake Eleanor and Lloyd receive surface water runoff from the Tuolumne River basin. A diversion tunnel links the two lakes so that they can be operated singularly. The Hetch Hetchy system delivers roughly 300 MGD to SFPUC. For this study, only the Hetch Hetchy reservoir was used as the drinking water source for SFPUC customers because Lloyd and Cherry lake are not used for drinking water, although they have a permit to use water from Cherry lake. However, these lakes are used to help meet instream flow requirements to satisfy the downstream water rights of the Turlock and Modesto Irrigation Districts (San Francisco Planning Department, 2008). Hetch Hetchy is the primary only reservoir to transmit water supplies directly to SFPUC customers in the Bay Area. Hetch Hetchy is also used to generate hydropower, but this feature of the reservoir was not included in the study. The remaining 15% comes from the combined use of the local reservoirs (i.e., Crystal Springs, Pilarcitos, and San Andreas), also known as the Peninsula reservoirs. The Alameda reservoirs (Calaveras and San Antonio) are used as well as a part of the Hetch Hetchy System. San Francisco’s Hetch Hetchy system developed over time with the O’Shaughnessy Dam, getting its start around 1913 through the Raker Act that gave the city water rights to Yosemite National Park and flows from the Tuolumne River that was used in 1934 (SFPUC, 2005). Most of the water for the Regional Water System naturally stems from Tuolumne River, making it and Hetch Hetchy Reservoir the cornerstone water sources for all SFPUC customers. The surface water flows from the surrounding Tuolumne River watershed snowmelt from 459 square miles area is collected by the Hetch Hetchy Reservoir (San Francisco Planning Department, 2008). The snowmelt provides 80% of its water to the reservoir during April through July. The local reservoirs act as a storage facility for some of the water from the Hetch Hetchy Aqueduct that is delivered by gravity to the area. The Hetch Hetchy water supplies are so pure that they can be delivered to SFPUC customers without filtration. In times of emergency or major maintenance of the Bay Division Pipelines that divert water to SFPUC customers, water is transferred through these pipelines to either the Santa Clara Valley Water District or the East Bay Municipal Utility District. Customer rationing is also implemented during normal drought procedure as well. However, it should be noted that these flows are exchanged and made under a separate agreement and they are not part of the normal operating agreements for the pipelines to the Bay Area. Hetch Hetchy water is also piped to the local reservoir system. The Crystal Springs (both upper and lower reservoir), Pilarcitos and San Andreas reservoirs compose the local reservoirs and collect natural drainage from their respective creeks (i.e., San Mateo, San Andreas, and Pilarcitos creeks). Most of the flows from Hetch Hetchy to the local reservoirs end up directly in the lower and upper Crystal Springs reservoir. This water can be used in either San Francisco or for wholesale customers. On the other hand, water from the Pilarcitos reservoir is mostly dedicated to the use of wholesale customers, but water can be diverted from this reservoir to the San Andreas or Crystal Springs. Finally, the San Andreas reservoir acts as the multi-source reservoir as it houses a mixture of water from the other two local reservoirs, Hetch Hetchy, and drainage from San Mateo Creek. Three regional pipelines disseminate water from the local reservoirs to San Francisco's local water system.

2.4 Methods

2.4.1 WEAP Model

In this research, we used the WEAP modeling tool to model the urban water system for SFPUC. To create the model, we began by defining the time frame, spatial boundaries, and system components that characterize the Regional Water System (RWS). The model was created for the time period of 2004 to 2060. A more historical time period (i.e., the 1930s) could not be chosen due to water use data constraints and WEAP time period constraints. We also desired the model to capture some of the historic drought years or dry periods, so we chose 2004 as the start year for all scenarios because it was a few years before the significant 2007-09 drought. Starting in 2004 allowed us to observe what streamflow, water use, water deliveries, precipitation, and other factors looked like during a normal year before San Francisco experienced drought. The RWS constructed in WEAP was composed of a series of GIS layers and vector files created using Q-GIS software in order to understand the long connections between San Francisco and the RWS and what areas are characterized as urban areas in that section of Northern California. The GIS vector files provided the backdrop look of San Francisco, California to more accurately model the RWS on. For the San Francisco, California water system we characterized the Residential area of San Francisco, the Hetch Hetchy Reservoir, the local reservoirs, wastewater treatment plants, Tuolumne River, and proposed water projects with data collected from various sources. The information and data needed to create the scenarios in WEAP came from sources including: San Francisco Public Utilities Commission (SFPUC), United States Geological Survey (USGS,) Environmental Protection Agency (EPA), National Oceanic and Atmospheric Administration (NOAA), California government websites, Census Bureau, National Centers for Environmental Information, and related literature. SFPUC and the EPA provided yearly and monthly wastewater treatment plant data as well as residential water use, consumption, demand, and supply data for the WEAP model. USGS provided the Hetch Hetchy Reservoir elevation, volume, storage capacity, and other related reservoir data. The California Data Exchange Center provided local reservoir data like storage capacities, as well as USGS. The California government website provided historical climate data as well as NOAA (i.e., average temperature, precipitation, etc.).

WEAP has a series of symbols (i.e., nodes and links) that can be used to characterize the study area. These nodes were situated in the model to the same location of where they are positioned in real time. These nodes were then connected through a series of withdrawal, transmission, and return links to depict the likeness of the current structure and function of the water sector in San Francisco. We then took these links and used data to characterize features of the exchanges between nodes (i.e., streamflow, effluent, influent, etc.) water demands, pollution generation, and ecosystem requirements. Historical and current water demand, consumption, resources and supplies data are used within the model. This can be viewed as the calibration step for the model and labeled as Current Accounts—the foundational information that the reference scenario and the following scenarios will be constructed after. We then crafted five different scenarios with their assumptions and future predictions for cost, climate, water supply and demand, reliability, etc. These scenarios that will be described later were then evaluated regarding water use efficiency, sensitivity to environmental goals, costs and benefits, water quantity, and performance to uncertainty in key variables. We also used yearly streamflow data for the Tuolumne River from the United States Geological Survey (USGS) to calibrate my model that produced a Nash-Sutcliffe value of 0.937986474 (acceptability range of 0.5 to 1). A Nash-Sutcliffe value close to 1 indicates your modeled data is close to your observed. Information from the SFPUC study projections was used to validate the model. The desired outputs from WEAP for this study were the demand site coverage, Hetch Hetchy reservoir storage volume, local reservoirs monthly inflows, Tuolumne river head flow, inflows to areas (demand sites), unmet instream flow requirements for Tuolumne River, and annual water use rate for high population growth scenario compared to the reference scenario (the scenario built on the current accounts scenario that factors in historical data and shows the trends for all parameters for if the water system was left as it is). A comparison of the yield and cost of each water supply alternative was also assessed and one of the desired outputs for this study. A closer look at the formal configuration of the WEAP modeling system and the scenarios created can be seen in Figure 2. The primary methodological approach to creating the WEAP model for San Francisco, California is as follows:

1) Identify potential water resource development projects in San Francisco, California that may best fit the needs of the San Francisco urban water sector, the residential area constituents, and SFPUC. Collect relevant water data.

2) Classify the potential alternative water resource projects regarding whether it seeks to improve demand or supply, quantity, quality, sustainability, accessibility, and convenience.

3) Create a model that accurately reflects these potential water resource projects so SFPUC can adopt, adapt and use the model with ease to support their decision-making process.

4) Create a series of portfolios that combine different alternative water systems and compare them concerning cost, yield, the time of

implementation, energy needs, technical feasibility, and legal and institutional feasibility.

5) Analyze and synthesize results of portfolio comparisons and the WEAP model scenarios and provide suggestions to SFPUC.

To find more detailed descriptions of the WEAP modeling system and its underlying mathematics, configuration, and methodology, please refer to the WEAP tutorial and user program guide (https://www.weap21.org/index.asp?action=213).

2.4.2 Scenario Design and Description

Three main scenarios were created in order to see how the Regional Water System would perform under Climate Change, High Population Growth, and Extreme Drought conditions. The scenarios are described below:

Scenario One- Climate Change/Water Year Method: This scenario depicted how the natural and progressing variation in climate data (i.e., greenhouse gases, rainfall, streamflow, extreme weather events, etc.) impact the source and overall supply of water to the San Francisco area. In order to model the effects of climate change in WEAP, we used time-series precipitation and temperature data from the World Climate Research Programme's (WCRP's) Coupled Model Intercomparison Project phase 3 (CMIP3) multi-model dataset from the year 1950 to 2060. We used monthly bias corrected spatially downscaled WCRP CMIP3 climate projections for the tributary area that encompasses San Francisco and its corresponding watersheds. The California Crop and Soil Evapotranspiration for Water Balances and Irrigation Scheduling/Design Report, created by the California Department of water resources, was used to create the Water Year Method definitions to determine what classifies a normal, dry, very dry, very wet and wet year for the area encompassing the Regional Water System based off of annual rainfall in inches (Irrigation Training and Research Center, 2003). The Palmer Drought Severity Index (PDSI) was also used as a means to validate the ranges chosen to characterize the water year type. We compared the drought severity in California for the total time period to that of the ranges created for the downscaled climate data to see if the same years and range the PDSI was showing as drought years was also showing as dry years for the ranges created using the downscaled climate data. Once the water year types were properly characterized, we determined what years were or were predicted to be very wet, wet, normal, dry or very dry and created a sequence of water year types for 2004-2060. This sequence was then applied as the new driving climate factor that all water supply alternatives, reservoirs and rivers would be subjected too over the time period. After running the model, we compared reservoir capacities, unmet demand and head flow of the Tuolumne River to that of results from the reference, high population, and extreme drought scenarios. Understanding how climate change affects the normal hydrological cycle in the San Francisco area will produce a better understanding of San Francisco's water supply weak points and identify areas in need of improvement to help manage the water supply more judiciously. Gauging how the water supply will be affected year to year by different climate regimes in comparison to the normal climate regime for the area will have future implications on San Francisco's use of its current water supply source and increase investigations into alternative supply sources and methods. This scenario helped to determine the potential impacts of climate change on water resource management in San Francisco. It was expected that unmet demand would become more erratic as climate change increases. The amount of source water available for San Francisco's use would decrease and become more unreliable. The Hydrologic cycle would be severely impacted leading to more prolonged and extreme droughts and floods depending on wetter and dryer years (higher population growth rate and dryer climate would increase unmet demand).

Scenario Two- Increased Population Growth Rate: This scenario depicted what would occur when the population growth rate changes from the expected Current Accounts 2004 rate of approximately less than 1% to an accelerated rate of 2 %. We used historical Census Bureau Data to characterize the annual activity feature in WEAP in the Current Accounts scenario. Using information from literature reviews on prediction for population and urbanization increase effects on the San Francisco area, we applied a 2% increase to the population growth rate for the high population growth scenario. After running the model, we observed the effects of the 2% growth rate change on the water use of the wholesale and retail SFPUC customers, and by association the drawdown effects on Hetch Hetchy reservoir and Tuolumne River. Understanding future implications of the effects of population growth on the San Francisco water supply is vital for assessing and predicting how it will impact supply and demand. This scenario allowed for the assessment of the stability and reliability of San Francisco's current water supply configuration and the ways in which the system could be improved in the face of a dramatic population increase. The evolution of demand compared to the evolution of unmet demand was observed in this scenario as well. Development of this scenario displayed the impacts of high population growth rate on the residential community of San Francisco and presents opportunities for improvement in management techniques. The expectation was that a higher population growth rate would produce a higher unmet demand / and higher demand and would put a strain on all water resources.

Scenario Three- Prolonged Extreme Drought: This scenario projected what may occur if San Francisco went through another extreme drought period akin to the 5-year drought that occurred from the year 2012 to 2016. In this scenario, the Water Year Method was used, but the downscaled climate data was reconfigured to create different intervals for the classifications of year type (i.e., dry year, wet year, etc.) to produce another 5-year drought scenario. In other words, the climate change scenario and the extreme drought scenario use the same underlying climate change model projections, but the projections were used to characterize intervals differently for the Water Year Method in the extreme drought scenario. The climate change projections, specifically the predictions for precipitation for the years 2018-2060, were used to help identify which years in the future are likely drought or “dry/very dry” years. Historical precipitation records were used to understand what amount of precipitation depicted in a very dry, dry, normal, wet, or very wet year. Historical information on previous major drought periods combined with climate model predictions and historical precipitation were collectively used to change and create new intervals for the Water Year Method (i.e., values that characterize very dry, dry, normal, wet and very wet year). Future 4-5-year periods of “very dry” to “dry” years were identified in the climate model predictions and used to change the sequencing in the Water Year Method. This allowed for the representation and increased frequency of other 4-5-

year drought periods to be modeled and the effects of these modeled changes on the Regional Water System to be observed. The individual alternative water supply options and combined portfolio options results were assessed under this scenario. Special attention was also given to the way the extended drought effects reservoir levels, unmet demand, supply requirement, and current water system consistency. The expectation was that reservoirs inflows would be severely less, lower than the inflows that occurred during the previous 5-year drought. Reservoir water levels will also decrease due to considerable variation in precipitation events during this scenario and increased annual temperatures. The portfolios containing the desalination options would have the lowest unmet demand and the highest reliability due to the process of desalination not being dependent on rainfall or a finite reservoir resource. The conservation techniques would play a significant role in preserving and offsetting the pressure on the water supply options like it did for the previous 5-year drought.

2.4.3 Alternative Water Supply Scenarios

The alternative water supplies chosen for this study is based on current water supply projects SFPUC proposed as additions for the Regional Water System. The assessment of these alternatives will determine which of these water supply projects will increase the provision of water supply to SFPUC customers consistently and reliably in the future. Not all potential water supply projects being considered by SFPUC were tested or discussed in this paper. Those chosen for the sake of this study were ones that produced at least one MGD of water for the SFPUC customers. The descriptions of these water supply alternatives will be discussed below: The WEAP model will be composed of 8 alternative water supply options:

Water Reuse/Recycling Options:

These scenarios depicted how water reuse projects in San Francisco would impact the amount of drinking water available and provide a way to better preserve the natural water bodies San Francisco Depends on. The scenarios were able to assess past, current, and potential water reuse projects in the San Francisco area and their impact on the supply and demand for different sectors. Reusing wastewater could increase the amount of water available for non-drinking water needs as well as help to conserve reservoirs like the great Hetch Hetchy. These scenarios showed how water reuse projects can help to diversify the local water supply. Exploring whether desalination, rainwater harvesting, greywater use, recycled water use, or other water reuse/conservation methods are the most useful and desirable for the San Francisco area. All data with descriptions below were provided to me by the SFPUC:

Option One: The Westside Recycled Water Project

This is a proposed project from the San Francisco Public Utility Commission. This project seeks to construct a recycled water treatment plant (RWTP) at the Oceanside Water Pollution Plant (WPCP) and is depicted in Figure 3. A small portion of the RWTP will be located on the California Army National Guard site. The recycled water end use will be for Golden Gate Park (irrigation and lake fill), Lincoln Park Golf Course (landscape and irrigation), Presidio (landscape and irrigation). The construction of these projects will include transmission pipeline along 36th avenue trailing from the RWTP to the Central Reservoir in Golden Gate Park. The pipeline will also extend to the three areas described in the recycled water end use. Expansion of a current pump station and the Central reservoir in Golden Gate Park to include additional pumping capacity and storage will occur. An underground storage reservoir will also be constructed under the existing Oceanside WPCP. The goal of this project is to provide roughly 2-4 Million Gallons per Day (MGD) of drinking water, 4 MGD during peak deliveries.

Option Two: The Eastside Recycled Water Project

This is a proposed seeks to build a recycled water treatment facility on the site of the Southeast Wastewater Treatment Plant. The layout of service areas of interest for this project can be seen in Figure 4. This project has currently been put on hold for further study and better coordination with the Sewer System Improvement program. The Recycled water will be delivered to customers for the use of irrigation and toilet flushing. The goal of this project is to provide roughly 2-4 MGD of non-potable water use (irrigation and toilet flushing).

Option Three: The Desalination Project

The Bay Area Regional Desalination Project is a project that has been in preparation since 2003. This project is ongoing and is a collaboration between some of the San Francisco Bay Area’s largest regional water agencies–the San Francisco Public Utilities Commission, Contra Costa Water District, East Bay Municipal Utility District, Santa Clara Valley Water District and Zone 7 Water Agency (Figure 5). The breakdown of the service area for each partner is color-coded and can be seen in

Figure 5. This project looks at the potential for the construction and use of a desalination plant as a regional water supply source. The project proposes building one or more desalination plants on one of the proposed starred sites in the corresponding picture. The resulting brine will be blended with the treated wastewater effluent. The recycled water end use will be for 5.4 million Bay Area residents and businesses. Will Ultimately serve the SFPUC clientele base and Zone 7. The goal of this project is to have the desalination facilities include a total capacity of up to 65 million gallons per day. These Agencies are focusing on optimizing technologies that minimize power requirements and environmental effects. This project started out proposing a 120 MGD desalination plant be built to use only during emergencies and facility outages but they are now looking at Contra Costa County has a site to turn 10-12 MGD brackish water into drinking water through a desalination plant. The project now seeks to build a desalination plant that will operate year-round in all weather conditions that will supply San Francisco with 9 MGD.

Option Four: In-City Desalination

A reverse osmosis ocean (Pacific Ocean) desalination plant would be built near the Oceanside Water Pollution Control Plant (Figure 6). It would be operational in 2030. Water would be blended with water from the Regional Water System at Sunset Reservoir. The water generated from this project will be used for drinking water for SFPUC customer. The goal of this project is to build desalination facilities that will produce 25 MGD of potable water.

Option Six: Tuolumne River Diversions

SFPUC diverts water from the Tuolumne River for its customers (Figure 7). Under SFPUC's current water use rights allows them to increase their current water diversions from the Tuolumne River up to the amount specified in the Programmatic Environmental Impact Report (PEIR). Available diversions based on water use rights are up to 18 MGD. Restrictions on diversions will apply during drought years. The water produced by this project will be used as potable water for SFPUC customers. The goal of this project is to generate 18 MGD of potable water.

Option Seven: Los Vaqueros Reservoir Expansion

This project proposes expanding the Los Vaqueros Reservoir storage from 160,000 AF to 275,000 AF. This increase in storage would create a reliable water supply for local water agencies and presents convenient methods for the integration of this extra storage into the regional water system network. The water agencies partnering in this project, as well as the site location, for Los Vaqueros can be seen in Figure 8. Water will be pumped from designated delta intakes into the regional water system where it will then be transferred to a pump station to be pumped directly to water agencies or to be sent to the Los Vaqueros Reservoir for storage and later use. The water generated from this project will be used as potable water for SFPUC customers. The goal of this project is to create 11.5 MGD of potable water stored in the reservoir for use in drought years.

Option Eight: Conservation Techniques and Demand Management Strategies

Water from this project will be used as residential irrigation, toilet flushing, and indirect potable water use. The goal of this project is to generate 25 MGD through a combination of greywater reuse, rainwater harvesting, green infrastructure, and groundwater use.

The research and case study were conducted over the course of two years and the observations were recorded in excel files, WEAP scenario tables and charts, and all changes or assumptions we made in the model was recorded in detail on a Word document. The configuration of the WEAP modeling system and the scenarios created from the modeling system can be seen in Figure 2. Other considerations specific to our approach to making the WEAP model was also recorded in an excel file with each scenario in a table. The resulting data from this study are presented in table and graphical form for easy comparison. The analysis of the data will be both quantitative (more heavily) and qualitative. The discussion of the model itself and the results from the scenarios are discussed quantitatively, but its relation to resilience and its impact on the culture of water in California is discussed more qualitatively. A drought resilience matrix was constructed to combine quantitative results (i.e., cost, the quantity of water delivered, quantity of unmet demand, etc.) with qualitative resilience concepts that can then be used to create management strategies and add to the water resource planning process. This matrix will be discussed more in chapter 3.

These eight water supply alternatives are projects that are being considered on an individual basis for implementation by SFPUC. The alternative water supply projects locations, connections, and deliveries to the Regional Water System can be seen in Figure 9. For this study, I sought to understand how these water supply alternatives would perform both individually and in groups. In order to protect the Regional Water System's water supply and decrease SFPUC customers mounting dependence on Hetch Hetchy Reservoir, it is essential t to implement a series of water supply alternatives with an effective cost-yield ratio. Creating groups, or portfolios, composed of these water supply alternatives could aid SFPUC in their decision making towards which projects to implement or which set of projects are the most worthwhile to implement. SFPUC needs to increase the reliability of the Regional Water System while also minimizing the amount of the current water supply that meets drinking water standards being used for non-drinking water purposes. Other points of interest when evaluating these water supply alternatives are cost, time of implementation and construction, yield, whether the yield can be used during drought and non-drought years, locality, etc. These were all factors in the way that I chose to group the eight water supply projects. I created three distinct portfolios that are outlined with the water supply alternatives in more detail in Table 1. Modifying Existing Supply, or portfolio A, is composed of the conservation techniques, Tuolumne river diversions, and the Los Vaqueros reservoir expansion water supply alternatives. I grouped these three projects together because they each propose making changes to the existing water supply or alterations to existing infrastructure. For example, the Los Vaqueros reservoir already exists and functions as a storage and emergency supply for Contra Costa Water District in drought and non-drought years. The proposed project for this reservoir seeks to enlarge its existing infrastructure and integrate the reservoir into the states existing water systems for conditional use by other water agencies like SFPUC. The conservation techniques project already has an existing foundation of regulations and some of the techniques have already been used throughout San Francisco and California as a whole. The same can be said for the additional Tuolumne river diversion project. The Regional Water System already has a set allocation for diversions from the Tuolumne River and the watershed feeds the Hetch Hetchy reservoir, so this project looks at simply increasing that allocation.

Recycling and Desalination, or portfolio B, is composed of the Bay Area Regional Desalination plant (BARDP), Westside recycling plant, Eastside recycling plant, and Daly City water recycling plant expansion. This group was put together in an effort to combine larger, more reliable water projects that can be looked at as renewable water resources. These projects do not directly depend on water resources that are prone to the effects of drought and other climate change impacts. Each of these four projects would help to preserve the quality drinking water that is currently used for non-drinking purposes. Two of the four projects (BARDP and Daly City water recycling plant expansion) add a collaborative element between water agencies and districts as well, increasing the opportunity for collaborative management, operation, and regional coordination. This portfolio also combines half local projects with half regional projects. The Local Approaches, or portfolio C, is the last portfolio.

It is composed of the conservation techniques, Westside recycled water project and the in-city desalination project. This portfolio focuses on those projects that would all be located in San Francisco and only service SFPUC customers. These projects are also extremely drought tolerant. With these projects, SFPUC does not have to worry about sharing that water with other agencies. Having a portfolio with centralized approaches, versus portfolio A and B with more decentralized approaches, allowed for a comparison of which techniques work best and provided a variety of options for SFPUC. Meeting the challenges that population increases and climate change pose require different water management techniques and solutions to be considered. These portfolios provide SFPUC with a combination of options for development that realistic with different environmental implications.

2.5 Results and Discussion

2.5.1 Alternative Water Supply Reliability

Evaluating the water supply options in terms of their ability to meet the demand site coverage requirements for retail customers in the future is one way I assessed the reliability of each project. Demand site coverage looks at what percentage each alternative water option can meet the demand of retail customers over the time period 2004-2060 (Figure 10 and Figure 10-1). Recall that deliveries of water supply to SFPUC from the Regional Water system average annually around 300 MGD and so the percentage of demand site coverage for each water supply alternative shows you how much of the demand during a given year the alternative can cover. The percentage of the water demand met for the residential community are displayed in Figure 10 and Figure 10-1. The conservation techniques, as an individual alternative, had the highest demand site coverage from the beginning of the project period to the end of the project period. The Los Vaqueros expansion, as an individual alternative, had the lowest demand site coverage. This is an interesting result considering the Los Vaqueros expansion project comes with a higher yield than the smaller recycling water projects (i.e., Eastside and Westside projects) that have a yield ranging from 2-4 Million Gallons Per Day (MGD). Regarding the climate change, extreme drought and high population growth scenarios, the extreme drought scenario and the high population scenarios showed the most variability and lowest demand site coverage near the end of the time period. Over the time period (2004-2060) the reference scenario had a demand site coverage total of 80%, the climate change scenario having 44%, extreme drought scenario having 40% and the high population growth scenario having 30%. Notably, the high population growth scenario appears to have more of an effect on the demand site coverage than the climate change and extreme drought scenario being that its percent coverage is the furthest in comparison to the reference scenario. This shows that all alternative water projects under increased population growth and extreme drought effects are only able to cover 0.00-0.04% of the demand for both sites. This shows that no one strategy alone will increase the reliability of the water distribution system but that it takes a combination of water supply alternatives to increase the demand site coverage of SFPUC customers.

2.5.2 Water Use and Demand in Different Scenarios

The water demand for both the retail and wholesale customers of SFPUC can range anywhere from 256-300 MGD. Under normal conditions, the water demand

and use for SFPUC customers are expected to gradually increase over time, which is what is displayed in Figure 11. During this period, it is important to note that the decrease in annual water use around the years 2014-2016 occurred because of drought. During this period of time San Francisco and much of California was experiencing drought, and around the year 2014, San Francisco residents had to reduce their overall water use to close to 20%. After that, the trend for water use only gradually increased. This slow increase may be due to SFPUC's expectation of the impacts of conservation projects and the use of conservation technologies like low flush toilets and low-pressure shower heads on a residential level will have residents using less water on average. There could also be an expectation that with more water supply awareness and education that customers will use less water. The supply assurance guarantee for wholesale customers from SFPUC does not change quickly, but desired increases must be contested and approved by SFPUC in order to change. This process can take a long time, and that slows down the increase of water use on the wholesale customer side. Some wholesale customers are also looking for more ways to diversify their water supply as well outside of what they receive from SFPUC, which may be allowing them to use less of their supply assurance guarantee.

The annual water use rate for the San Francisco Public Utilities Commission wholesale and retail customers under the high population growth scenario is displayed in figure 12. A 2% population increase characterizes the high population growth rate scenario. The water use begins to increase at a faster rate after the historical period of 2004-2017. In 2018 the rate of water use for both customers increased rapidly and ended up at almost three times more the annual water uses of the reference scenario near the end of the study period in the year 2060. From this scenario we can see that in the future as more people move into San Francisco and the surrounding Bay Area, they will begin to place more pressure on the water supply, causing population growth to outweigh the effects of conservation techniques and thus increasing overall water use per capita. The altered flows of the natural environment can impact communities demand and water use as well. As seen in figure 13, the unmet instream flow requirement for the Tuolumne River affects how much water is available not only to Hetch Hetchy to be used for water supply, but also the water that exists as unimpaired environmental flows that help sustain wildlife. The influence of temperature changes and the occurrence of dry years can be seen in the altered hydrology of the Tuolumne River in figure 13. SFPUC must meet a range of instream flow requirements for the Tuolumne River depending on the year type (i.e., dry, wet, normal, etc.). During a given year the minimum flow requirement/releases from Hetch Hetchy range from 35 cubic feet per second to 125 cubic feet second. To convert these numbers, or any others in this study, to million gallons per day or acre-feet per second refer to the conversion table labeled Table 2. Hetch Hetchy reservoir already diverts roughly 33 % of the average annual unimpaired runoff coming from the Tuolumne River watershed, and SFPUC is required to release 64 cubic feet per second into the river if the Canyon diversion tunnel goes above 920 cubic feet per second (San Francisco Planning Department, 2008). These supplemental flow requirements are important to SFPUC to meet in order to have the aquatic environment function optimally and for the agreement with the U.S. Department of Interior to be honored. This amount changes depending on the time of year. Figure 13 displays the unmet instream flow requirement that occurs in the climate change, high population growth rate scenario and the extreme drought scenario. This has implications for the hydrology of Tuolumne River in the future as well as the longevity of the Hetch Hetchy as a main supply since it depends on Tuolumne River flows. This also has implications for the way environmental flows and how they should be handled in the future and what effects will be seen in other water districts. Other water districts use Tuolumne River as well and have minimum flows they must adhere too. These districts water supplies may also be severely affected in the future based more on the occurrence of high population growth than climate change and extreme drought. If all these scenarios were to occur at the same time, layered challenges in the way to manage the system might arise, resulting in more than one water utility having to plan differently for the future.

2.5.3 Drought Effects Under Different Scenarios

Hetch Hetchy reservoir storage volumes over the 2004-2060 period are displayed for the climate change, extreme drought, and high population growth scenarios in Figure 14. The high population growth effects on the amount of water present in the reservoir over the time period displays the lowest reservoir volumes, implying that the effects of population growth on San Francisco and wholesale customers may outweigh the effects of extreme drought and climate change. The Extreme drought scenario and climate change scenario display variability in minimums and maximum volume storage over the time period, with extreme drought diminishing the reservoir volume more than the climate change scenario. The local reservoir monthly inflows displayed in Figure 15 includes San Antonio, Crystal

Springs (upper and lower), Pilaricitos, San Andreas, Calaveras, Los Vaqueros and a summation of all monthly reservoir inflows under the climate change scenario. There is a lot of variability in the magnitude frequency of monthly inflows to the reservoirs. More frequent low monthly inflows to reservoirs can be seen here, but the magnitude of those low inflows is still higher than some of the maximum inflows in the extreme drought scenario. The monthly local reservoir inflows displayed in this Figure 16 includes San Antonio, Crystal Springs (upper and lower), Pilaricitos, San Andreas, Calaveras, Los Vaqueros and a summation of all monthly reservoir inflows under the extreme drought scenario. The monthly inflows to the reservoirs are characterized by more frequent periods of low inflow throughout the time period, with notable periods of low inflow during the years 2036-2042. The Tuolumne River head flow over the project period 2004-2060 under the climate change scenario is shown in Figure 17. This head flow is characterized by a more frequent period of 2,000 cubic feet per second than any other flow level. The Tuolumne River head flow over the project period 2004-2060 under the extreme drought scenario is displayed in Figure 18. This head flow is characterized by more frequent periods of 1,000 or less cubic feet per second than any other flow level, with maximums only reaching just above 4,000 cubic feet per second. Inflows to both the wholesale and retail customers are displayed in figure 19 for the climate change, extreme drought, and population growth scenario. Inflows are more variable with large minimum and maximum magnitudes during the climate change scenario than the extreme drought scenario. The high population growth scenario had no noticeable variability but in some years was much lower than the extreme drought and high population growth scenarios.

Streamflow below the head of the Tuolumne River is displayed in Figure 20 for the climate change, extreme drought, and high population growth scenarios. There is higher variation in the streamflow during the climate change scenario than in the drought scenario. Most interestingly, the high population growth scenario displays a sharp decline in the streamflow over the project period 2004-2060, with only an increase in streamflow near the beginning of the time period around the year 2005.

Under the climate change scenario and extreme drought scenarios, there was an overall shift in streamflow, reservoir volumes and magnitude of inflows, streamflow, and head flow. Warmer temperatures and increased occurrence of drought produce an overall shift in the hydrology frequency and magnitude of flows and volumes. Increased evapotranspiration could also have affected the reservoir levels and streamflow in the extreme drought and climate change scenarios. Peak streamflow in the Tuolumne River occurred earlier in the high population growth scenario that it did in the extreme drought or climate change scenario. The influence of population growth and demand on inflows to the demand sites and streamflow is apparent in figures 19 and 20. This further reinforces that temperature-driven changes on hydrology are just one impact and may be of a lesser impact that population growths influences. The reliability of the Regional Water System in the form of supply and source quantities is decreased over the project period under the high population growth and extreme drought scenarios but is much more variable under the climate change scenario. Increased temperature and occurrence of droughts resulted in modeled changes in reservoir volume monthly and yearly maximums and minimums. Volumes of excess water released into the Tuolumne River decreases during wet years and increases during dry years, showing even greater implications for the unmet inflow stream requirements in the future. The need for releases into the Tuolumne River would increase. If we recall, the Hetch Hetchy reservoir system is replenished by a snowpack, precipitation, and inflows from the Tuolumne River. Close to 80% of the inflows to the reservoir happen during the months of April-July, which is the normal snowmelt period (San Francisco Planning Department, 2008). Climate change and extreme drought will bring challenges to these collections during the normal snowmelt period, which can be seen in the low levels of reservoir storage volumes and inflows to the demand sites in October. The snowmelt period may be shifting to earlier months. The potential for meeting demand is variable under the extreme drought and population growth scenarios, but under the high population scenario the potential for meeting demand is severely decreased over the time period. San Francisco has agreements and policies created in order to prepare for climate change impacts of water resources and incorporate more resilience into their distribution system and management structures. In some ways, they are prepared for climate variability through the adaptation and risk reduction measures placed into management plans. But not many plans have factored in high population growth and the conceivability that its effects, alone or in combination with climate change, will alter the management of water resources and conditions of natural hydrology. An essential but challenging next step is for managers to consider how they can factor in water supply alternatives that's infrastructure lends its self to resilience and adaption in the face of increased urbanization and population growth. Because most water resource infrastructure is made with limitations, specific specs and maintenance and, operation requirements, but innovation is needed to determine what technologies, alternatives, and policies that will allow for a way to meet the future demand without compromising exploiting the natural environment. More research needs to be done on the potential impacts of extreme drought in San Francisco, and California as a whole, in tandem with high population growth to better be able to characterize its impacts on snowmelt, streamflow, and reservoir levels frequency and magnitude. The results of this study display that high population growth, extreme drought, and climate change will have an impact on SFPUC's goal of reliably and consistently meeting the water supply needs of their customers. A portfolio of water supply alternatives must be considered and employed in order to increase the resilience and reliability of the Regional Water System because presently no one supply alternative can. Overall, modeled 2% high population growth effects outweighed the extreme drought and climate change effects over the study period 2004-2060.

2.5.4 Portfolio Development

San Francisco needs to implement a full array of different water management actions. Each contributes in different ways to the overall reliability of the water management system. Water conservation, water recycling, watershed management, conveyance, desalination, water transfers, groundwater storage, and surface storage are all needed in a diversified management portfolio. An expanded Los Vaqueros Reservoir will help to address several important aspects of water supply management that cannot be addressed by other actions alone. Water storage is an important component to protect against droughts and provide emergency water supplies. Without storage, water conserved in one year cannot be saved for a future dry year.

An expansion would also improve the quality of water delivered from the Delta, which is an important consideration for the agencies like CCWD that rely on Delta water for drinking water supplies. Therefore, CCWD and other local water agencies utilize a mix of strategies, including water conservation, recycling, and storage to improve water quality and reliability. The portfolios were put together based on an effort to combine different centralized versus decentralized strategies (Table 1). The portfolios also are arranged in a way where cost, quantity, construction/ implementation time, and proximity to the San Francisco were considered. Some portfolios have projects that are more collaborative on a regional level while others have projects that focus solely on the SFPUC municipality and its immediate customer base. Different projects offered different levels of environmental impacts that were also considered when they were created.

2.5.4.1 Cost vs. Yield Comparison

Three potential portfolios composed of a combination of different alternative water projects were constructed. Modifying Existing Supply, or Portfolio A, contains the Los Vaqueros reservoir expansion, Tuolumne River diversions, and Conservation technique projects. The projects in portfolio A focuses on combining small scale additions that would be implanted in the existing infrastructure of current practices, making the cost of each project more affordable. Portfolio A resulted in being the most cost-effective portfolio, at $3,024 per acre-foot, that SFPUC could choose. Recycling and Desalination, or Portfolio B, is composed of Bay Area Regional Desalination plant, the Eastside and Westside Recycled water project, and the Dale City project. Portfolio B was observed as the most expensive, containing the larger projects that require newly constructed pipes, underground reservoirs, treatment facilities, and collaboration with a network of other agencies. Portfolio B focused on the use of recycled treatment plants as an additional water source. This portfolio also looked at the increasing SFPUC's communication and collaboration with other water agencies and districts to foster a sharing of information and innovative ideas. The Bay Area Regional Desalination plant is the project that requires a significant amount of collaboration, and this could add resiliency to the Regional Water System through having institutions share a resource and potentially build water resources together, coming up with more holistic and innovative solutions. However, portfolio B came with the least yield of 20.4 MGD, and the highest cost, of $18,039 per acre-foot, making it a less than ideal portfolio of choice from a cost-yield perspective (Figure 22). Local Approaches, or Portfolio C, contained the Eastside Recycled water project, the In-city Desalination, and the Conservations techniques. This portfolio was designed with a focus on more local solutions. This portfolio was very close concerning yield (54 MGD) to portfolio A, but in terms of cost it was more expensive, at $7,049 per acre-foot, than A, but less expensive than B (Figure 21). To study the cost and yield of each alternative water supply project individually, see Figure 23. The alternative water supply projects are described with their associated yields in Table 1. Depending on what SFPUC desires and what goals they have for the Regional Water System, portfolio A or C could be a good fit. But for further analysis, the timing of construction and implantation should also be considered before making a decision.

2.5.5 Model Limitations

Planners and managers, like SFPUC, of water resource systems, are responsible for solving water-supply problems or meeting the needs of needs. Failures that occur in the process of the planning and management are noted and broadcasted anytime failures occur. Pressure is then put on these managers and planners from the public and other federal entities any time major problems arise that comprise those that depend on the water resource or the water source itself. This brings many challenges when public perception and expectations are not the same as those of the planners and managers. Institutions and municipalities are working with limited financial and human resources that affect the decisions they make. The goal then becomes providing reliable and consistent water service, taking quality and quantity into account. Understanding how the results from modeling influence planners and managers towards different water supply options and their impacts are not always easy to determine. A lot of it heavily depends on what assumptions were made, data collections were used, and time scales were chosen for the model. The model is also affected by the scale of the project and any data gaps that may affect how a component of the water supply system is functioning. These results can range in their advisement of what to do, why to do it, and how to move forward. These models aim at providing planners and managers with meaningful information that is easy to process and understand but interoperating the data that results from these models are not always straightforward. The same can be said for WEAP. The model is not meant to tell the user what to choose but rather more easily present the user with options and knowledge on the potential benefits or disadvantages of those choices in the future. This information also serves to understand the Regional Water System better.

Modeling is a process intended to promote clearer thinking and more informed decision-making. Modeling involves problem recognition and clearly defining the system of study with the necessary boundaries keeping in mind the goals of objectives of the project. Identifying and evaluating alternatives and effectively communicating the information presents challenges. The inputs and goals of the model and the additional packages that can be used with WEAP provide some limitations. This study did not include MODFLOW or PEST packages that could have been used to more accurately characterize groundwater use and hydropower use in the San Francisco area. WEAP was also not able to have the base year be in the 1930s which limited the amount of historical data we were able to include in the model. We were also not being able to model individual conservation techniques and water supply demands for wholesale customers individually. If we were able to do so it would have provided a more holistic picture of the system at large and the effects of climate change and population growth on the system on an individual wholesale customer basis. Each wholesale customer has a supply assurance guarantee that was drafted in the water supply agreement made with SFPUC and the allocated amount changes based on the county's needs. If we were able to model each wholesale customer, we could have seen which of the wholesale customers are more vulnerable under the various scenarios. Projection uncertainties can also arise from the model we created due to the way we represented water distribution and natural flow connections and processes along with the variability in climate data/modeling used (Ackerly et al.

2018). The use of downscaled Global Climate Models (GCMs) comes with a level of uncertainty as well due to the different assumptions and processes used to downscale said data which may produce biased results based on the regional climate models selected that come with their own set of limitations and statistical methods (Ackerly et al., 2018). How fine or how coarse the GCMs may be will as well as if the downscaling is based on historical patterns also impacts the effectiveness or accuracy of the results.

2.6 Conclusion

The San Francisco Bay area has decreased its inherent water resiliency over time as the natural hydrologic processes have been affected or interrupted by anthropogenic factors. Moreover, the sensitivity of the water supply for San Francisco has only increased as precipitation and temperature dynamics vary, due to climate change and increased urbanization. Based off of the WEAP results from all three scenarios, future urban water demand and unmet demand will increase in San Francisco. It should also be noted that San Francisco's demand and unmet demand increased the most in rate and magnitude under the population growth scenario, suggesting that increased population growth effects may outweigh those of climate change effects. This also has significant implications for the future of San Francisco's water supply if both stressors should affect the Regional Water System at the same time (i.e., increased droughts and precipitation variability with increased urbanization). Results for the high population growth scenario and extreme drought scenario also displayed decreased reliability of the Regional Water System deliveries to both wholesale and retail customers. The annual water use rate increased rapidly in the high population growth scenario compared to the reference scenario around the year 2040 displaying that population growth in both wholesale and retail customers should be factored into future planning for SFPUC. The compound effects of both high population growth and climate change may increase the need for additional alternative water supplies than what was considered in our study. Out of the three portfolios, portfolio A and C provide the most benefits for SFPUC in terms of cost and yield when compared to scenario B. Potentially more emphasis needs to be put on demand-side management with conservation techniques and more encouraged reductions in water use, while at the same time exploring the primary addition and initiation of Portfolio A options. Reliability will be sensitive to modeled changes in temperature in the future as it will decrease with increased temperatures, increasing evaporation and exacerbating dry years. Decreased observed volumes and shifts in streamflow timing and magnitude were seen in Tuolumne River, Hetch Hetchy Reservoir and the local reservoirs, but reservoirs with large storage like Los Vaqueros and Don Pedro will still able to meet demands. Flexibility (through the addition of water supply alternatives) will buffer the regional water system's response in severe droughts.

Overall, SFPUC wholesale and retail water demand and use in all three scenarios increased over the time period. To meet these additional demands, Portfolio A should be adopted and used by SFPUC. It has been predicted by other studies that wholesale and retail customers will have to purchase 35 MGD more water from SFPUC and its projected to continue to increase (Cooley, 2007). It is also predicted that SFPUC will need to increase its diversions from Tuolumne River to 25 MGD and add at least 10 MGD from conservation techniques, water recycling and reuse plants, and groundwater supply programs in order to meet future demands of customers (Cooley, 2007). With this knowledge, portfolio A’s legitimacy only increases as it contains both Tuolumne River diversions and conservation techniques. Further study is needed on the impacts of high population versus extreme drought on the regional water systems and urban systems around the United States. These findings have major implications for how SFPUC should proceed in the future planning and implementation of water resources for its customers. A reevaluation of the projected future demands should be done that factors in both climate change and high population growth, as these are key drivers in changes made to the quality and quantity of water available in the Regional Water System. This study displays the importance of evaluating a system holistically, focusing on institutional, environmental, social, and financial factors in order to make more accurate projections and plans for the future in a sustainable way.

Finally, this research could have implications for other states and increase the implementation of reliable and resilient water resource projects. Having a framework that allows for the holistic evaluation of the urban water sector could produce new and creative solutions to age-old water resource management problems and help managers save time and money in the process of vetting different projects. Gaining a better understanding of the way climate change and population growth is impacting California could have implications for predictions for other states in similar climates with similar water systems. Having a framework like this be successful could allow for projects and evaluations like this to become standardized and reproducible in any city and any climate.

Chapter 3: Developing a Drought Resilience Matrix to Evaluate Water Supply Alternatives

3.1 Abstract

Cities around the world are facing increased sensitivities to drought effects. Climate change induced drought effects not only alter the natural hydrology of the broad macro climate but those in the urban microclimates. The increasing frequency and duration of droughts are creating challenges for urban water utilities to convey water through the distribution systems to customers reliably and consistently. This had led many urban areas like San Francisco, California, to search for unique alternative water supply projects to help bolster the drought resilience of the coupled human and natural water system. This research focuses on applying the features of resilience (i.e., plan, adapt, absorb, recover), through a drought resilience matrix, to water supply alternatives to analyze how the addition of these projects would increase the overall water system drought resilience. San Francisco, California was used as the case study to test the use of this matrix. Three portfolios (Portfolio's A, B, and C) were created and tested in the matrix. Each portfolio is composed of various alternative water supply projects that the San Francisco Public Utilities Commission (SFPUC) is considering for implementation. Results concluded that portfolio C provided the most drought resilience with portfolio B providing the least resilience. The process of how a portfolio for recommendation was chosen is described in the study. The implications and process of creation of the drought resilience matrix are discussed. The considerations for managers and planners as they seek to create,

measure and incorporate more drought resilience into their systematic water resource planning are explored.

3.2 Introduction

3.2.1 Defining Resilience

Cities are increasingly becoming more vulnerable to inside and outside stressors. Two of the major stressors affecting cities around the United States is climate change and increased urbanization. Paired together, urbanization and climate change are creating unique challenges for water drainage infrastructure and water resources. It is predicted that roughly 86% of the developed world will be urban by 2050 (Tribune, 2008; Hassan-Rashid, Manzoor, and Mukhtar, 2018). With the rapid increase of greenhouse gas emissions (GHG), many areas around the World are warming significantly with adverse effects being seen in both the human and natural water systems (Hoornweg et al., 2011). The negative impacts of an increase in precipitation and temperature extremes are compounded by urbanization, leading to the degradation of water conveyance systems with an increase in nutrient and pollutant water quality issues (Zhou, 2014). In order to combat these issues, urban areas are growing a broad array of approaches to help plan the incorporation of sustainability into planning for their water resources. One of the approaches that have emerged in growing importance is the use of resilience and adaptive management.

For the purposes of this study, notions from the term's urban resilience, drought resilience, and the National Academy of Sciences resilience definition were used to create a combined definition to address the effects of drought on water resources in the future. The term urban drought resilience was created to represent the specific concerns of drought and combating its effects on the urban water sector. Urban drought resilience is defined here as*: the ability of an urban system—and its social, technological, and ecological pathways, across spatial scales—to maintain, adapt, absorb or rapidly return to supplying core water demands including environmental minimum requirements in the face of drought.* Resilience is not a new concept, but the term has been reimagined and redefined in multiple ways to capture the complexity of a specific problem and altered solutions. The original introduction of the term resilience came out of the area of mechanics and was used to show the ability of a system or object to bounce back to its original state after an external force was applied (Blackmore & Plant, 2008). However, the term resilience has been defined and explored by various disciplines that have added personal, biological, social and environmental factors to it (Herrman et al., 2011). In many circles today, resilience is associated with reducing the impact of disasters focusing on a systems ability to resist, absorb, accommodate and recover from a stressor in a timely and efficient way (United Nations International Strategy for Disaster Risk Reduction, 2009; Johannessen and Wamsler, 2017). But the nature of the problem or discipline that resilience is trying to be applied to can often determine its definition. Sociologist, ecologists, engineers, and other professions have studied, applied and defined resilience in different ways. Engineers place more focus on the ability of a system to return to a stable state of equilibrium and the amount of return time it takes to achieve this after a disturbance (Folke, 2006). Engineering resilience has also been defined in a way that focuses on a systems ability to anticipate failure and have either intrinsic abilities or the learning capacity to be able to adapt to the failure or extreme event (Connelly et al., 2017). In the world of ecology, resilience has more of an emphasis on the ability for a system to persist through a shock and various thresholds the system may have (Holling, 1996; Connelly et al., 2017). In social science circles resilience factors in governances and institutional structures like the different rules and behaviors that knowingly or unknowingly guide society at large. Social resilience has been defined as “the ability of communities to withstand external shocks to their social infrastructure” (Adger, 2000). The focus is placed more directly on humans, and the impacts that political, social, and environmental changes have on different groups of people. However, sometimes a new or merged definition of resilience must be created to encompass the study of more complex and interconnected systems. For example, social-ecological systems can be understood through resilience by defining resilience as being able to cope with shocks and disturbances to a system and persist through it, keeping factors in mind like ecosystem services and social institutions and economic/ market structures that are affected directly by disturbances. Even scale can be a factor in the way one defines resilience. If we are concerned with the resilience in the urban water sector, resilience can be structured to refer to the ability of the infrastructure, used to treat and distribute water, to bounce back after a disturbance (i.e., floods, hurricanes, earthquakes. Etc.) or reliably and consistently meet the water demand through a disturbance. The use of resilience across so many disciplines has created problems for understanding the commonalities and central ideas that underline the concept and how to apply them. It is very apparent throughout the literature that employing the use of the term resilience can lead to some confusion regarding the definition of resilience and how to methodologically apply it if it is not made clear (Jabareen, 2013; Connelly et al., 2017). The problem, objectives, goals, and people involved will often play a large role in determining how to define and apply the use of resilience. But one of the more general definitions of resilience is the one developed by the National Academy of Sciences that says resilience is “the ability to prepare and plan for, absorb, recover from, and more successfully adapt to adverse events” (National Research Council, 2012; Connelly et al., 2017). When studying the urban water sector and the need for more resilience to be built into the system, in the face of climate change and increased population growth, any number of these definitions for resilience could be applied. The urban water sector includes both the natural water source, like rivers and reservoirs, and the built environment like the water distribution network. Resilience could be applied to the urban water sector in order to understand how the distribution system will respond and adapt to shocks and stresses. If we are more concerned with the environment’s response to climate change and population growth, we could look at how water sources and their hydrology will absorb, adapt, transform, and recover from those stressors. But there are also social aspects to an urban water system so that we could study the effect of climate change and population growth on social constructions, institutions, different demographics, etc. With the many components of an urban system, it is easy to see how the urban water sector can relate to different definitions of resilience.

In order to understand the impacts of climate change and population growth on the urban water sector, it is essential to have a definition that can factor in all facets of the urban environment. It is also important to understand how climate change or increased urbanization will affect an area (i.e., more droughts, floods, less precipitation, warmer temperatures, etc.) so those concerns can be included in the definition of resilience as well. For the purposes of this study, we will be employing the use of drought resilience and urban resilience definitions. The best definition of urban resilience that captures the components of the urban water sector holistically is the one given by (Meerow et al., 2016):

> *Urban resilience refers to the ability of an urban system-and all its constituent socio-ecological and socio-technical networks across temporal and spatial scales-to maintain or rapidly return to desired functions in the face of a disturbance, to adapt to change, and to quickly transform systems that limit current or future adaptive capacity.*

This definition includes many parts of the previously mentioned definitions while remaining tailored explicitly to the urban environment. As was stated before, resilience is a concept that has been developed, used, and defined differently across disciplines. This causes significant challenges in operationalizing and understanding resilience. For this study the 'urban resilience' definition will be one terms that govern the term 'resilience' since various aspects of resilience for the urban water sector will be studied. The term drought resilience, as defined by the University of California, Davis Sustainability Group as "the maximum severity of drought during which core water demands can still be met, including social and minimum environmental requirements," will also be used. Drought resilience offers a buffer for areas like San Francisco, CA and its Regional Water System that faces increased droughts in the face of climate change. In order to better equip areas like San Francisco that suffers from drought, we created a drought resilience matrix. This matrix operates off the definitions of drought resilience and urban resilience mentioned earlier. The intended use of the matrix is for those water resource planners and managers in urban areas around the world considering adding enhancements or additional features to their water distribution system. Literature suggests that not many frameworks or tools exist that are able to measure the resilience of the urban system (Jabareen, 2013). The incorporation of the matrix into the management of urban water systems offers the opportunity to be able to measure how resilient alternative water supply options, or other employable water features, help to make the current distribution system. An urban water system is drought resilient if it can reliably and consistently meet the water demand of the urban area through drought periods. A water supply alternative can also be considered drought resilient if it, on its own or in collaboration, can help to meet the minimum water supply needs and consumption of the urban environment during dry years. This framework aimed at helping managers make more informed decisions when choosing which water supply alternatives to add to the urban water system in order to increase the system’s overall drought resilience. While we believe this matrix could be employed for use in any urban area that suffers from droughts or is expecting an increase in dry years, we chose San Francisco, California and its Regional Water System as the case study to test the effectiveness of the matrix.

3.2.2 Urban Challenges and Urban Resilience

Urban settings play a vital role in the inflaming the effects of climate change. While the extent of this contribution to climate change varies from city to city, some commonalities in underlying urban dynamics exist. Each urban area has a unique climate, and they tend to absorb more heat than surrounding suburban and rural landscapes (Howard, 1818; Oke, 1982; Arnfield, 2003; Hoornweg et al.). These microclimatic differences are due in part to the materials of the different surfaces present in the urban environment, from paved asphalt roads to large concrete buildings, that love to absorb and store heat. The thermal, radiative, moisture and aerodynamic properties of the materials in these surfaces can affect the way heat and water are transferred (Hoornweg et al., 2011). These urban areas are known to contribute to climate change through the urban heat island effect, or the characteristic warmer surfaces and air present in the urban environment due to the alteration of earth surfaces with constructed human surfaces (Valsson and Bharat, 2009). The construction of urban areas alters the natural hydrology and atmospheric processes through the alteration of natural vegetation, construction of buildings, and the concentration of normal human activities. So not only do urban environments have to plan for adaptations to large-scale climate change, but they also must consider the preexisting microclimate drivers that will further alter the climate, resulting in more emissions and effects on the environment. Besides the urban heat island effect, urban areas and increased urbanization bread large fluxes of nutrient and microbial loads that pollute the surrounding natural waterbodies (Maillard and Santos, 2008; Krishnan et al., 2013; Ghosh et al., 2014; Hassan-Rashid, Manzoor, and Mukhtar, 2017). This type of pollution can be far-reaching and has major implications for water sources and habitats on multiple scales.

Increased urbanization paired with climate change creates significant impacts on the hydrology of the surrounding area and the optimal functioning of water treatment systems. Surrounding freshwater bodies feel the effects of the altered hydrology in the urban environments and the chemistry, temperature, and quality of the freshwater body may be altered. The occurrence of drought only exacerbates these problems. Drought can lead urban areas to exploit groundwater resources and encourage saltwater intrusion (Al-Kharabsheh and Ta’any, 2002). When buildings and structures are more scattered in urban environments and are experiencing high population growth, it can lead to increased pressure on water resources. Not only will new water supplies have to be found but some alternative water supply sources will be located far from the urban boundaries. Some studies show that alternative water sources will not be able to adequately meet the needs of the growing population that’s existing water system is vulnerable to drought because of poor governance structures and collaboration between water agencies (Vo, 2007; Srinivasan et al., 2013). Other studies contest this claim stating that urban water supply will not be severely affected depleted water resources because most urban areas water distribution system operations account for the reallocation of agricultural water in trying times (Srinivasan et al., 2013). However, this viewpoint does not consider the chances of the urban and agricultural areas depending on the same water resources for supply. The contention between the two views only increase the needs for studying water supply alternatives and their potential benefits to increase the resilience of the urban water system under drought conditions.

Urban resilience factors in the ability of systems under stress to maintain key functionalities and to reduce the risks associated with disasters and hazards like droughts and increased temperatures (Leichenko, 2011). Treating cities more as highly functional urban networks that are connected to the environment helps to produce more focused approaches on how to help increase the urban areas adaptive capacity. For the urban water sector, the two key functionalities would be essential to maintain during droughts are the ability of the system to reliability and consistently meet the minimum demand and provide flows to the environment. Very few efforts have been made to increase the recognize and incorporate various adaptation measures to increase the resilience of urban environments and the water bodies they depend on for supply from climate change (Da Silva, Kernaghan, and Luqu, 2012). Understanding what makes an urban water system drought resilient is challenging to do as climate change projections are variable and the complex connections between the urban environment and its water supply are not easily understood. Climate change induced droughts affect the overall transmission network, power operations, drinking and wastewater supply and treatment, increasing the effects felt on a local level (Da Silva, Kernaghan, and Luqu, 2012). Although there have been studies that have sought to create guidelines for the sustainable operation of urban water services, few have focused on improving urban water services to allow for the reduction of risks associated with disasters using an operational form of resilience (Johannessen and Wamsler, 2017). Studies have also shown that the concept of quantifying resilience and creating a way to measure resilience has been difficult though some have tried. Evaluating the resilience of infrastructure systems like the water system in urban areas are becoming increasingly crucial as planners and managers determine how to help the system recover from disaster events like drought (Leichenko, 2011). Here we seek to fill in the gap when it comes to having a tool that allows one to determine if a set of water supply alternatives will help to buffer the urban water system from effects of drought increasing the water supplies ability to be drought resilient.

3.3 Social Resilience

In order to understand how extreme drought events, affect the planning and management of the urban water system, one must consider more than just the environmental, institutional, and financial factors. Droughts have social implications, causing disruptions in water supply distribution that may result in water use reductions for residents, reallocations of water, and increased pricing for high water usage (Krannich et al., 1995; Mitchell et al., 2017). Not all communities are affected the same by droughts, with some residential areas being more vulnerable to water shortages than others. Water agencies abilities to create urban water management plans that are able to address both the concerns of the high-risk vulnerable communities and the low-risk communities are needed. Urban social systems and hydrological systems are interconnected, allowing for any environmental changes to majorly affect the social structure of these communities, increasing their vulnerability to natural disasters resulting from climate change (Krannich et al., 1995). Depending on the conditions of the social system, the resources available, and the level of the social systems drought preparations can determine a lot when it comes to how both the social system and urban water system respond to the increased occurrence of these conditions. While most water managers are able to adjust to short term drought conditions, prolonged droughts have proven to be more challenging to respond too adequately. These are just some of the reasons for why it is essential for water managers and planners to incorporate concepts of social resilience into their preparation, response and contingency planning for threats like a drought to water resources. Using concepts of social resilience allows for some of the focus to be on how droughts affect human systems rather than merely observing how anthropogenic activities change the water systems. Other studies suggest that the socio-economic status of urban environments can be advantageous in detecting the level of resilience present in human systems against hydrological impacts (Mao et al., 2017; Kumar, 2015; Plummer and Armitage, 2007). Having a tool that can incorporate and assess social considerations with environmental, economic, institutional, and political considerations would allow for a more accurate assessment of potential water supply alternatives in the face of major ecological events.

The proposed drought resilience matrix in this study sought to incorporate social and political elements in evaluating alternative water supplies drought resilience. Many modeling systems and frameworks that seeks to assess these water supply alternatives are not able to adequately account for social and political implications, leaving a gap in the creation of effective management plans for drought resilience. The San Francisco Bay Area, on the subject of social resilience, should be most concerned with how the current conditions of water infrastructure conditions affect the low-income communities and their ability to afford water services during droughts (Cooley et al., 2016). In San Francisco, the increase in the occurrence of droughts exacerbates these conditions and creates a larger gap in water use between higher and lower- income households. In order to build up the Regional Water Systems resilience capacity, San Francisco's social infrastructure has to be acknowledged and built up to make certain that communities get more involved in a meaningful way in planning and policy decisions associated with urban water management (Ahern, 2011). Different aspects of San Francisco's water infrastructure require updates and improvements. Many of the water delivery pipes, treatment systems, and storage facilities within the city of San Francisco were named "high priority" in 2013 because the system is significantly old (stemming from the 20th century) and many of the systems are in need of repair (San Francisco Public Utilities Commission, 2015; Cooley et al., 2016). San Francisco also partially as a large centralized system and research has shown that centralized systems in an urban setting and more vulnerable to failure than decentralized systems (Ahern, 2011). These repairs are costly and can take long periods of time to fix, leaving the distribution system vulnerable and in need of major capital investment. Droughts cause reduced infiltration which can leave the water table very low and more susceptible to aquifers being over-pumped that ends up leading to land subsidence (Cooley et al., 2016). Land subsidence, changes in water pressure, corrosion of pipes, and decreased water quality are just some complications that affect the water distribution system that can arise from drought conditions. These conditions, in the long run, can produce financial issues for consumers and water utilities down the line when drought becomes more frequent, consumers use less water, and infrastructure updates are delayed because of financial drops. Not to mention how the effects are magnified on the social level due to inequitable water use. Water equity, making sure people have the same access and opportunities to life necessities like water, is something that has been neglected in California that has a significant impact on the resilience of and measure of drought resilience urban water systems. During droughts, water rates and water use are variable among different social classes. When water management plans are being constructed, and new water supply sources are being considered, it is important to factor in some of these social considerations. Only then will one be able to measure holistically how the urban water system's drought resilience could be improved through the potential addition of alternative water supply projects. Having a way to assess social considerations for proposed alternative water supply systems is needed in order for the interconnected human and nature urban water systems to build drought resilience and function efficiently for all. The incorporation of social resilience into this drought resilience matrix factors in important questions like "resilience for whom?", thinking not simply of the water utilities and high water use customers but shaping the decision making on what is considered drought resilient partially based on who benefits or loses as a result of implementing some of these alternative water supply projects (Meerow et al., 2016). The matrix seeks to factor in urban communities' perception of the use of certain water supply technologies like desalination, wastewater recycling, etc. It is important to educate and incorporate multiple stakeholders into these decision-making processes, especially the local customers and community, in order to foster effective communication and trust between water utilities and customers. Because the desire is to see the Regional Water System persist presently as well as know how to respond to difficult events like drought, it is important to have a tool that can incorporate looking at the interactions between not just the physical structures and the natural environment, but the various water processes and human interactions to create a fully integrated perspective (Mao et al., 2017). This matrix incorporated useful results and outputs from The Water Evaluation and Planning Tool (WEAP) modeling system, combined with resilience metrics to evaluate the effectiveness of potential alternative water projects in San Francisco, CA at increasing the Regional Water Systems drought resilience.

3.4 Study Area

3.4.1 San Francisco, California

The city and county of San Francisco house 884,363 people, based on a 2017 population estimate (United States Census Bureau, 2018). It is connected to the illustrious San Francisco Bay, which houses exotic and invasive species of plants and fish, tidal mudflats, and almost two-thirds of the state's salmon (California Department of Water Resources, 2013). The Bay supports important wetland, tidal marsh, and small agricultural areas but has lost most of its wetlands and their associated ecosystem services because of channelization and transference of Bay area streams to assist in flood control. As a part of the Bay Area, San Francisco is known as northern California's largest metropolitan area. San Francisco has a Mediterranean climate inland and experiences sweltering and dry summers and wet and cold winters, leading to more outdoor water use in the summer (California Department of Water Resources, 2013). Overall, the weather patterns in San Francisco are facilitated by patterns of weather present on the Pacific Ocean. San Francisco's water system is complex as most of it depends on water supply from the Central Valley. San Francisco Public Utilities Commission (SFPUC) is the water utility that services San Francisco's and conveys water from the Regional Water System in the Central Valley to San Francisco residents and wholesale customers. SFPUC also governs wastewater and drinking water treatment, in addition to power in various forms for their customers (Cooley, 2007). This Regional Water System depends on water surface flows from the Tuolumne River, Alameda, and Peninsula watersheds. Tuolumne River is the main river the Regional Water System depends on, as it receives snowmelt from the Sierra Nevada and transfers a portion of that water to Hetch Hetchy Reservoir (Figure 1). Hetch Hetchy Reservoir is the principal reservoir for water supply to SFPUC customers with a storage capacity of 360,360-acre-feet, delivering roughly 300 MGD to SFPUC customers. This principle reservoir satisfies 85% of San Francisco's water needs with the remaining 15% being satisfied by local reservoirs (SFPUC, 2016). This system also houses 11 reservoirs, two drinking water treatment plants for filtrations, 5 or more pumping stations and over 340 of combined pipeline and tunnels (San Francisco Planning Department, 2008). If San Francisco experiences any disasters of stressors like droughts that may impact their water supply, the water is transferred through pipelines connections to either the Santa Clara Valley Water District or the East Bay Municipal Utility District. Customer rationing is also implemented during normal drought procedure as well. However, it should be noted that these flows are exchanged and made under a separate agreement, and they are not part of the normal operating agreements for the pipelines to the Bay Area. SFPUC continues to seek to move towards increasing the resiliency of the Regional Water System form drought effects.

Few studies have been done on how climate uncertainty, severe drought, and population growth will holistically affect that natural and build components of water systems like the Regional Water System. While some studies have looked at drought resilience on a household scale, even fewer studies have looked at measuring and assessing the drought resilience of an urban water system (Keil at al. 2007). No studies could be found on using the concept of drought resilience to understand if which combination of water supply alternatives would act as the best buffers for the natural water system. As urban areas like San Francisco seek to explore resiliency and the addition of alternative water sources, it is important to understand how alternatives will compete with one another and how they will perform under these future conditions. The proposed drought resilience matrix seeks to compare and evaluate alternative water projects for San Francisco. The drought resilience matrix is designed viewing resilience from the perspective of a “safe-to-fail” mentality. The “safe-to-fail” mentality focuses on anticipating different system failures and designing the system in a way that allows the failures of the system to have minimal impact while keeping primary functions intact (Ahern, 2011). The drought resilience matrix focuses on identifying which of the water supply alternatives will enable the Regional Water System to become more resilient against long drought periods, allowing the system to fail successfully during droughts in ways that do not compromise its ability to convey water to customers. Some elements of redundancy are also analyzed using this drought resilience matrix as the incorporation of such a concept is said to help spread the risk across systems through space and time (Ahern, 2011). Redundancy is produced when numerous elements in a system provide the same or similar functions that allow for spread mutual support of those system functionalities. The redundancy in this study is seen in some of the grouped water supply alternatives in their respective portfolios. For example, some of the alternative water supply portfolios propose the implementation of multiple water recycling plants. Having more than one water recycling plant would increase the redundancy of the Regional Water System allowing for the associated risks of drought to be better spread across the system in theory.

3.4.1.1 San Francisco Water Resource and Resilience Challenges

San Francisco is a vibrant city that has been faced with numerous water challenges. Its water infrastructure and watersheds are subject to changes caused by climate change effects in the form of increased temperatures, seasonal pattern shifts, and increased drought. Climate studies predict that the Sierra Nevada snowpack that San Francisco’s Regional Water System depends on will decline by 80% near the end of the later century (Ackerly et al., 2018). In addition to this, climate change threatens the three wastewater treatment plants that discharge into the Bay and the Pacific Ocean through the increase in sea level rise and increased flooding, damaging part of the stormwater system in the future as well (Ackerly et al., 2018). Climate change will increase the energy demand in the summers, increasing temperatures and the rates of evapotranspiration, and the frequency and duration of droughts. These droughts will have a tremendous impact on the operation of the water distribution system and the quality and quantity of water supply available. Having natural infrastructure incorporated into the water supply system would provide a form of climate change adaptation to the system through the addition of biodiversity and various ecosystem service benefits. For this very reason, many Bay Area communities are looking to incorporate resilience into their climate adaptation and vulnerability plans and projects. Many of the strategies San Francisco is trying to implement in order to increase the Regional Water System resilience include infrastructure improvements or installation of new infrastructure, vulnerability assessments, and new governances in order to address the impacts of climate change (Ackerly et al., 2018). Understanding and planning for climate changes impacts on the natural water bodies in the Central Valley are just as important as exploring the effects of what will happen to the urban area of San Francisco locally. Coastal areas are expected to warm up slightly slower than inland areas due to its proximity to a body of water that provides fog and breeze. That is why it is important to study both the local expected climate changes and those larger scale climate changes that affect distant parts of the urban system.

Creating strategies to test current infrastructure and the development of alternative sources is important in order to maintain the integrity of the system under stressors, but this can be a challenge. Pinpointing specific threats driven by climate change is important when developing a plan incorporating resilience because it helps to determine what you are assessing the system to be resilient too. For San Francisco, the increased occurrence of droughts is the area of concern. New insights were gained from the 1976-77 and 1987-92 droughts that reinforced the need for San Francisco to diversify its surface water supplies and facilitating more investments being made into drought resilience measures (Mitchell et al., 2017). Some of the suggested ways in which to increase the resilience of water systems like the Regional Water System is through the increased use of wastewater recycling, collaborating with neighboring utilities, increasing water transfers, and encouraging the decline of indoor water use (Mitchell et al., 2017). This research will help them develop and test out the performance of different alternative water supply combinations to help enhance and develop more efficient and successful drought resilient water management strategies. San Francisco is considering engaging a variety of water system improvement projects that incorporate strategies like desalination, recycled wastewater, and river diversions to help increase the drought resiliency of SFPUC's water supply. This drought resilience matrix has major implications for drought resilience management of urban water systems. San Francisco provides the perfect case study for the use of this matrix because of the alternative water supply options they are considering and the expected increase in drought activity. San Francisco has employed strategies before to combat drought resilience after the two significant drought year periods mentioned earlier, but suppliers' effects fell short as their implemented strategies were tested during the five-year drought that started in 2012. SFPUC's methods to achieve and drought resilience through bolstering water planning requirements, increasing water trading availability during shortage periods and increasing financial assets were found to be inadequate in providing drought resilience for water supplies during the 2012-2016 drought (Mitchell et al., 2017). The problem occurred in the fact that SFPUC had not included long-term drought resilience measures into their planning, but instead focused on short-term measures. Extreme conservation measures had to be forced by 2015 during the drought because of the severity of the drought's effects on water supply. While this helped San Francisco through the tail end of the drought, it produced issues on the level of local authorities versus state authorities. When the state of California enforced urban water conservation during the 2015 drought, it caused tension between the state and local authorities as historically local authorities made those judgment calls (Mitchell et al., 2017). That is why it is important to incorporate institutional changes and arrangements on a local and statewide scale into drought resilience strategies because better development and communication between governance structures can lead to the promotion of adaptation to climate change (Leichenko, 2011). Strategies suggested by literature to help improve institutions and management towards a more adaptive style includes more accountability on state and local levels, transparency of water utilities and associated state officials, flexibility in the planning process, etc. (Tanner et al., 2009; Leichenko, 2011). There are not many tools San Francisco, nor other urban areas, are employing in order to determine the drought resilience strength of strategies before employing their use. Nor are there tools to measure and assess the drought resilience of current or future water supply implementations both structurally and institutionally. The drought resilience matrix seeks to close these gaps and provide a user-friendly tool that aids in the planning and management for future drought impacts.

3.5 Methods

3.5.1 Drought Resilience Matrix

In order to create the drought resilience matrix, we first had to determine what characteristics or strategies are favored in order to improve drought resilience in urban water systems. It is important to note that this drought resilience matrix was created with the underlying belief that sustainability is a component of resilience. When we increase the sustainability of the urban water system using alternative water supplies and institutional structures, it allows the system to become more resilient, but not necessarily in the reverse order (Marchese et al., 2018). More attention is put on the critical functionality of the water systems during droughts. We had to identify what areas of water systems were the most vulnerable based on ways they have responded in previous droughts. Five main areas were identified and adapted from (Mitchell et al., 2017):

> 1) Creating and coordination water shortage contingency planning on the local and state levels: For San Francisco, this is one of the most important improvements that could be made to bolster drought resilience after the 2012-2016 drought where state and local authorities did not entirely agree on the steps that should be taken to ensure the conservation of the water supply. Having a contingency plan that

incorporates mandated urban water conservation on the local level if and only if they cannot demonstrate their supply is drought resilient.

2) Encouraging water system flexibility and integration: This area mainly focuses on increasing the state and local investments put into integrated regional supply management. The additions of innovative water supply projects and regulatory planning and investments are encouraged.

3) Elevating water suppliers' financial resilience: Utilities can increase their ability to recover and adapt to droughts through a method of instituting drought pricing with their customers. The state can provide more partnership opportunities by helping local water utilities to factor in constitutional water pricing with flexibility.

4) Addressing water shortages in vulnerable ecosystems and communities of people: Understanding how saving water supply in the urban, city-like, should inform planners and managers more of how these savings will affect outside communities like the rural areas. Some rural areas that depend on wells may experience shortages during droughts that are largely affecting city supplies. Vulnerable communities in the environment must be identified, and water shortages that affect them need to be planned for.

5) Creating more long-term plans for water use efficiency and drought resilience: In order the plan for future benefits from long-term

> conservation effects, planners and managers must find ways to limit the reduction of water used primarily on urban landscapes or balance it out with allocating more water to long-term savings or creating a better way to store water that allows for reliability during droughts.

After these areas were identified it was important to acknowledge then the stakeholders involved in fostering this drought resilience. For California, state entities that oversee policies and arrangements made in relation to the urban water systems include the California Public Utilities Commission, Department of Water Resources, and the State Water Board. Some of these agencies help provide funding sources for local water projects. Once relevant governmental entities are discovered and included, the next step is to focus on the problem in its current present condition. We know that for places like San Francisco, the urban area uses 10% or more of the state water supply and almost half of that is used for irrigation purposes (Mitchell et al., 2017). The share of water used as environmental flows is ok, but it depends heavily on surfaces water flows, which during drought years would be much lower affecting water available for aquatic and non-aquatic habitats. We then identified the three major goals and strategies used to incorporate drought resilience into urban water management. The goal is to shift the focus on management strategies to allow minimal disruptions to occur during droughts that draw down the natural environments ability to function and well as impacts on the social and economic structures in the urban environment. The second goal is to incorporate more supply investments to reduce the impact of water shortages like new storages for supplies. This second goal also includes the increased use of more demand-side management measures. These measures usually include some water use reductions/restrictions or water pricing increases for those that go past a certain level of use to incentivize them to use less. These demand strategies must be both long-term and short-term procedures in reducing water use. We focused on these goals and strategies as we selected a range of infrastructure projects in order to create portfolios of water supply projects for San Francisco. SFPUC has a desire to see their dry year reliability goal for their water system be at least 80% (Mitchell et al., 2017). Keeping these important variables in mind, we crafted the four overarching areas of resilience: plan, absorb, adapt, and recover. We created new descriptions for these four areas built on how they could be represented in the water community. We focused on areas of drought that are most important for urban water communities and classified those areas of concerns with one of the four metrics that related the most to the goals specified. Each metric was then given a weight, or score based on the importance of the metric for drought resilience, with recover and absorb weighted more heavily than plan and adapt. Using this matrix, we evaluated and scored each of the three portfolios and compared them regarding their drought resilience scores.

3.5.2 Measuring Resilience: Plan, Absorb, Recover, and Adapt

Each of the four metrics below was chosen as a measurable characteristic of resilience that are major areas of importance for drought resilience (figure 2). These four metrics are identified in many resilience papers and studies and are four main features you see mentioned in different definitions of resilience. Each of the four metrics is assigned a score based on their level of importance and difficulty in providing drought resilience. A series of water supply alternatives were evaluated and discussed in chapter 2 for the San Francisco Regional Water System. These water supply alternatives were then grouped into three diversified portfolios (figure 1). The portfolios are then assessed using the drought resilience matrix for these four metrics, and an overall score is calculated for each portfolio. The portfolio with the highest overall score out of 55 points is the one that will provide the Regional Water System with the most drought resilience. Each of these factors plays a vital role in a systems ability to cope with and through stresses successfully. We recognize that for this matrix to be effective, the urban water systems current functionalities and its complex interconnections and reactions to drought historically must be understood (Linkov, et a., 2014). The modeling from chapter 2 sought to accomplish this by simulating the complex San Francisco Regional Water System structure and identify weaknesses under high population growth, climate change, and extreme drought stressors. The development of each metric will be discussed below and. A description of each metric and the associated factors that each portfolio of options is scored on, as well as the breakdown for the scoring, can be seen in Table 1.

3.5.2.1 Plan Metrics

A breakdown and description for each of the four metrics are located in table 1. For the description of the planning metrics, I tried to incorporate the alternative water supply projects and policies. The planning feature of resilience focuses on the institutional aspects of resilience as well as the ability of the physical infrastructure to provide its water supply services reliably and efficiently (Connelly et al., 2017). The total score a portfolio could achieve for this metric is 10 points. These points were allocated to portfolios based on a series of associated factors like consideration of cost, water yield, implementation time, and location of proposed projects in portfolios. The portfolio containing the water supply alternatives that collectively have the highest yield, shortest implementation times, lowest cost, and will be geographically close to San Francisco received higher scores for this metric than their counterparts. The planning aspect of this matrix focused on the quality and spatial organization of the proposed water supply alternatives. Having projects that balance or increase the wellbeing of the environment while also increasing economic vitality and servicing more at risk in the urban environment for droughts helps to increase the system's coverage of critical faculties during drought (Healey, 2007; Jabareen, 2013). The planning metric seeks to address the uncertainties of drought occurrences and magnitudes, rating more highly those water supply options that have a higher yield and are spatially closer to the SFPUC customers, as it helps fortify the reliability of the water supply by having closer access to more water. The implementation time and project location were factors that were weighed less heavily for this metric (Table 1) with an associated score of 1 each because they have smaller trade-offs than some of the other factors. Project implementation time is variable and can change depending on permitting, budget considerations, and weather. So, while it is something that is an important part of the planning process, the drought resilience of the overall Regional Water System will not be as affected as it would be by a smaller water yield or low reliability. Project location receives similar point valuation as decentralized and centralized approaches to location come with pros and cons but do not ultimately affect the drought resilience of the Regional Water System dramatically. The geographically closer projects will have a quicker response and distribution time than those farther away but out of the factors considered it is not one of the weightier matters. Addressing how the interconnectivity of the urban water system can be improved will increase the drought resilience of the overall network (Linkov et al., 2014). Planning, in essence, is looked at as a way to control some of the narratives of the unexpected droughts that take place by creating and implementing actions that will be used now and ones that will be necessary for the future.

3.5.2.2 Absorb Metrics

The absorb metric focuses on the use of thresholds that are intrinsic to the water supply system and additional water supply alternatives. This metric encompasses the ability of the alternative water system to endure stress and the sensitivity of the system's functions based on the level of their exposure to drought variables (Connelly et al., 2017). Each portfolio was assessed and given a score based on the associated factors described for the absorb metric listed in Table 1. This metric was worth 15 points and each portfolio's water supply alternatives were scored on factors like the threshold for drought frequency, redundancy, supply stress, etc. The associated factor supply stress was an idea adopted from (Gonzales and Ajami, 2017) that sought to use supply stress as an indicator for assessing the fraction of allocations from the San Francisco Regional Water System that is currently being used. (Gonzales and Ajami, 2017) were looking at assessing the resilience of the Bay Area Water Supply and Conservation Agency (BAWSCA), the 26 water agencies that are the wholesale customers of San Francisco Public Utilities Commission (SFPUC) that depends on SFPUC 's Regional Water System. Each of these wholesale customers has an individual supply guarantee for the water delivery amount each wholesale customer is entitled too. Those water agencies that do not have individual supply guarantees were considered more supply stressed than the other water agencies. For the sake of this study, I took this concept of supply stress and altered it to identify which portfolios were able to alleviate stress off of the Hetch Hetchy reservoir water supply, thus allowing for more of that water to be preserved or potentially used in the future as individual supply guarantees for those water agencies that need it. The focus for this metric was also on the portfolio's intrinsic reliability based on the shortcomings of demand vs. delivery during the projected project period. This sought to determine which portfolio or individual alternative water sources combined with the existing Regional Water System allow one to limit rationing to 20% systemwide reductions during droughts. Each portfolio was also assessed for the level of redundancy they would provide to the regional water system as a whole. This metric is weighted more than in total possible points than the plan or adapt metric because absorbing is a concept of resilience that is regarded more highly as an integral component by system managers, planners, and decision-makers as the area of absorption is critical to ensure important societal systems and processes are sustained through known and new threats (Connelly et al., 2017). The absorb feature is characterized by thresholds as well, and one of the best ways to increase the strength of resilience in the urban environment is through acknowledging these thresholds and feedbacks. For drought resilience, effectively spreading out a failure if one should occur and understanding the frequency of drought these portfolios can bare and how much of the demand each portfolio can cover is more imperative because it lets you know which portfolios are going aid the Regional Water System in providing more longevity for the supply of water to be delivered to customers during extreme drought periods.

3.5.2.3 Recover Metrics

The Recovery feature of resilience focuses on time and scale of disturbances like drought and how long the performance of the urban water system is degraded (Connelly et al., 2017). It looks at how long it takes for the system to bounce back and the dynamics of the system's ability to function at or above its original capacity before the drought. The total points assigned to this metric is 20. Recovery is assigned a larger point valuation because it is a resilience feature that characterizes systems that can move from a "fail-safe" mindset in urban areas to a "safe-to-fail" mindset. Many water managers and planners have focused on managing cities and the urban environment by trying to produce a stable environment that tries to control change and growth ("fail-safe") while strategies focusing more on the use of resiliency in the urban environment where one expects failure and disturbances because of uncertainty but has the urban system organized in such a way that it encourages recovery despite the failure ("safe-to-fail"). The recovery feature provides important information about how far an urban water system can be pushed before it exceeds the desired threshold and help one determine what alternative water supply projects may help to increase the elasticity of this threshold. The disturbance timing (and the magnitude and frequency of the disturbance) can determine a lot in terms of how the state of the water system may react and how it will impact the system performance and functioning (Connelly et al., 2017). One of the most important parts of the urban water system is its ability to safely and reliably deliver water to its customers. Any time that is interrupted, not only do the customers suffer from lack of water supply, but the economy suffers. Millions of dollars are poured into the operation and maintenance of these large treatment and conveyance systems so knowing how well these proposed water supply alternatives will aid the urban water system in recovery from drought is paramount, making it a weightier issue. The portfolios were assessed for associated factors like degradation time, supply diversity and the maximum amount of water supply that was degraded over the extreme drought WEAP scenario. This metric assessed the ability of the alternative water supplies to help the system bounce back from an imposed extreme drought scenario, where another five-year drought occurs. The portfolio that can bring the system functions back (i.e., meeting the demand and restoring diminished reservoir levels and river streamflow) was given a higher score. Factors of the amount of time it takes for each alternative water supply system and portfolio to recover from drought periods were assessed using this metric. Also, the quantity of water recovered by each alternative water supply was considered. The supply diversity associated factor is another term I have adapted from (Gonzales and Ajami, 2017) study where most of the BAWSCA agencies depend on SFPUC for water supplies while the others have varying sources (i.e., imported water, recycled water, groundwater, etc.) that they get water supply from. The agencies with more diversified water supply sources will be able to combat future droughts better as they will have options to choose from that allows their demands to still be met reliably and resiliently, stepping back from those sources that are jeopardized and shared with others. With the uncertain future of the water supply reliability for both SFPUC and many BAWSCA agencies and the expected economic losses due to water supply variability from interruption of flow through drought, it is important to diversify the type of water supply alternatives that are available (Gonzales and Ajami, 2017). To measure the potential reliability of the regional water system with the addition of these portfolios, I sought to see which portfolios offered the most diversity in water supply types and which of those portfolios contained the most water supply alternatives that could be used in both drought and non-drought years. This shows which portfolio's offer the most consistent diversified water supply options.

3.5.2.4 Adapt Metrics

Adaptation metric seeks to assess the ability of these water supply alternatives in the portfolios to enhance the drought resilience of the water system through measures that allow for greater mitigation. Adaptation acknowledges that the change will occur (i.e., there will be more droughts) and seeks to assess the infrastructures ability to last through the disturbance and reduce the vulnerability of the water system to major drawdowns. This metric focuses on actions that can be taken to reduce the impacts of the event of droughts and to anticipate the changes that will be made to the infrastructure and counteracting them with measures that will support the persistence of the system through drought (Heltberg et al., 2009; Jabareen, 2013). The form of the urban environment and its ability to accommodate different alternative water supply structures are factored into this metric's score as well. The qualities of urban design and form greatly impact the urban resilience that is present in the system through the identification of mixed land uses (i.e., residential, commercial, industrial, etc.), amount of green space present in the environment, diversity of structures sizes, density of the population, and the compactness of the infrastructure that may or may not lend itself to easy connectivity for future alternative water supply structures (Wheeler, 2002; Jabareen, 2013). Redefining portfolios, examining existing policies and proposing new policies or amendments to old policies were a part of the structure of this metrics assessment.

3.5.3 WEAP Extreme Drought Scenario

3.5.3.1 Scenario Design

As a reminder from chapter 2, this scenario projected what may occur if San Francisco went through another extreme drought period akin to the 5-year drought that occurred from the year 2012 to 2016. In this scenario, the Water Year Method was used with downscaled climate data to create different intervals for the classifications of year type (i.e., dry year, wet year, etc.) to produce another 5-year drought scenario. The individual alternative water supply options and combined portfolio options results were assessed under this scenario. Special attention was also paid to the way the extended drought effects reservoir levels, unmet demand, supply requirement, and current water system consistency. The expectation was that reservoirs inflows would be severely lower than the inflows that occurred during the previous 5-year drought. Reservoir water levels were also predicted to decrease due to considerable variation in precipitation events during this scenario and increased annual temperatures. We expected that the portfolios containing the desalination options would have the lowest unmet demand and the highest reliability due to the process of desalination not being dependent on rainfall or a finite reservoir resource. We considered that the conservation techniques would play a major role in preserving and offsetting the pressure on the water supply options like it did for the previous 5-year drought since it is focused more on demand-side management.

3.6 Results and Discussion

3.6.1 Portfolio Drought Resilience Performance

SFPUC is seeking to improve the reliability of the Regional Water System in the face of climate change and drought through the incorporation of new water supply alternatives. These water supply projects vary from the creation of wastewater recycling facilities to Tuolumne River diversions and collaborative desalination plants. Each contributes in different ways to the overall reliability of the water management system. Increasing water storage in the form of reservoir expansions are also being considered by SFPUC and have been factored into the portfolio options. Having adequate conveyance of water during droughts and storage of water are essential components for providing emergency water supplies to SFPUC customers during droughts. Without storage, water cannot be adequately conserved for future use. Water agencies utilize a mix of strategies, including water conservation, recycling, and storage to improve water quality and reliability. Centralized and decentralized techniques were combined for different portfolios. Cost, the yield of water, construction/ implementation time, and proximity to the San Francisco were factors that affected the arrangement of the portfolios. Some of the water supply projects are more collaborative on a regional level while other portfolios are composed of projects that focus solely on the SFPUC municipality and its immediate customers. The environmental impacts of each portfolio were considered as well.

We created three potential portfolios composed of a combination of different alternative water projects for San Francisco. Portfolio A contains the Tuolumne River diversions, Conservation technique projects, and Los Vaqueros reservoir expansion. The projects in portfolio A focus on combining small-scale water supply projects that would be added to the existing infrastructure or current practices, making the cost of each project more affordable. Portfolio B was comprised of the Bay Area Regional Desalination plant, the Eastside and Westside Recycled water projects, and the Dale City project. Portfolio B placed more emphasis on the use of recycled treatment plants as an additional water source. These recycled water treatment plants would be located in the city of San Francisco and would use wastewater from the Oceanside or the Southeast wastewater treatment plants as influent that would be treated and used for non-potable uses. This portfolio also was attempting to increase SFPUC’s communication and collaboration with other water agencies and districts to foster a sharing of information and innovative ideas through the desalination project. The Bay Area Regional Desalination plant is the project that requires a lot of collaboration, and this could add resiliency to the Regional Water System through having institutions share a resource and potentially build water resources together, coming up with more holistic and innovative solutions. Moreover, Finally, portfolio C contained the local but large water yielding Eastside Recycled water project, the In-city Desalination, and the Conservations techniques. This portfolio was arranged with the intention of putting more focus on local solutions SFPUC fortifying their water supply through droughts.

Portfolio A received a drought resilience score of 49 out of 55 points. When the individual water supply alternatives were assessed using the 4 metrics Portfolio A lost points from the Tuolumne River Diversion project because the 18 MGD allowance would be limited during drought years, and while that helps to prevent further harm to the natural environment, it limits the amount of water available for SFPUC during those drought years. It makes the Tuolumne River project less attractive for use concerning drought resilience because the yield does not significantly increase the functioning of the Regional Water System during drought. The same project also cost portfolio A points because these diversions would be added to the diversion that is already being taken from Tuolumne River to be used by Hetch Hetchy Reservoir to satisfy the needs of SFPUC. This project has the potential to create a negative feedback loop during a drought where water in the Tuolumne River is lowered leading to less water available in Hetch Hetchy Reservoir and any additional water diverted downstream would negatively impact the downstream communities and doubly decrease the amount of water supply available for the competing uses. It could also lead to the exceedance of the minimum environmental flow requirements that SFPUC must uphold for instream flow in the Tuolumne River.

Portfolio B received a drought resilience score of 38 out of 55 points. Portfolio B lost points when the four metrics analyzed each water supply alternative due to issues associated with the Bay Area Regional Desalination plant. This desalination plant requires much collaboration as it is a project that SFPUC is partnering with six other water districts. While this desalination plant would provide 9 MGD, and 10-25 MGD during both non-drought and drought years, it comes with a series of complications regarding conveyance of the water from the Mallard Slough Plant to SFPUC customers. Multiple entities competing for the same limited capacity makes the use of this water supply source more complex during drought years. There are also the environmental considerations for this project where the brine from the desalination plant could impact the surrounding water bodies water quality, affecting sensitive fish communities. Some institutional considerations and constraints caused this portfolio to lose points as well. The desalination plant would require complicated negotiations between SFPUC and all six water districts and participating permitting agencies. This could cause the timing of the project from construction to implementation to be longer, costing SFPUC more and increasing their financial sensitivity to climate change as they wait for the project to come online. Only one point was lost from the potential that the public's perception of desalination may be harmful, and acceptance of consuming desalinated water would be hard to encourage.

Portfolio C received a drought resilience score of 52 out of 55. This portfolio lost points when its alternative water supply projects were assessed under the four metrics because of the desalination process and a part of the Eastside Recycled Water project. The desalination in this portfolio is an in-city desalination plant, and it offers 25 MGD with its source being the Pacific Ocean making it a very drought resilient source. However, there could be challenges with acquiring the necessary permits because of the various review cycles and feasibility studies that would have to be done. There are also limitations on where this desalination plant could be located because of densely populated areas near the coast. To some, the desalination plant may also not be aesthetically pleasing, and just like with the Bay Area Regional Desalination plant, the public may push back because of negative perceptions of the treatment and taste of desalinated water. The Eastside recycling project offers up to 2 MGD for non-potable uses. The only two drawbacks from this project is that it is one of the lower yielding projects and customers that would be served by this (for landscape and irrigation) may have to undergo retrofitting to allow the conveyance of the water, and this would interrupt the current operations of the facility which prolongs the use of the water and can be very expensive. However, overall the ability of this portfolio to aid to drought resilience based on its score was the highest out of the three portfolios.

3.6.2 Matrix Limitations

The limitations of this drought resilience matrix stem from the lack of inclusion of certain social aspects on the residential level that should be considered when planning for drought resilience. Many studies have stressed the importance of looking at an operationalized concept of urban resilience and making sure to ask who, what, when, where why to holistically address and acknowledge factors that influence or determine the strategies that will be employed to increase resilience. The “five W’s” were created to help those trying to measure resilience to properly address all aspects of resilience, including recognizing the politics that underly decisions and tradeoffs when trying to apply resilience to something (Meerow and Newell, 2016). Some of the questions can range from who determines the goals or what is desirable for the system in questions? Whom will these resilience measures affect (both positively and negatively)? What specific stressors is the urban water system seeking to be resilient to? Is the focus on short-term or long-term resilience strategies? Where are the spatial boundaries for the system being studied? (Meerow and Newell, 2016). The use of the drought resilience matrix we developed could have better incorporated some of these questions as a part of the process of achieving a drought resilience score. Addressing the "resilience for whom?" is a question that could only be generally answered for this study (Meerow and Newell, 2016). Understanding the effect of the implementation of specific water supply alternatives on different demographics of San Francisco residents would have allowed the matrix the ability to identify potential equity issues with how different communities would be affected. Political underpinnings of resilience could only be incorporated into the framework in a more general way in terms of looking at the collaboration between state and local water authorities. The drought resilience matrix could be made better with the incorporation of strategies that help to assess the equity of the proposed water supply alternatives. Resilience is often viewed as a positive addition to any system, but studies have shown that the push for resilience in one area may have detrimental effects on another area. This once again brings us back to the 'resilience for whom?' question and dealing with the unintended consequences of actions taken in the name of increasing resilience. The drought resilience matrix may have some limitations concerning the scale it can be used on and its ability to factor in those potential unintended consequences. Studies have shown that resilience sought on a community level scale could have adverse effects on the resilience of households (Adger, Arnell, and Tompkins, 2005; Sapountzaki, 2007; Leichenko, 2011). To alter the drought resilience matrix, the addition of a way to look at communities and households that are most impacted by drought in the area of study, cross-referenced with the access to the water distribution system and associated poverty issues would need to be molded into a quantifiable metric to aid the matrix in its ability to capture the effects of drought resilience decisions holistically. More work can be done to bolster the matrix and allow it to be used in other urban areas by engineers, managers, and planners.

3.7 Conclusion

The use of the drought resilience matrix allowed for the successful assessment of water supply alternatives that may be employed in San Francisco, California. Portfolio C was found to have the highest drought resilience score (52), with portfolio A coming in second with 49 points, and portfolio B coming in last at 38 points. This is a result of interest because portfolio A was suggested as the best portfolio for SFPUC in chapter 2 based on modeling analyses of the portfolio and the cost-benefit analyses. Yet here, regarding drought resilience, Portfolio C provides the most benefits. It would be worth re-exploring those portfolios to see if the high population growth was a part of the cause for the difference in portfolio choice. Figure 2 was created with the intention of looking at the tradeoffs that may occur between cost, yield, and resilience. It appears from Figure one that the more expensive portfolios and water supply alternatives with the greater yields produce higher drought resilience. Portfolio C is displayed in Figure 2 and is the most drought resilient with portfolio A but depending on the goals of the water managers and what is most important may determine which portfolio is chosen. If drought resilience and a low cost are the most important then a different portfolio would be suggested but if yield and drought resilience is the most critical factors the suggestion may change, and there are tradeoffs present that can be seen in Figure 2 depending on what factors (cost, yield, or drought resilience) are most important. Portfolio C displayed high marks for most of the metrics due to the type, cost, yield, reliability, institutional, construction, implementation, and public perception considerations. This matrix could be adapted to be used in different urban areas. It has successfully been applied to a complex urban water system that suffers from drought with results that will have implications for managers and planner's choice in water supply alternatives to implement. We desire that this matrix can be used in areas across the United States that also struggle with drought and have created opportunities to increase their water systems resilience.

Chapter 4: Conclusions and Recommendations

4.1 A Holistic Framework for Urban Water Resource Management: The Case of San Francisco, CA

This research could have implications for other states and increase the implementation of reliable and resilient water resource projects. Having a framework that allows for the holistic evaluation of the urban water sector could produce new and creative solutions to age-old water resource management problems and help managers save time and money in the process of vetting different projects. Gaining a better understanding of the way climate change and population growth is impacting California could have implications for predictions for other states in similar climates with similar water systems. Having a framework like this be successful could allow for projects and evaluations like this to become standardized and reproducible in any city and any climate. In other places, Singapore, composed of 5.5 million people receiving 2.4 m of rainfall per year, has had success with reclaimed water use calling it “NEWater” (Lee & Tan, 2016). Singapore suffers from limited land space making it difficult for them to collect and store water, so they depend heavily on water imports from Malaysia to meet their growing water demand- roughly 1.82 million m^3/day (Lee & Tan, 2016). They now use NEWater as a part of their indirect potable and non- potable use. Their success with essentially drinking treated wastewater is impressive, the public was effectively included in the decision to do so, and they are not the only ones utilizing this alternative water supply system. Numerous water reuse projects have been implemented in Australia on a smaller scale, with most the water being used for the following: landscape irrigation, toilet flushing, agricultural irrigation, and industrial water recycling (Po et al., 2003). In Australia, many of the projects were initiated and followed through by a strong partnership between landowners and the government (i.e., New South Wales government and landowners working on pursuing integrated water cycle management) (Po et al., 2003). One of the most famous cases in Australia was in Sydney, and it was called the Water Reclamation and Management Scheme and it took place on the site of the 2000 Olympics in Sydney, where wastewater was used from the system and treated to be used to water lawns and flush toilets near the Olympic areas (Po et al., 2003).

Results for the high population growth scenario and extreme drought scenario also displayed decreased reliability of the Regional Water System deliveries to both wholesale and retail customers. The annual water use rate increased rapidly in the high population growth scenario compared to the reference scenario around the year 2040 displaying that population growth in both wholesale and retail customers should be factored into future planning for San Francisco Public Utilities Commission (SFPUC). The compound effects of both high population growth and climate change may increase the need for additional alternative water supplies than what was considered in our study. The Hydropower operations of Hetch Hetchy should be modeled in the future using this Water Evaluation and Planning tool (WEAP) model and framework because the use of the water in Hetch Hetchy and the alteration of future water supply due by urbanization and climate change will have impacts on the production and dissemination of hydropower. Since the water from Hetch Hetchy and

Tuolumne River are used for hydroelectric generation, the impacts of increased temperature and drought occurrence will affect the efficiency and ability to produce electricity for customers. The drawdown of Hetch Hetchy Reservoir first seeks to serve the demand of water SFPUC water customers and then providing water for hydroelectric generation at the Kirkwood Powerhouse (San Francisco Planning Department, 2008). In this case, it would be important to run a priority scenario testing the tradeoffs between the ability to meet urban water demand and produce electricity depending on which is given a higher preference. This recommendation could help SFPUC plan to not only make sure the water supply is reliable for SFPUC customers but also that the competing use for hydroelectric generation is also able to be sustained. A further study like that could reveal if alternative water supply for hydropower needs to be chosen and assessed for future use.

California has also had significant success with water reuse projects for many years now, having over 230 water reuse projects in operation and man still being developed in places like San Francisco (Po et al., 2003). In 1967 the Irvine Ranch Water Recycling Program was introduced in California and was one the more successful multi-use recycling projects that were built to decrease the Irvine Ranch Water Districts dependence on imported water for agricultural and domestic use (Po et al., 2003). In the end, the project helped to offset the imported water and the project created 15% of the water supply to be used annually for agriculture and domestic needs (Po et al., 2003). In most of these cases around the world, the water reuse was able to improve the overall water supply and use portfolio more resilient, allowing for a more resilient urban water sector. This research could pave the way to vetting these water reuse projects more efficiently and provide a way to forecast how these projects will fare under climate change conditions. The success of the various projects also depended heavily on the support of the local community and the active engagement, education, and partnership with the local community. WEAP images and results are easily translatable across stakeholder groups which could encourage more transdisciplinary work to take place in the future. This only goes to show how useful water reuse can be as an alternative system to add resiliency to the overall water sector as well. This may also lead to the adoption of better development options. This research could help improve different water governance strategies from "fit-for-purpose" governance framework, centralized vs. decentralized, and both informal and formal governance to enhance the resilience of urban water systems (Rijke et al., 2013). Effective governance can help create a positive impact on the resiliency of urban water systems and help overcome water governance challenges. Having a framework that promotes good governance and stakeholder communication and collaboration is essential and could increase the resiliency and sustainability of the urban water

4.2 Drought Resilience Matrix

Urban environments around the world are facing increased sensitivities to drought effects. Climate change induced drought effects not only alter the natural hydrology of the broad macro climate but those in the urban microclimates. The increasing frequency and duration of droughts are creating challenges for urban water utilities to convey water through the water distribution systems to customers reliably and consistently. The proposed drought resilience matrix can be used to test alternative water supply projects to help bolster the drought resilience of the coupled human and natural water system.

The use of the drought resilience matrix allowed for the successful assessment of water supply alternatives that may be employed in San Francisco, California. Portfolio C was found to have the highest drought resilience score (52), with portfolio A coming in second with 49 points, and portfolio B coming in last at 38 points. This is a result of interest because portfolio A was suggested as the best portfolio for SFPUC in chapter 2 based on modeling analyses of the portfolio and the cost-benefit analyses. Here, regarding drought resilience, Portfolio C provides the most benefits. It would be worth re-exploring those portfolios to see if the high population growth was a part of the cause for the difference in portfolio choice. Portfolio C displayed high marks for most of the metrics due to the type, cost, yield, reliability, institutional, construction, implementation, and public perception considerations. This matrix could be adapted to be used in different urban areas. It has successfully been applied to a complex urban water system that suffers from drought with results that will have implications for managers and planner’s choice in water supply alternatives to implement. We desire that this matrix be able to be used in areas across the United States that also face drought-related water stress and have created opportunities to increase their water systems resilience. This resilience matrix could have implications for managers and planner’s definition and design of resilient cities concerning the configuration of water supply. The drought resilience matrix could have major implications for what water managers include into their water shortage contingency plans, how portfolios are created and what they include, as well as the way drought resilience is defined and measured in the urban environment. The use of the drought resilience matrix can become a more standard practice in San Francisco that is spread across the water agencies in the surrounding area, allowing for further ease of collaboration to be fostered on projects involving drought resilience and alternative water supplies. Urban water managers that adopt this framework and San Francisco water managers could continue to further foster flexibility into the water system and improving how vulnerable the system is to climate change and population growth socially, economically, environmentally, etc. The continued use of this framework can help to produce both effective long-term and short-term strategies for building resilience into the urban water system. Urban water managers in a similar position to San Francisco water managers may begin to reevaluate what combinations or types of water supply alternatives are the most effective in increasing the reliability and resiliency of the overall urban water system.

4.3 Collective Conclusions

The use of the WEAP in combination with the Drought Resilience Matrix (the framework) could be used and tested on other urban areas susceptible to drought and population increases. This framework could become standardized and reproducible in urban water management, but further testing is needed in different geographic regions with more complex urban water systems. WEAP proved to be an excellent modeling system choice for studying both the urban and natural water systems under different conditions. WEAP’s flexible structure, user-friendly platform, and the inclusion of a variety of ecological, economic and political considerations helped to make it uniquely qualified modeling tool for managing and evaluating the state of water resources under different conditions. Unlike other modeling systems, WEAP can model priority differences between municipal, environmental, and agricultural sectors as well as evaluate ranges of demand and supply-side management strategies with policy and financial considerations inputs. WEAP will allow for more stakeholder engagement and understanding of modeling outputs while still being a robust enough tool to engage those more concerned with water balancing and simulation data. The only factor where WEAP, and most water resource modeling systems, fall short is the lack of further incorporation of social and political factors. For example, WEAP does not consider communities at different risk levels for impacts of climate change and population growth and well as socioeconomic statuses of residents. The resident's proximity and access to the water distribution system are varied and could not be factored into the modeling as well as residents' perceptions of water supply alternatives like desalination and potable water reuse. This is where the drought resilience matrix proved to be a necessary addition and tool for evaluation in a framework with WEAP. The matrix allowed for some of these social and political factors to be considered when assessing water supply alternatives for implementation in the face of climate change. WEAP used together with the matrix created a truly integrated and holistic approach to evaluating the water supply alternatives under different conditions.

The study using WEAP suggests that high population growth might be a more dominant stressor on urban water resources than climate change. More side-by-side research needs to be done on the effects of population growth versus climate change on urban areas in order to draw further conclusions. Unmet demand and system's reliability are major concerns for the future of urban water supply in San Francisco. Temperature changes, snowmelt decreases, decreased reservoir volumes, and shifts in streamflow timing and magnitude will further stress meeting demands of the San Francisco Public Utilities Commission (SFPUC) customers. It is critical for SFPUC to reevaluate their projected demands for the future as well as the which alternative water projects they employ. Comparing SFPUC's supply options in groupings/portfolios rather than individually provided a more comprehensive approach to understanding how different types of water supply alternatives could function together to produce the most efficient means of enhancing water availability and delivery under future conditions. Evaluation of the same water supply alternatives using the drought resilience matrix produced different suggested project adoptions than when using WEAP alone. Portfolio A was considered the more advantageous combination of water supply alternatives when using WEAP alone, but when using the drought resilience matrix portfolio C was deemed more advantageous. This could be due to the difference in the inputs considered or the selection criteria used to characterize WEAP and the drought resilience matrix. The drought resilience matrix also factors in more social and political implications of drought than WEAP does, which could have also contributed to the difference in the recommendation. Further testing should be done to develop the drought resilience matrix and to understand what other factors may be influencing the differences in recommendations. More case studies should be conducted using WEAP and the drought resilience matrix in places that also suffer from drought or expect drought impacts to increase. A recommendation for a place of study to use these tools would be Cape Town, South Africa. Cape Town has a similar climate to San Francisco in that it experiences a Mediterranean climate with wet winters and dry summers, so they face similar issues as is characteristic of their climates with the impacts of climate change. Cape Town also is suffering from an increase in severity and occurrence of droughts. In 2015 Cape Town experienced a water crisis due to a severe drought that caused the region to have to reduce their daily water use by more than 50%, leading it down the path of becoming the first major city to run out of water (Cassim, 2018; Poplak, 2018; York, 2018). Doing another case study outside the U.S. would be able to test the frameworks ability to be used across geographical boundaries and test its ability to work with more severe cases.

Appendices: Chapter 2

Table 1. San Francisco Public Utilities Commission's alternative water supply projects expected project yields (MGD), and associated portfolios.

Water Supply Alternatives/Projects	Project Description	Project Yield (MGD)	Associated Portfolio(s)
Conservation Techniques	Includes techniques such as rain water harvesting, potable reuse, high efficiency fixtures, rebates, etc. to be used in drought and non-drought years.	25	Modifying Existing Supply, Local Approaches
Additional Tuolumne River Diversions	Diverting additional water from Tuolumne River (past current 265 MGD limit) due to annual deliveries being increased to 290 MGD. Water used as drinking water in non-drought years.	18	Modifying Existing Supply
Los Vaqueros Reservoir Expansion	Increasing reservoir capacity from 160,000 AF to 275,000 AF. This reservoir may also be used during drought years to store water from BARDP.	11.5	Modifying Existing Supply
Bay Area Regional Desalination Plant (BARDP)	A multi-water agency desalination project that seeks to turn brackish water into drinking water for SFPUC customers for use in drought and non-drought years.	9	Recycling and Desalination
Westside Enhanced Water Recycling Plant	Recycling wastewater effluent from Oceanside Water Pollution Control Plant to be used for non-potable water purposes (i.e., irrigation) in drought and non-drought years.	4	Recycling and Desalination
Daly City Water Recycling Plant Expansion	Increasing the capacity of the existing recycled water plant to offset current groundwater use for SFPUC wholesale customers in drought and non-drought years.	3.4	Recycling and Desalination
Eastside Enhanced Water Recycling Plant	Recycling wastewater effluent from Southeast Water Pollution Control Plant to be used for non-potable water purposes (i.e., irrigation, commercial, industrial, and toilet flushing) in drought and non-drought years.	4	Recycling and Desalination, Local Approaches
In-city Desalination Plant	Constructing a desalination plant in San Francisco that treats sea water from the Pacific Ocean to service local SFPUC wholesale and retail customers drinking water needs in drought and non-drought years.	25	Local Approaches

Table 2. Conversion table for units associated with water supply projects such as acre-feet, cubic feet per second and million gallons per day.

Dimension	**Unit**	**Equivalent Unit**
Volume	1 Gallon	$3.06889\text{x } 10^{-5}$Acre-feet
Flow	1 Million gallons per day	3.0689 Acre-feet
Flow	1 Million gallons per day	1,120 Acre-feet per year
Volume	1 Acre-foot	325,851 Gallons
Flow	1 Acre-foot per day	$3.26\text{x}10^{5}$ Gallons per day
Flow	1 Acre-foot per year	892.15 Gallons per day
Flow	1 Acre-foot per year	325,851 Gallons per year
Flow	1 Cubic-foot per second	7.481 Gallons per second
Flow	1 Cubic-foot per second	646,317 Gallons per day
Flow	1 Cubic-foot per second	236,062,197 Gallons per year
Flow	1 Cubic-foot per second	$2.296\text{x } 10^{-5}$ Acre-feet per second
Flow	1 Cubic-foot per second	1.983 Acre-feet per day
Flow	1 Cubic-foot per second	724.4Acre-feet per year

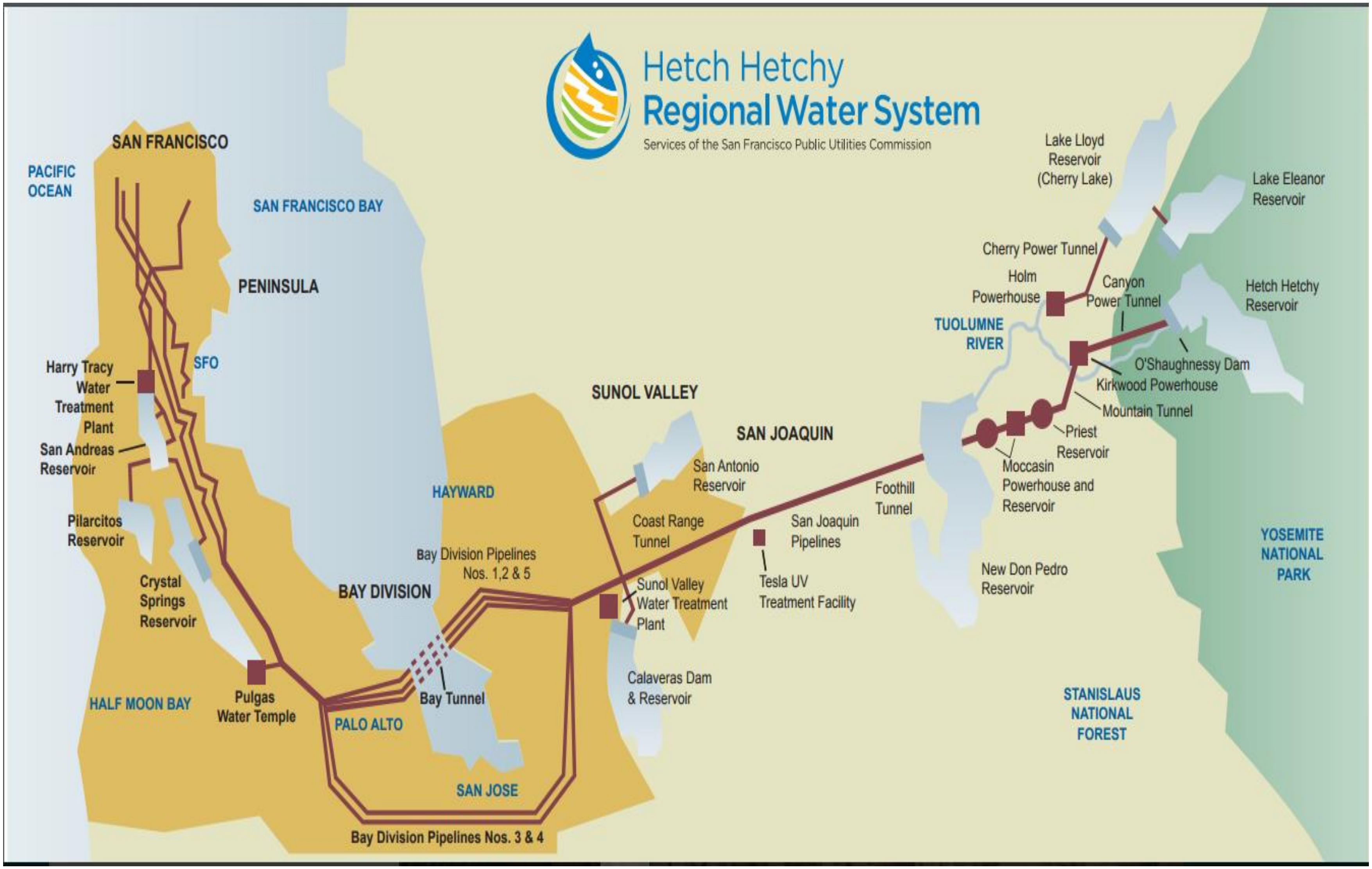

Figure 1. The Regional Water System Configuration. The water distribution system for San Francisco Public Utilities Commission Customers. Source: SFPUC, 2016. https://sfwater.org/index.aspx?page=355

WEAP Model and Scenario Configuration for Regional Water System Study

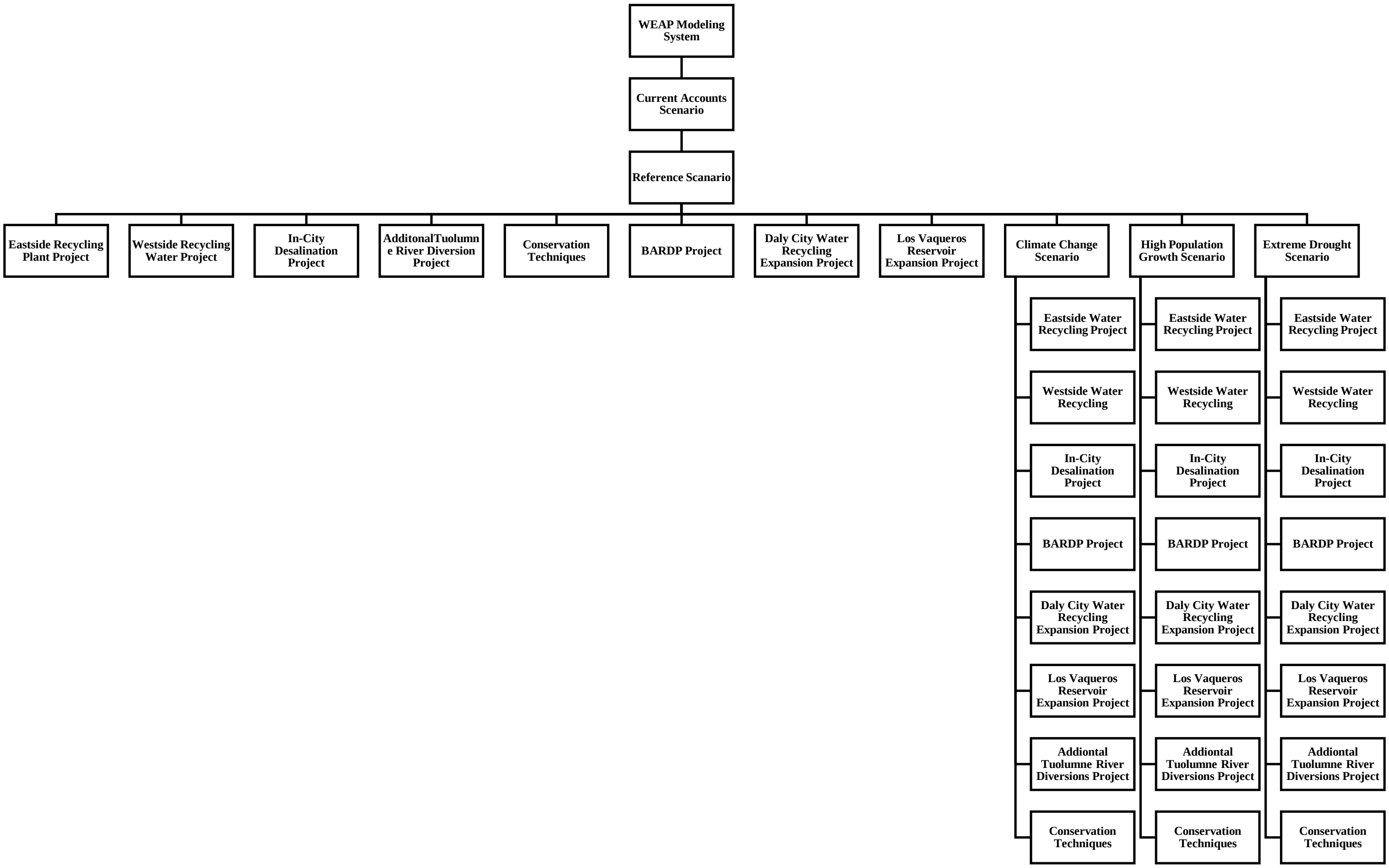

Figure 2. The configuration of the WEAP modeling scenario structure for modeling and assessing the Regional Water System and additional water supply under climate, drought, and demand growth conditions.

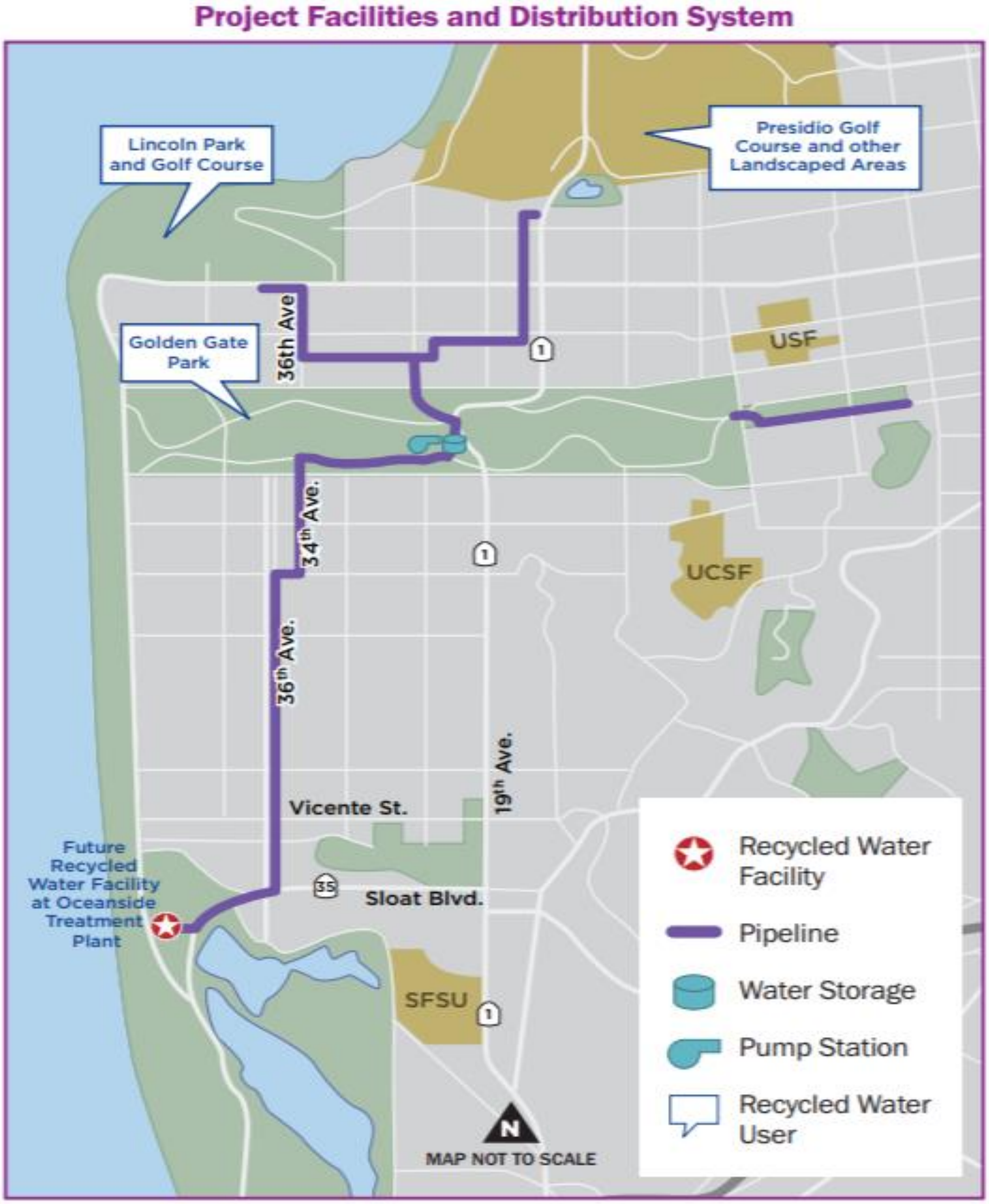

Figure 3. The Westside Enhanced Water Recycling project. Source: SFPUC, 2018; http://sfwater.org/modules/showdocument.aspx?documentid=11707

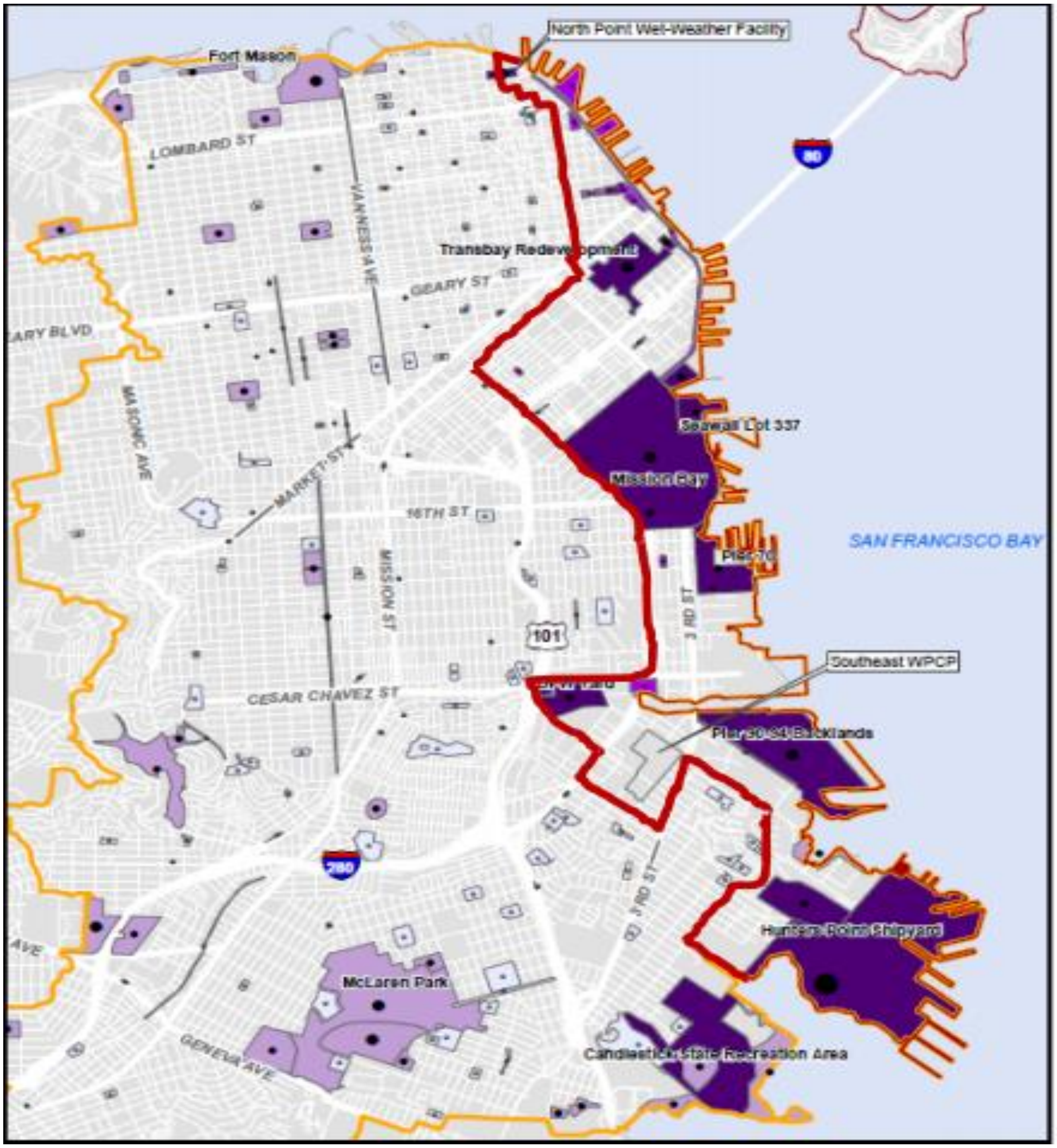

Figure 4. The Eastside Recycled Water project. The Dark purple areas signify the residential areas that will receive water deliveries from the Eastside recycled water plant. Source: SFPUC, 2012; http://sfwater.org/Modules/ShowDocument.aspx?documentid=2811

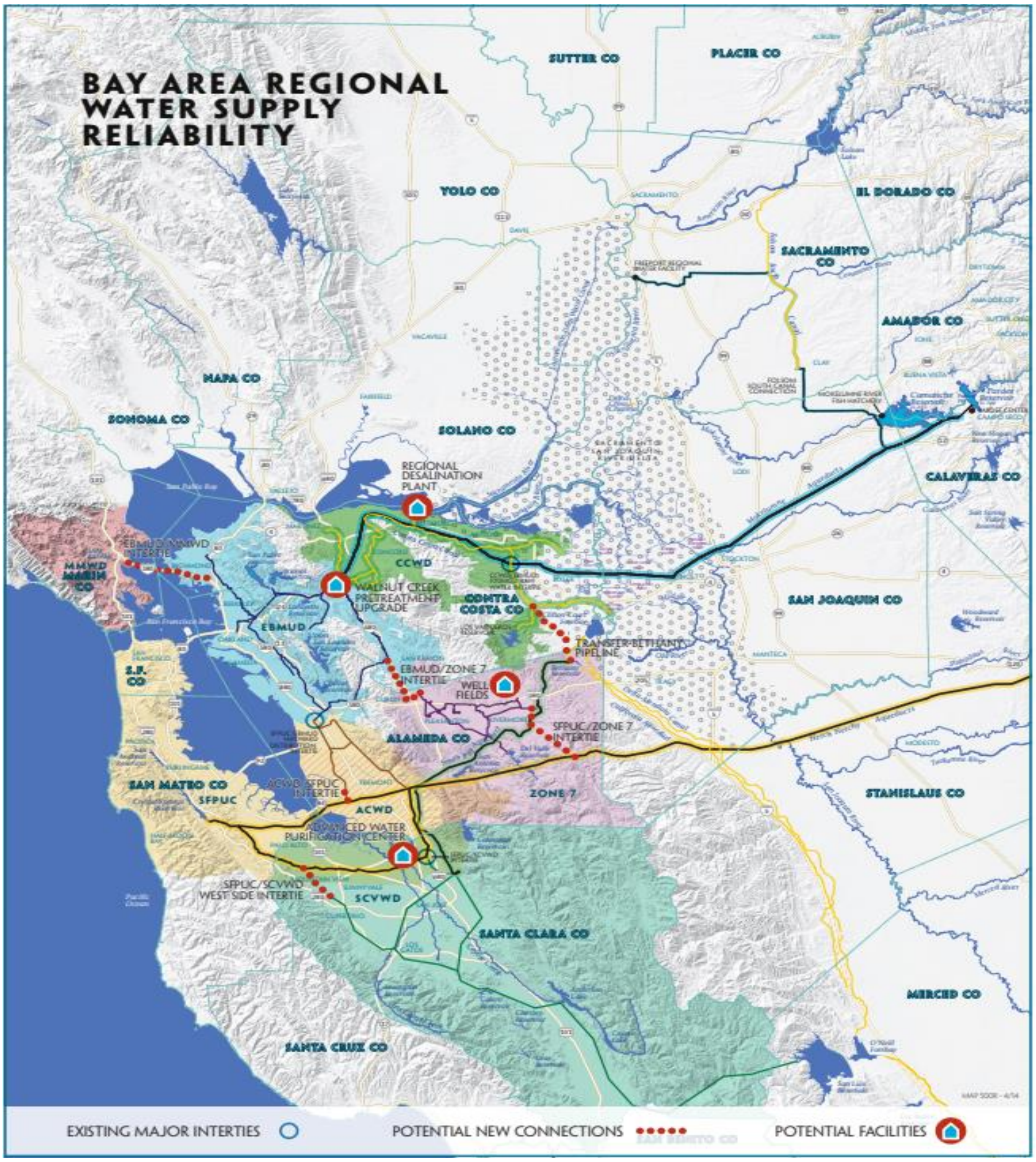

Figure 5. The potential Bay Area Regional Desalination project and color-coded five collaborating regional water agencies collaborating on this project. Source: East Bay Municipal Utility District, 2014; https://www.ebmud.com/about-us/construction-my-neighborhood/desalination-bay-area-regional-reliability/

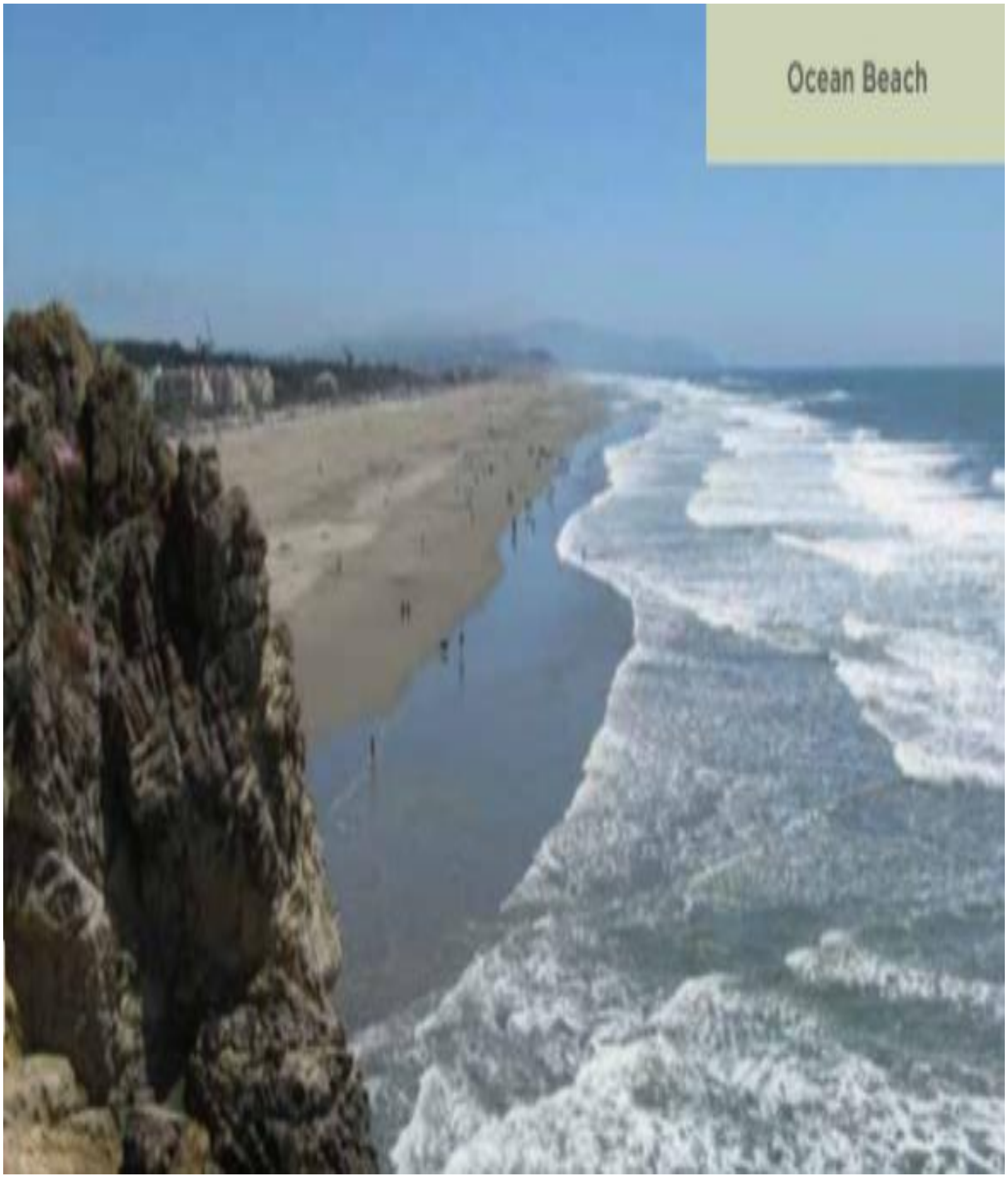

Figure 6. The Pacific Ocean- the potential source water for the In-City Desalination Plant. Source: SFPUC, 2016 http://sfwater.org/Modules/ShowDocument.aspx?documentid=9750

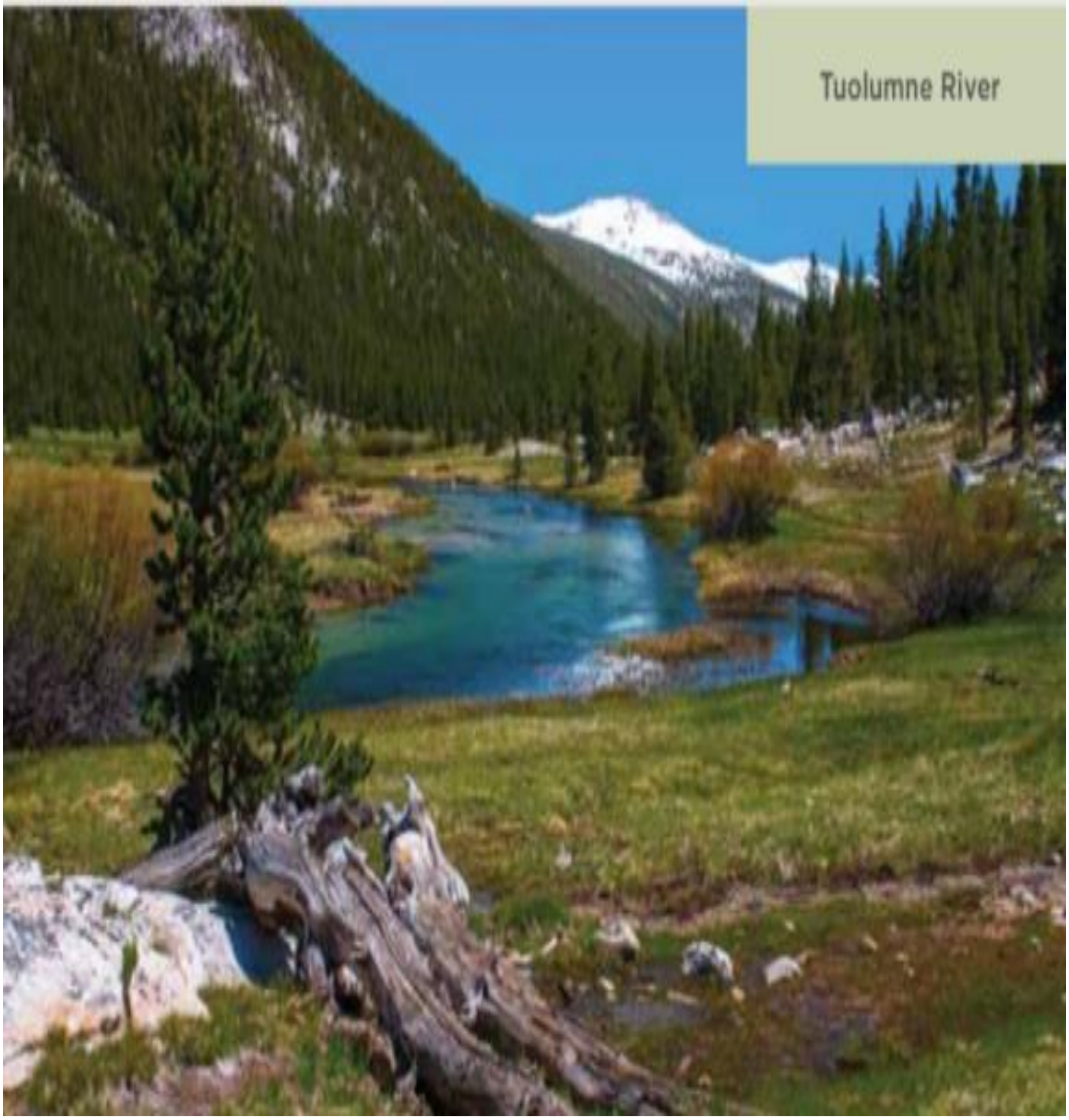

Figure 7. The Tuolumne River and Meadows with the Sierra Nevada mountains.
Source: SFPUC, 2016
http://sfwater.org/Modules/ShowDocument.aspx?documentid=9750

POTENTIAL PARTNERS

These agencies have provided funding and in-kind services, and are evaluating potential participation in the project to diversify their water supply portfolios against drought, emergencies, climate change and regulatory challenges.

- ◎ Los Vaqueros Reservoir
- 1 Contra Costa Water District
- 2 City of Brentwood
- 3 East Contra Costa Irrigation District
- 4 Byron Bethany Irrigation District
- 5 East Bay Municipal Utility District
- 6 San Francisco Public Utilities Commission
- 7 Zone 7 Water Agency
- 8 Bay Area Water Supply & Conservation Agency
- 9 Alameda County Water District
- 10 Santa Clara Valley Water District
- 11 Del Puerto Water District
- 12 Grassland Water District
- 13 San Luis Water District
- 14 San Luis & Delta-Mendota Water Authority
- 15 Westlands Water District

Figure 8. Los Vaqueros Reservoir Expansion Project potential partners and their locations. Source: Contra Costa Water District, 2018 https://www.ccwater.com/DocumentCenter/View/4033/11805_CCWD_LVEFactSheet

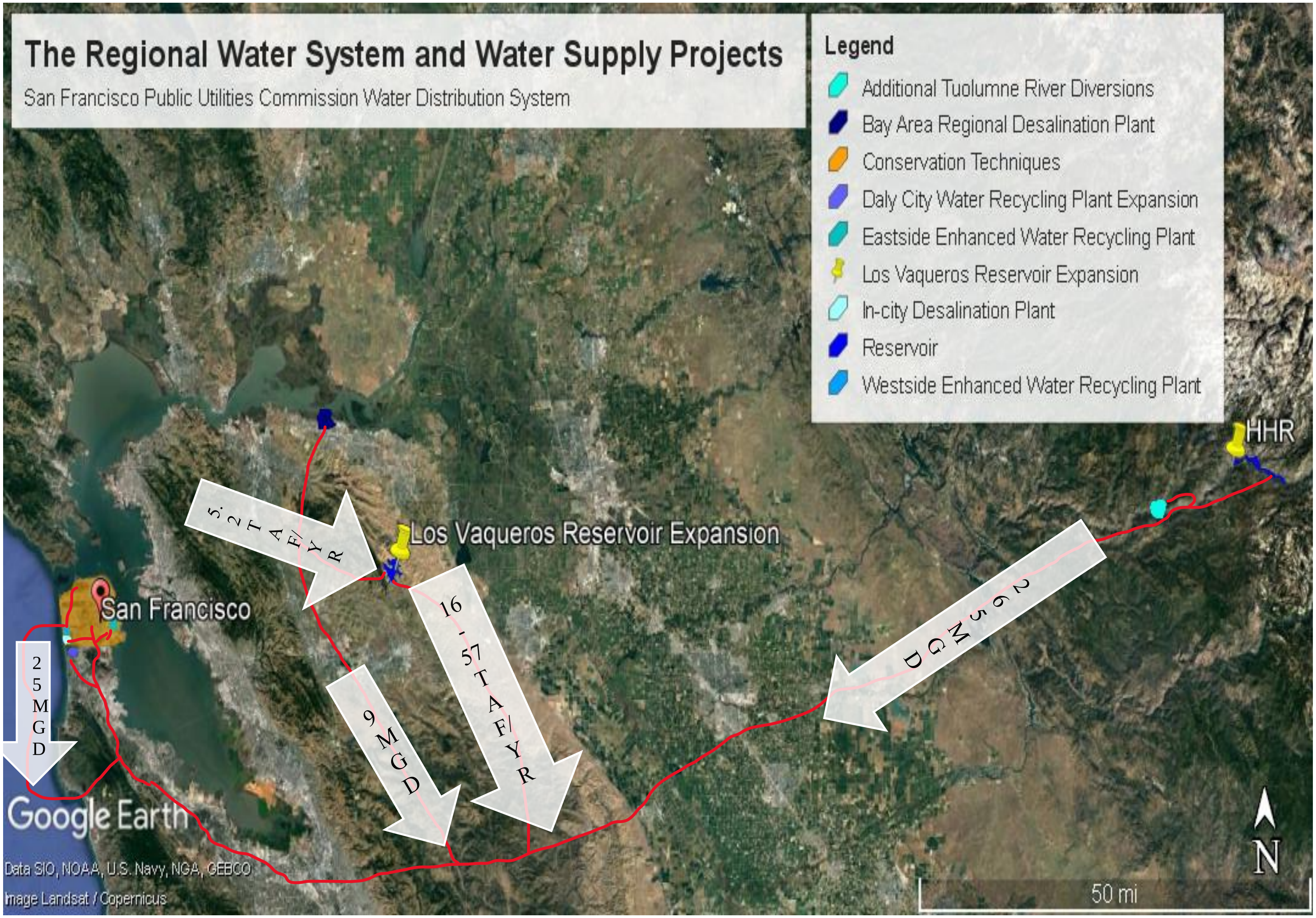

Figure 9. The Regional Water System, the proposed alternative water supply projects with associated yields, and Hetch Hetchy Reservoir (HHR) water deliveries.

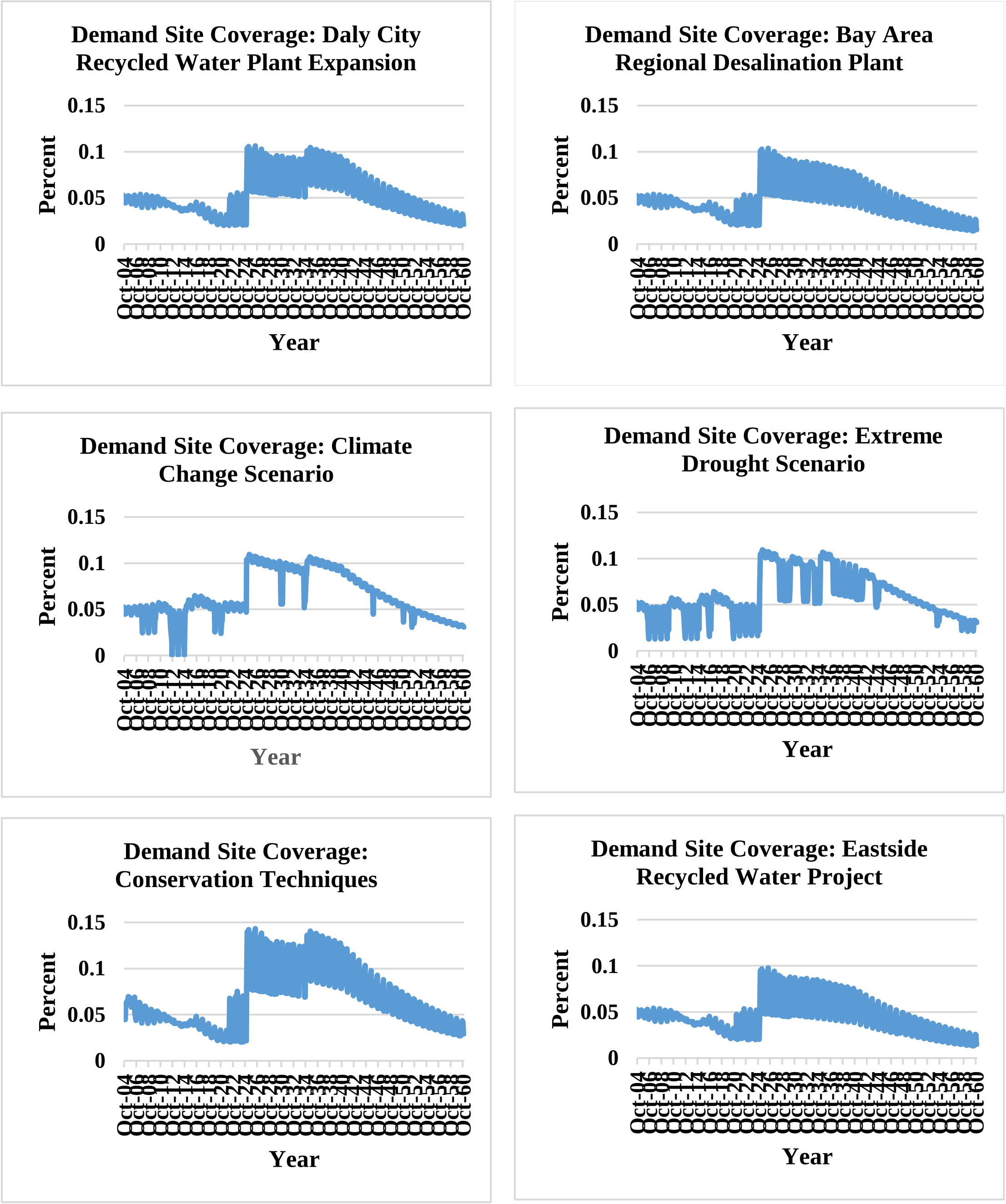

Figure 10. The demand site (retail customers) coverage for the scenarios and alternative water supply projects.

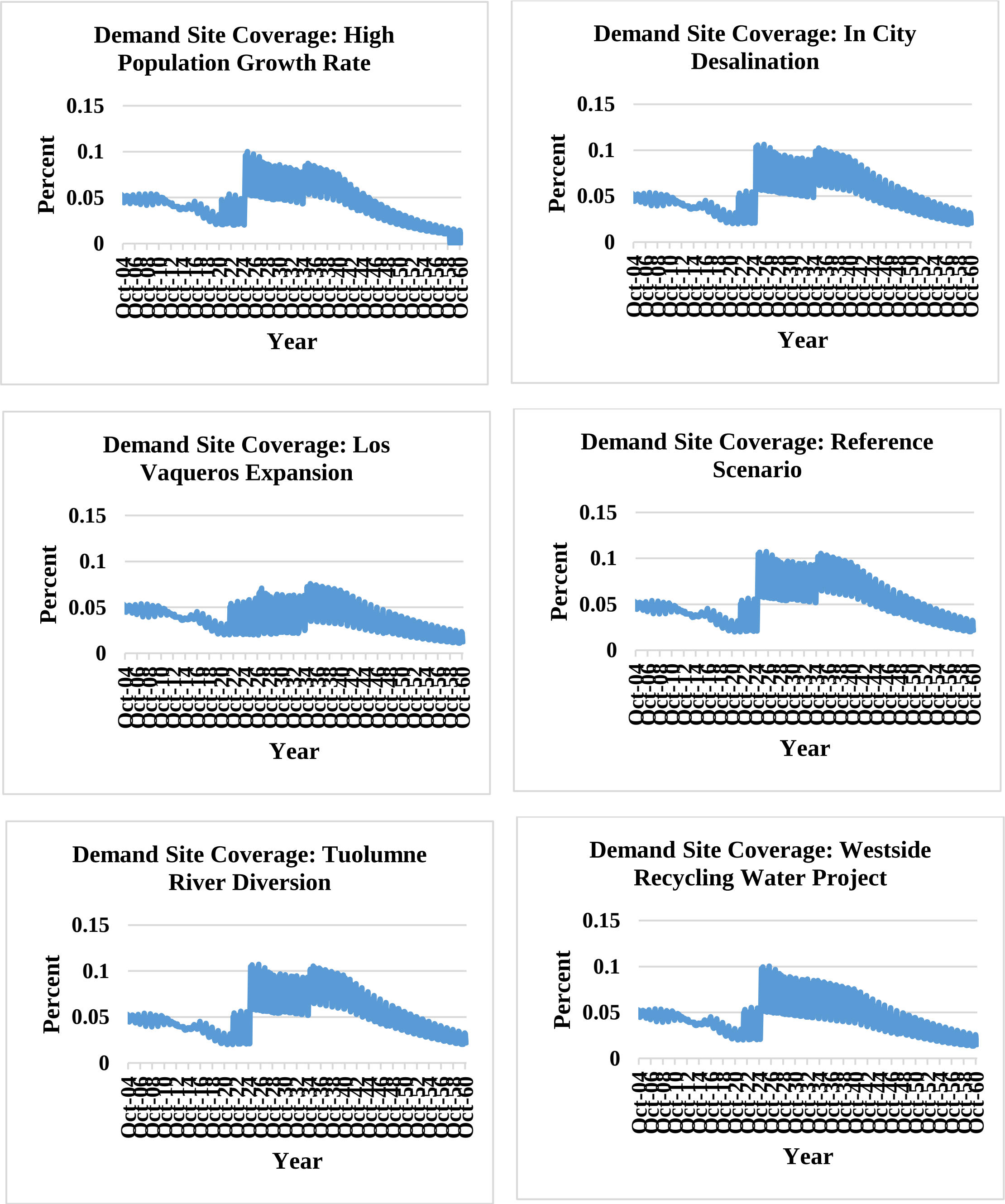

Figure 10-1. The demand site (retail customer's) coverage for the scenarios and alternative water supply projects.

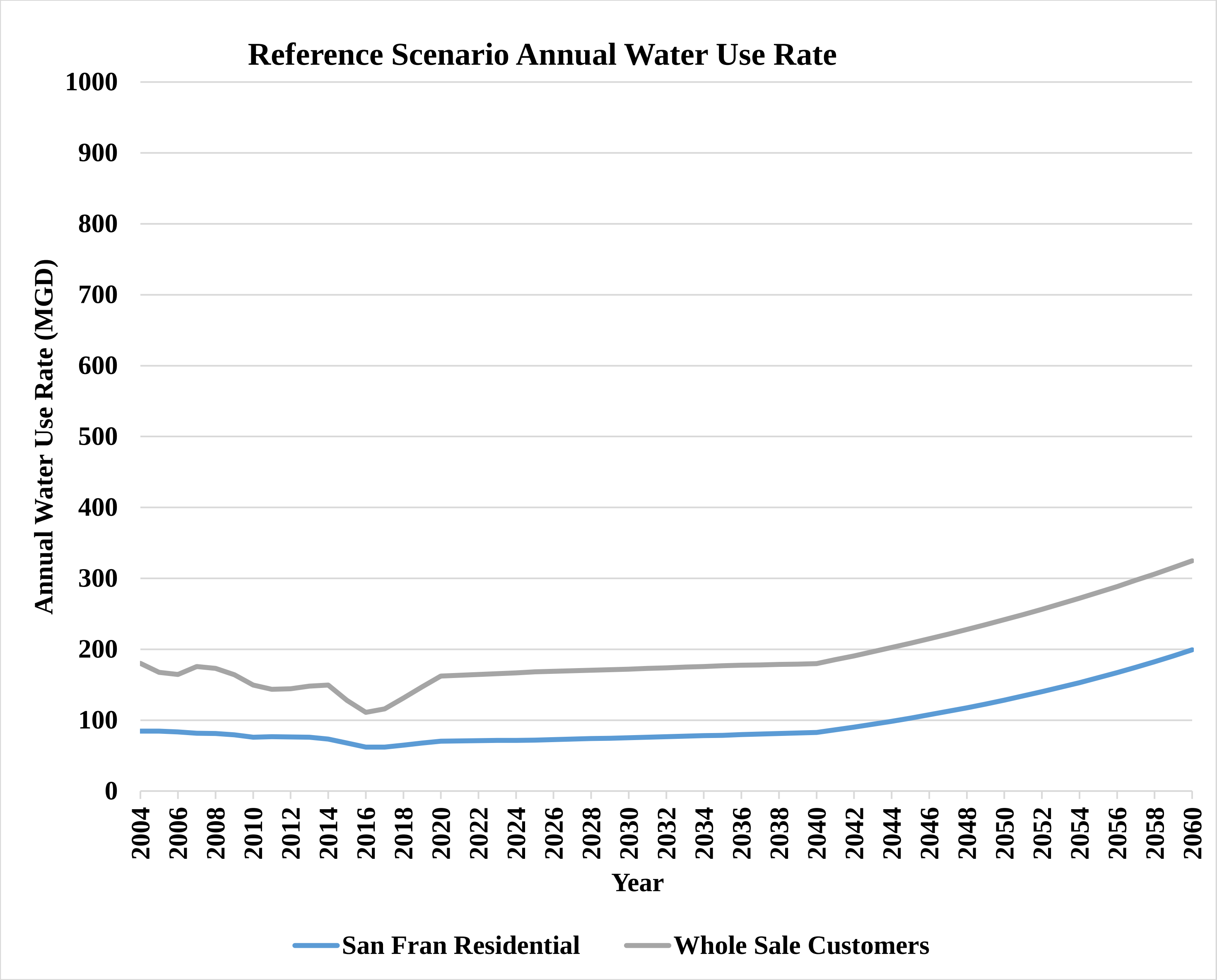

Figure 11. The annual water use rate for San Francisco Public Utilities Commission's wholesale and retail customers under normal projections for the years 2004-2060.

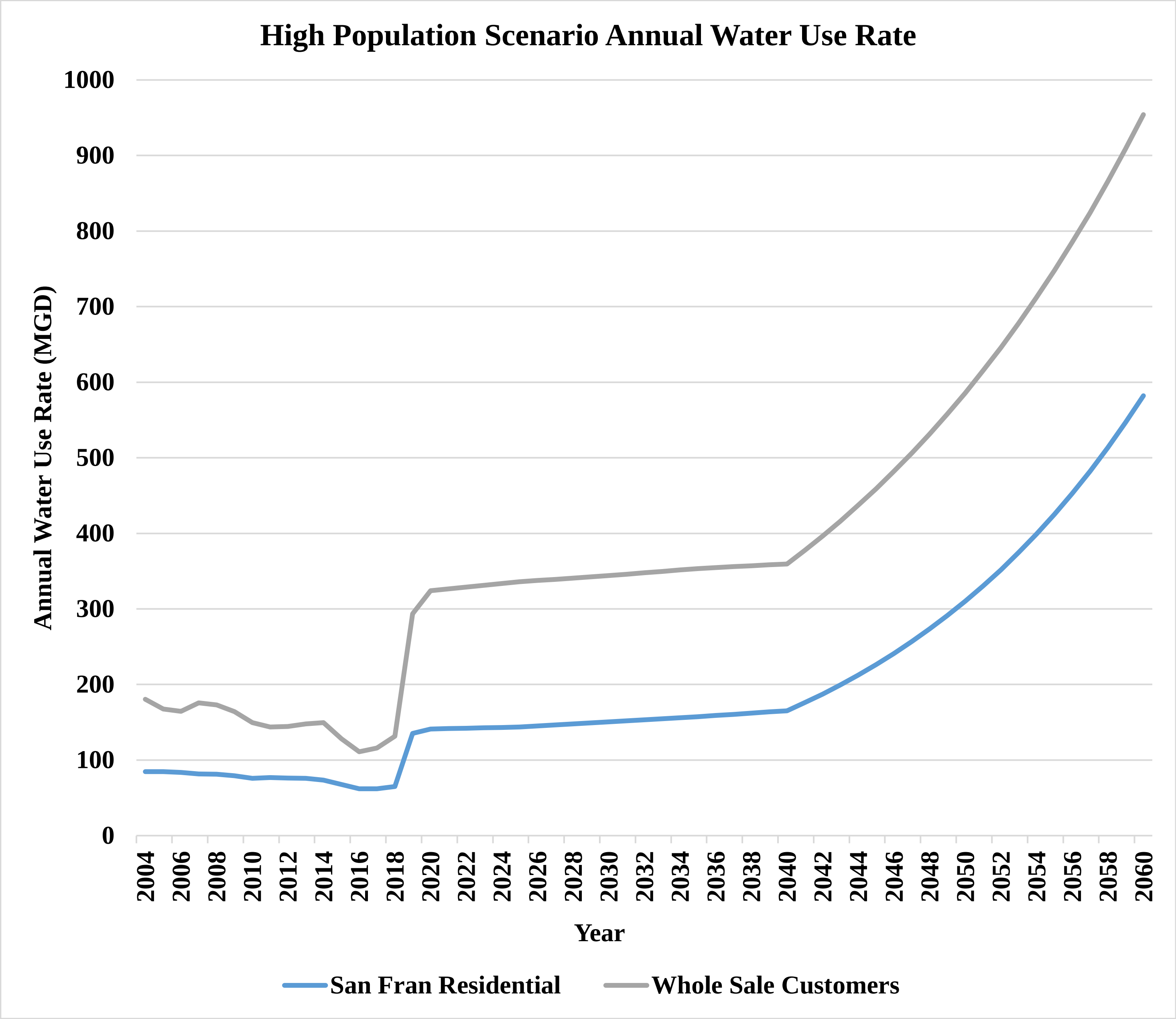

Figure 12. The annual water use rate for San Francisco Public Utilities Commission wholesale and retail customers for under the population growth scenario for the years 2004-2060.

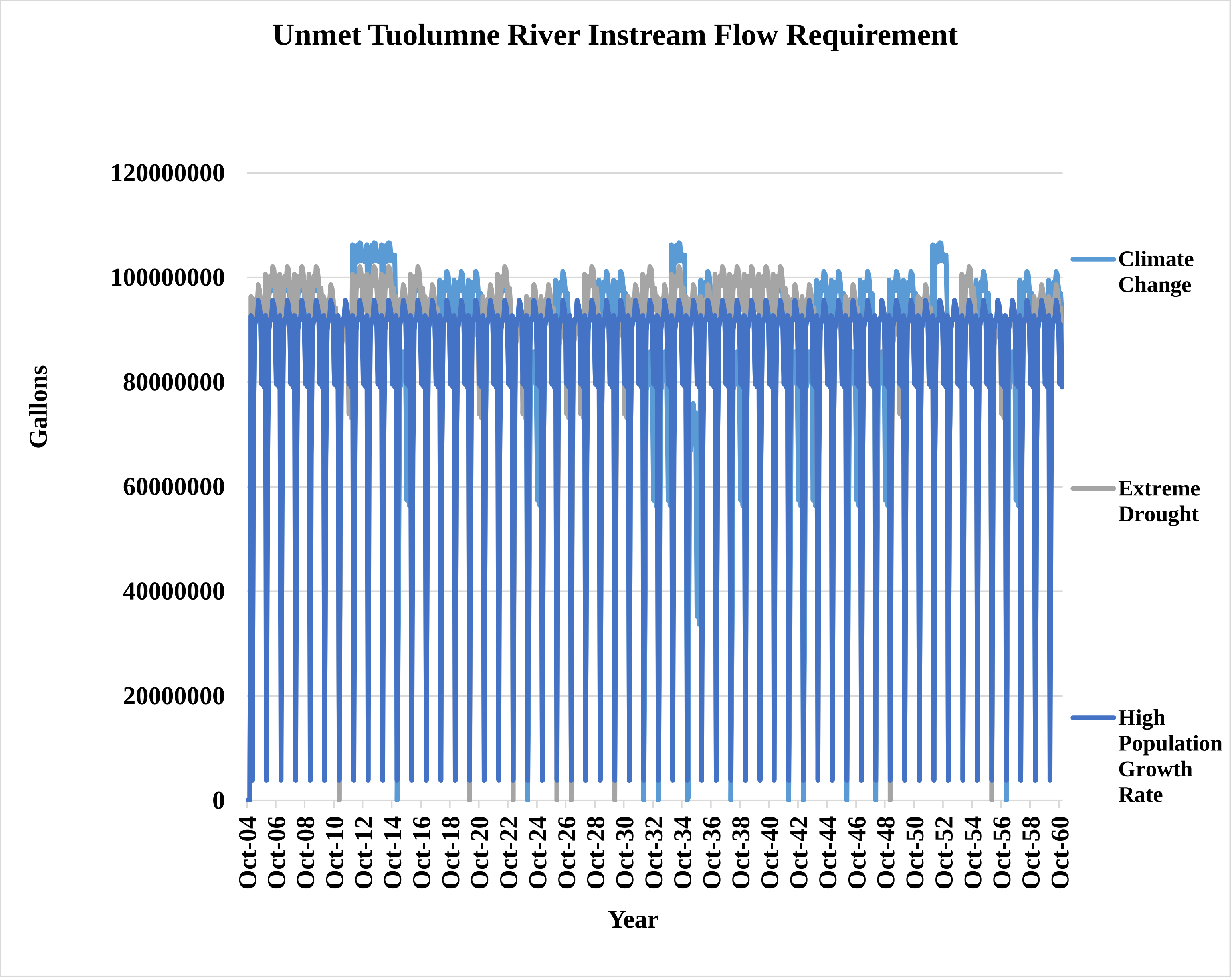

Figure 13. SFPUC’s unmet instream flow requirements for the Tuolumne River during the climate change, high population growth rate, and extreme drought scenarios.

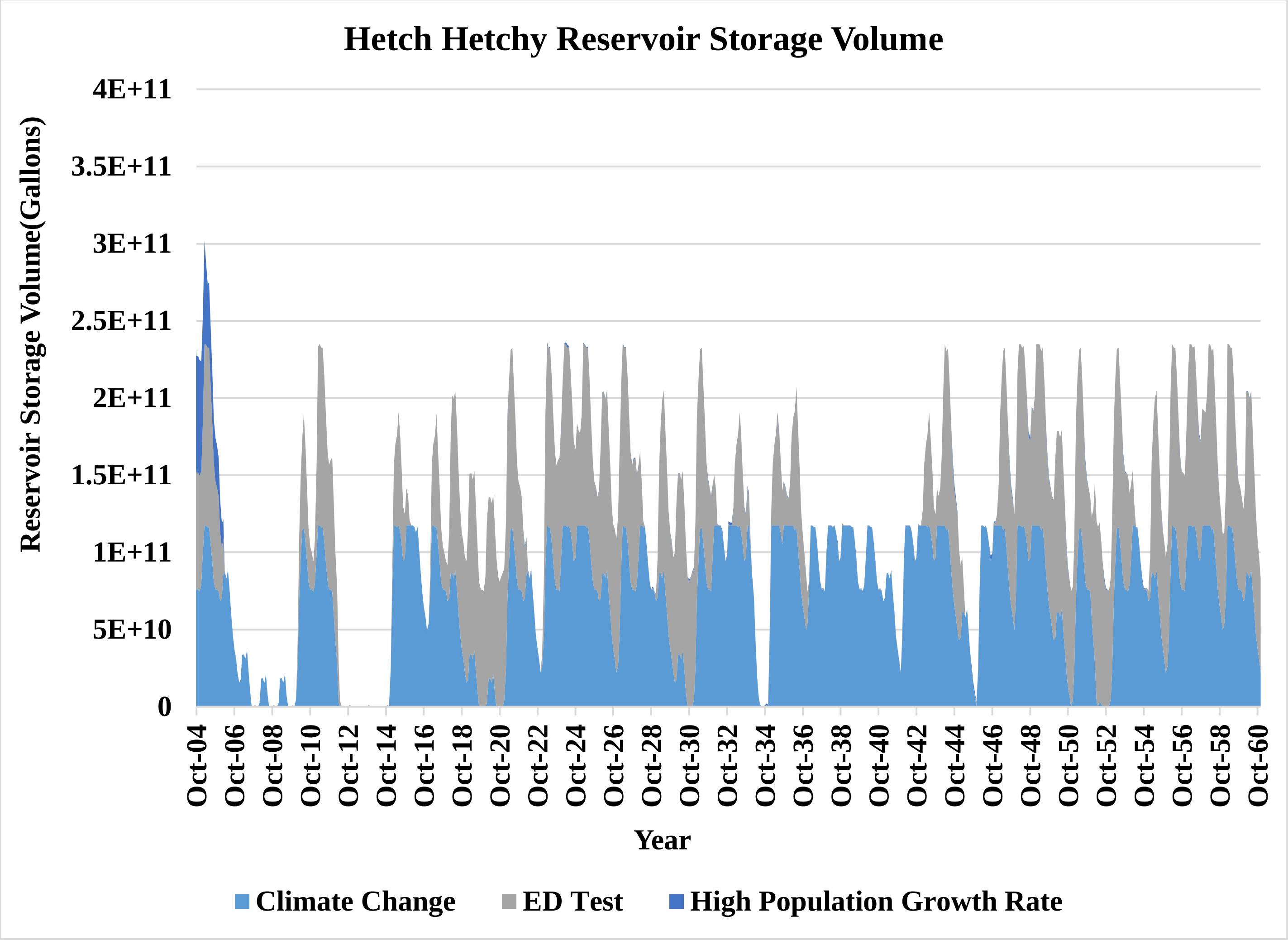

Figure 14. The Hetch Hetchy reservoir storage volumes over the 2004-2060 period for the climate change, extreme drought, and high population growth scenarios.

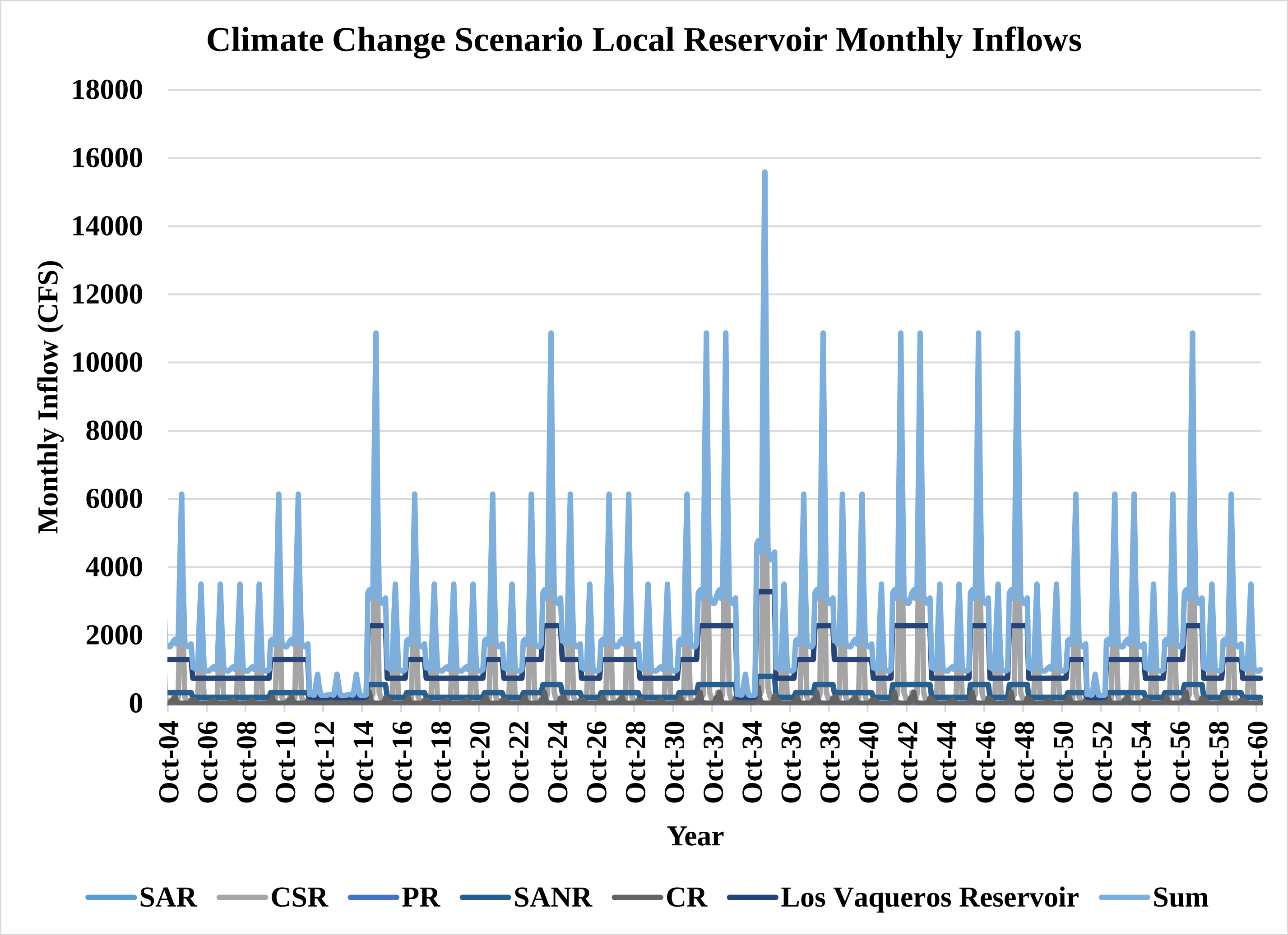

Figure 15. The local reservoir monthly inflows for the San Antonio, Crystal Springs (upper and lower), Pilaricitos, San Andreas, Calaveras, Los Vaqueros and a summation of all reservoir monthly inflows under the climate change scenario.

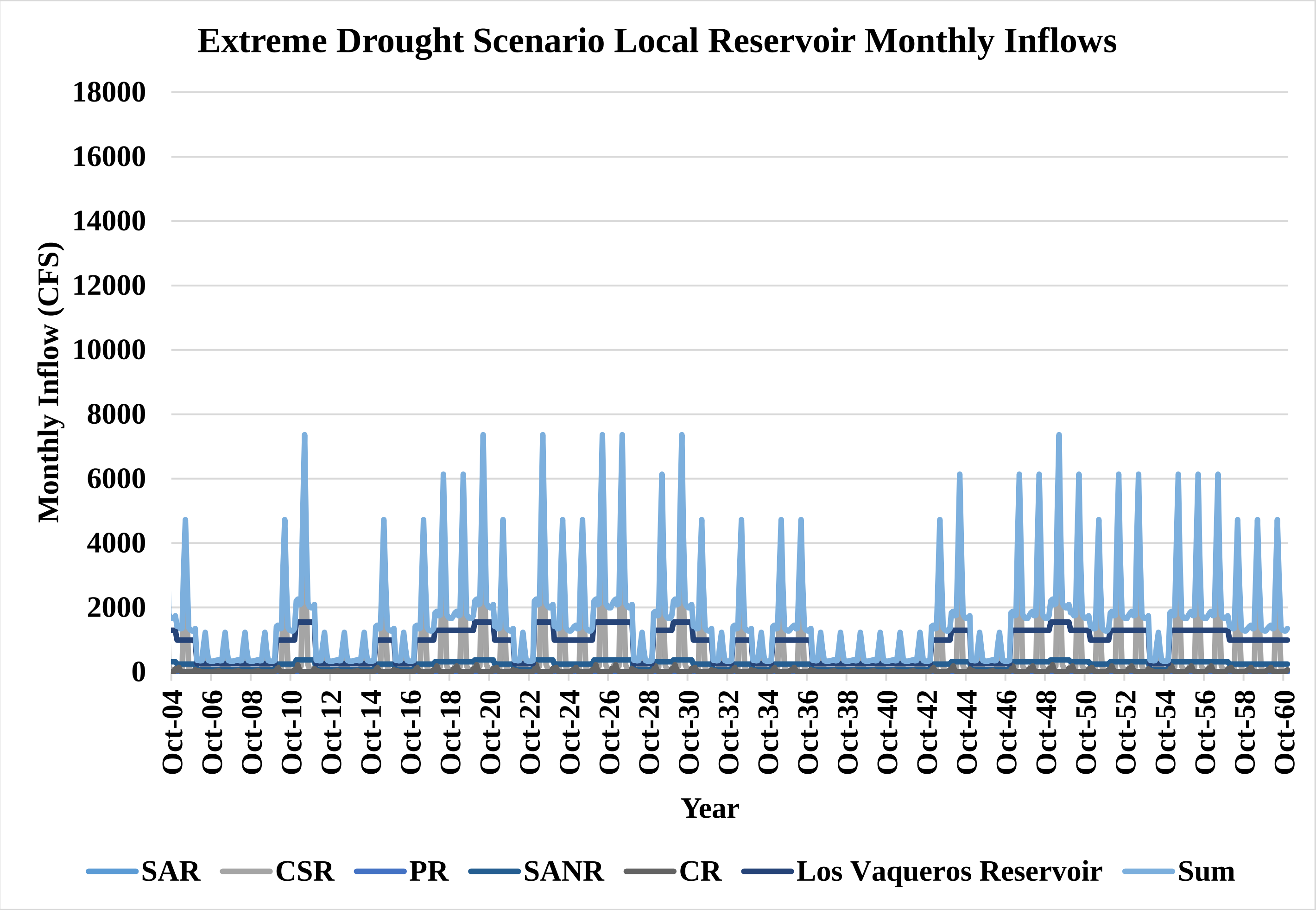

Figure 16. The local reservoir monthly inflows for the San Antonio, Crystal Springs (upper and lower), Pilaricitos, San Andreas, Calaveras, Los Vaqueros and a summation of all reservoir monthly inflows under the extreme drought scenario.

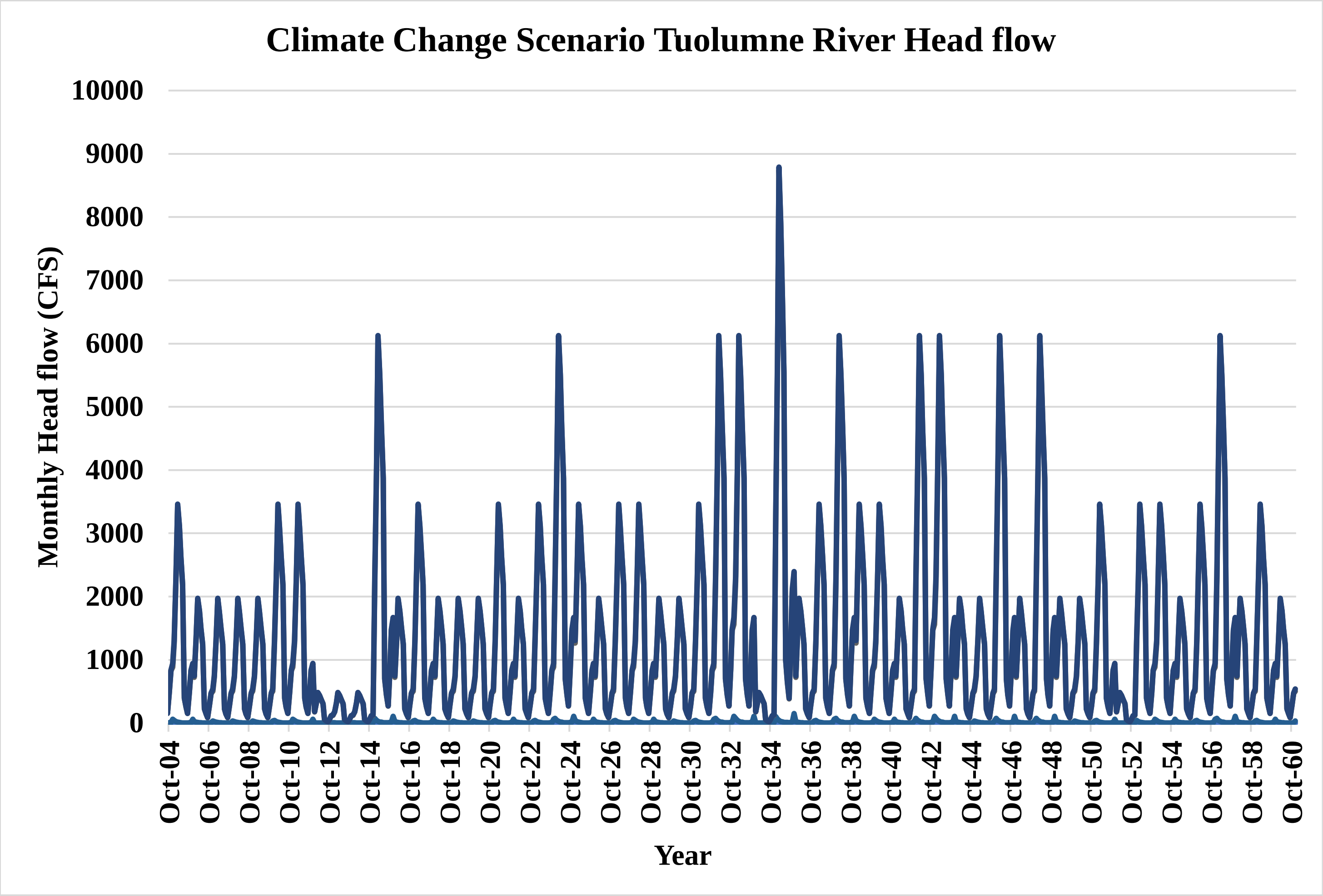

Figure 17. The Tuolumne River head flow over the project period 2004-2060 under the climate change scenario.

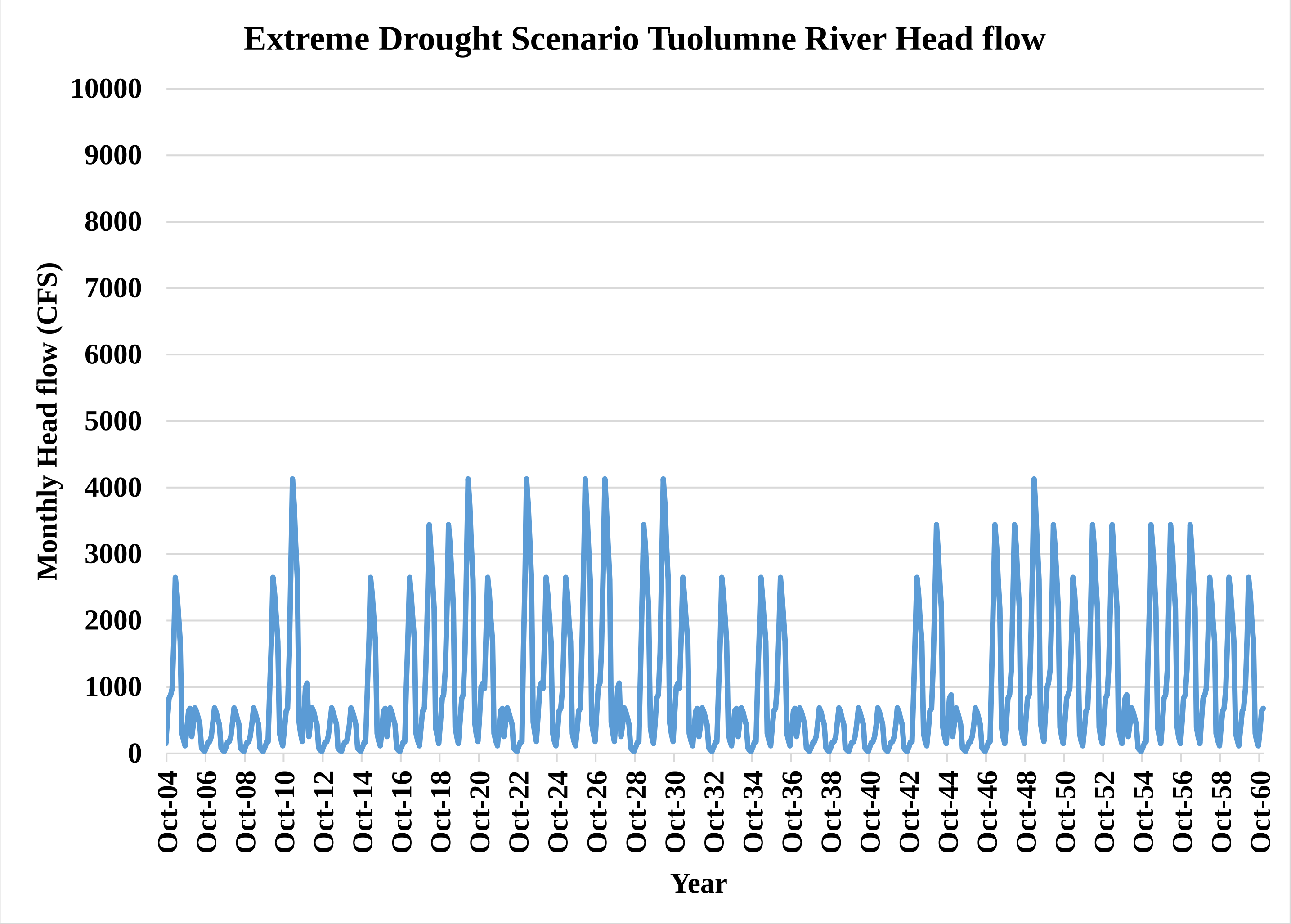

Figure 18. The Tuolumne River head flow over the project period 2004-2060 under the extreme drought scenario.

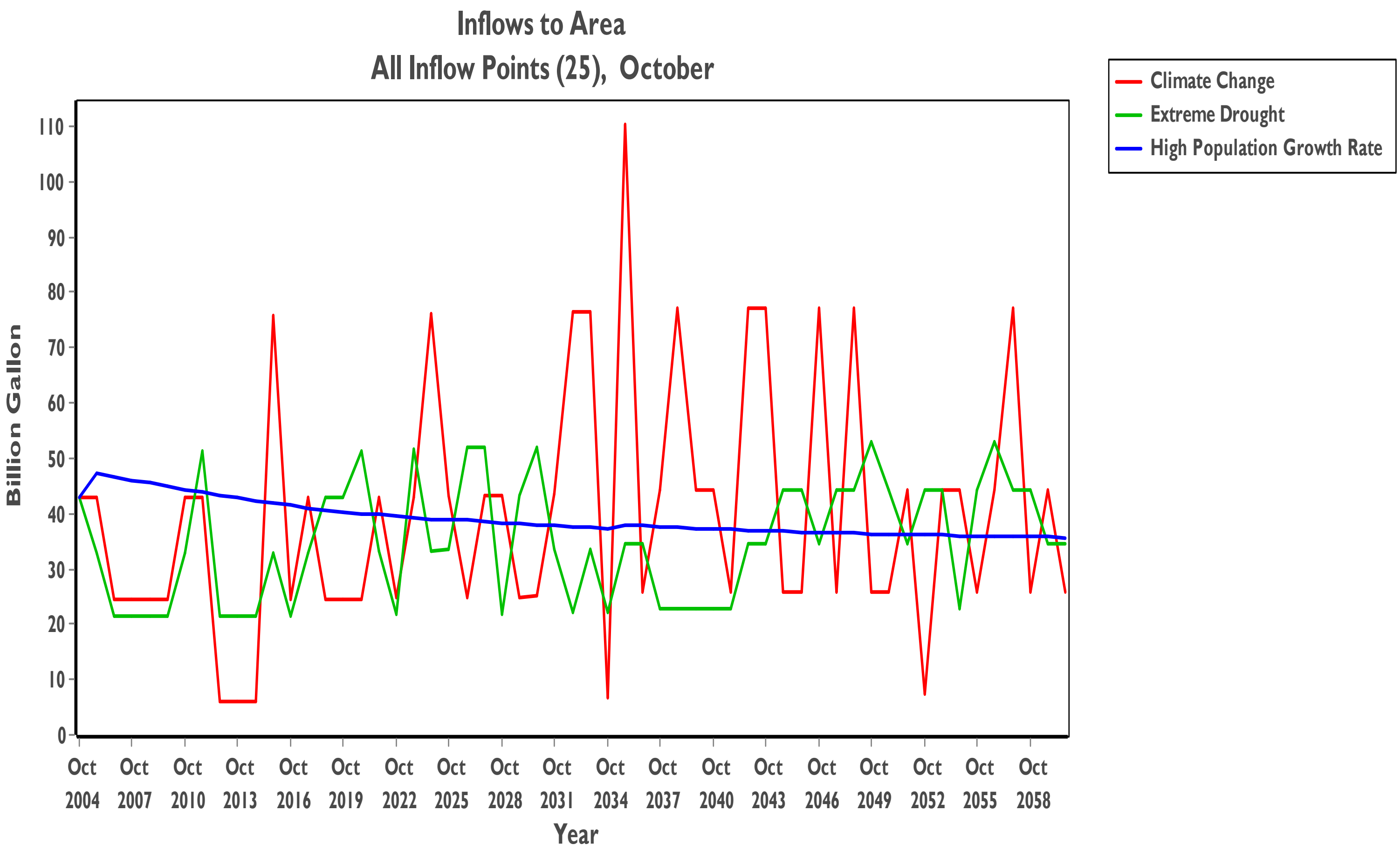

Figure 19. Inflows to both the wholesale and retail customers for the climate change, extreme drought, and population growth scenario.

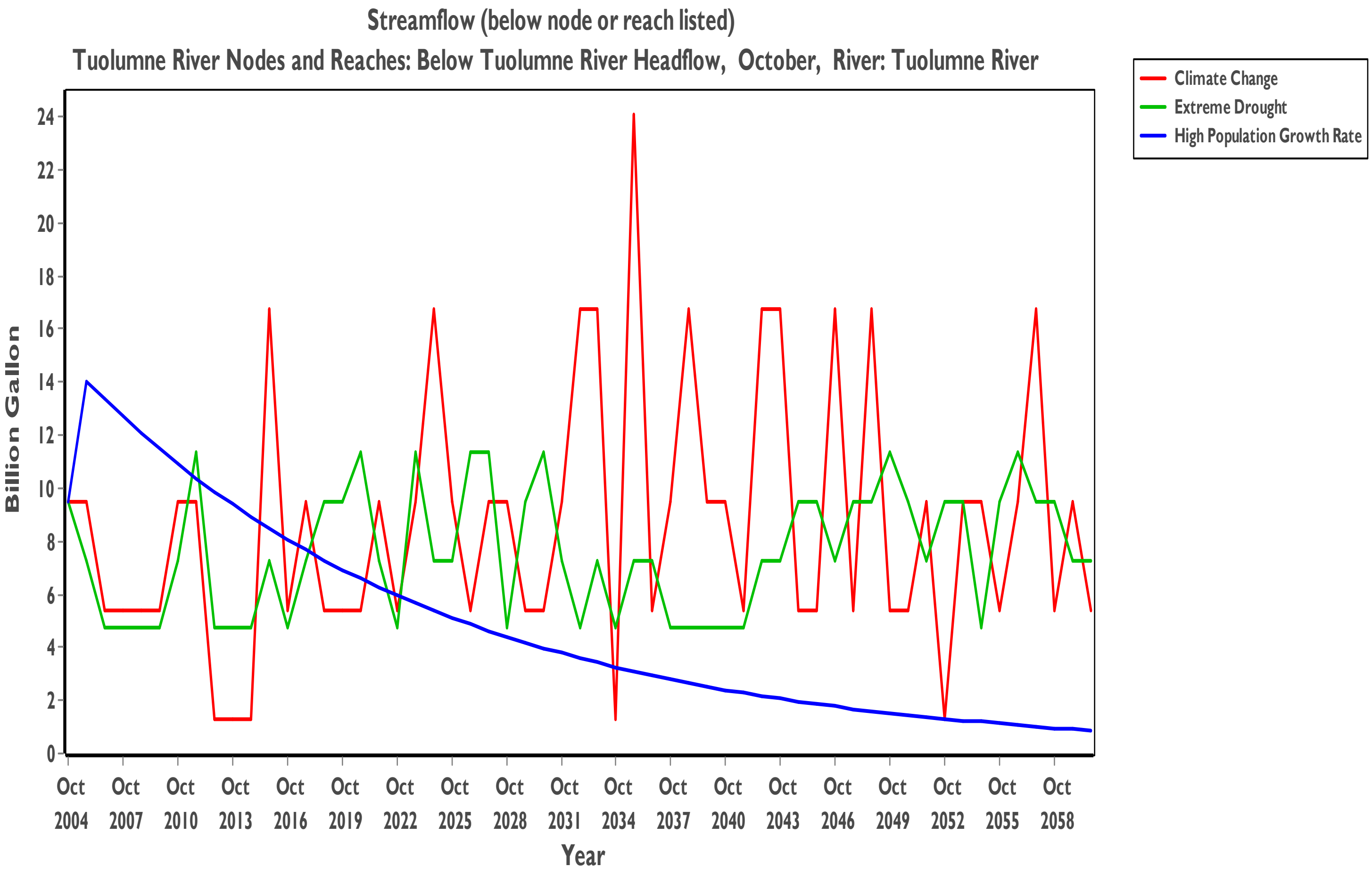

Figure 20. Streamflow below the head of the Tuolumne River is displayed above for the climate change, extreme drought, and high population growth scenarios.

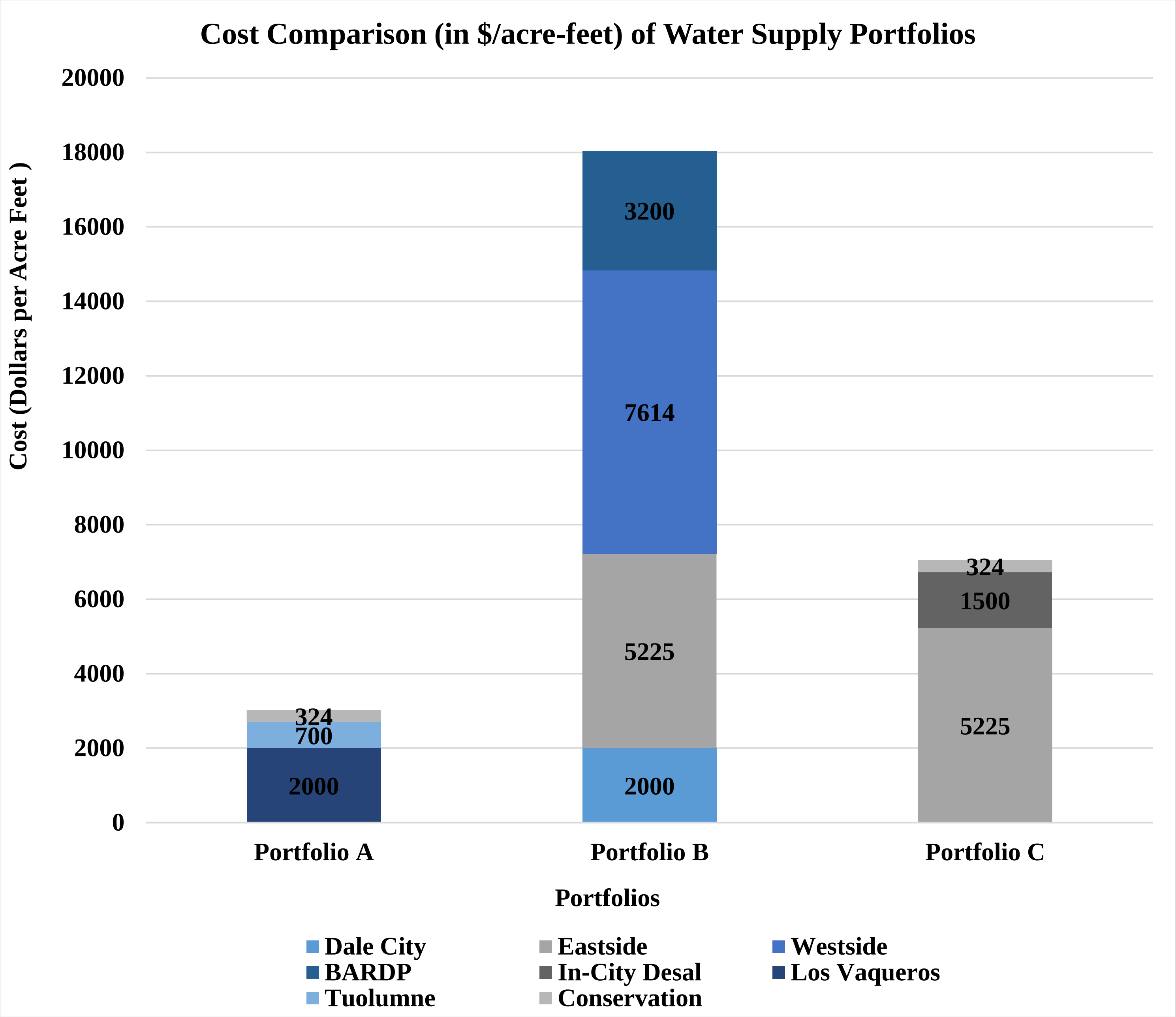

Figure 21. Three potential portfolios composed of a combination of different alternative water projects with the portfolios associated cost.

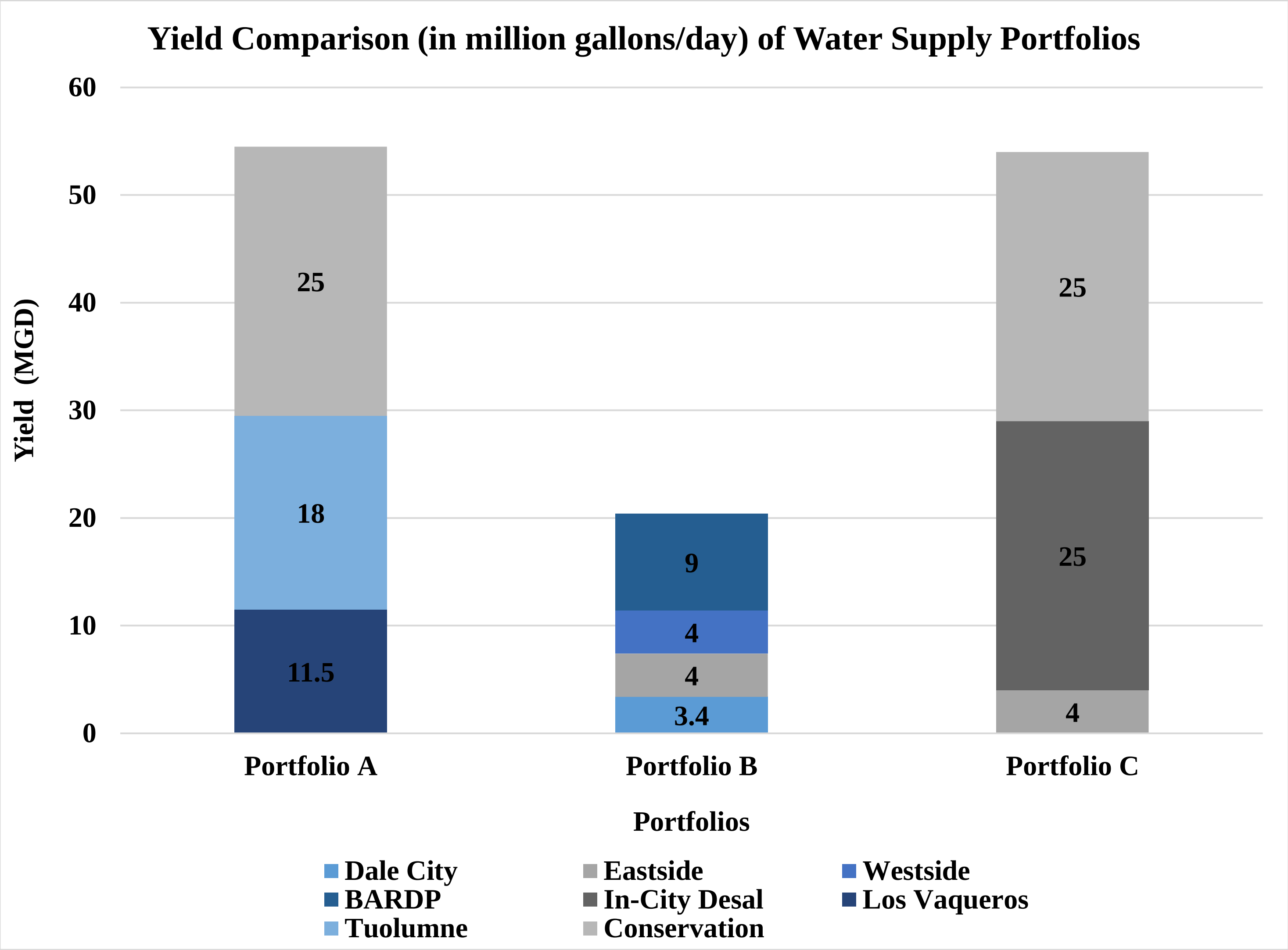

Figure 22. Three potential portfolios composed of a combination of different alternative water projects are depicted above with the portfolios associated yield.

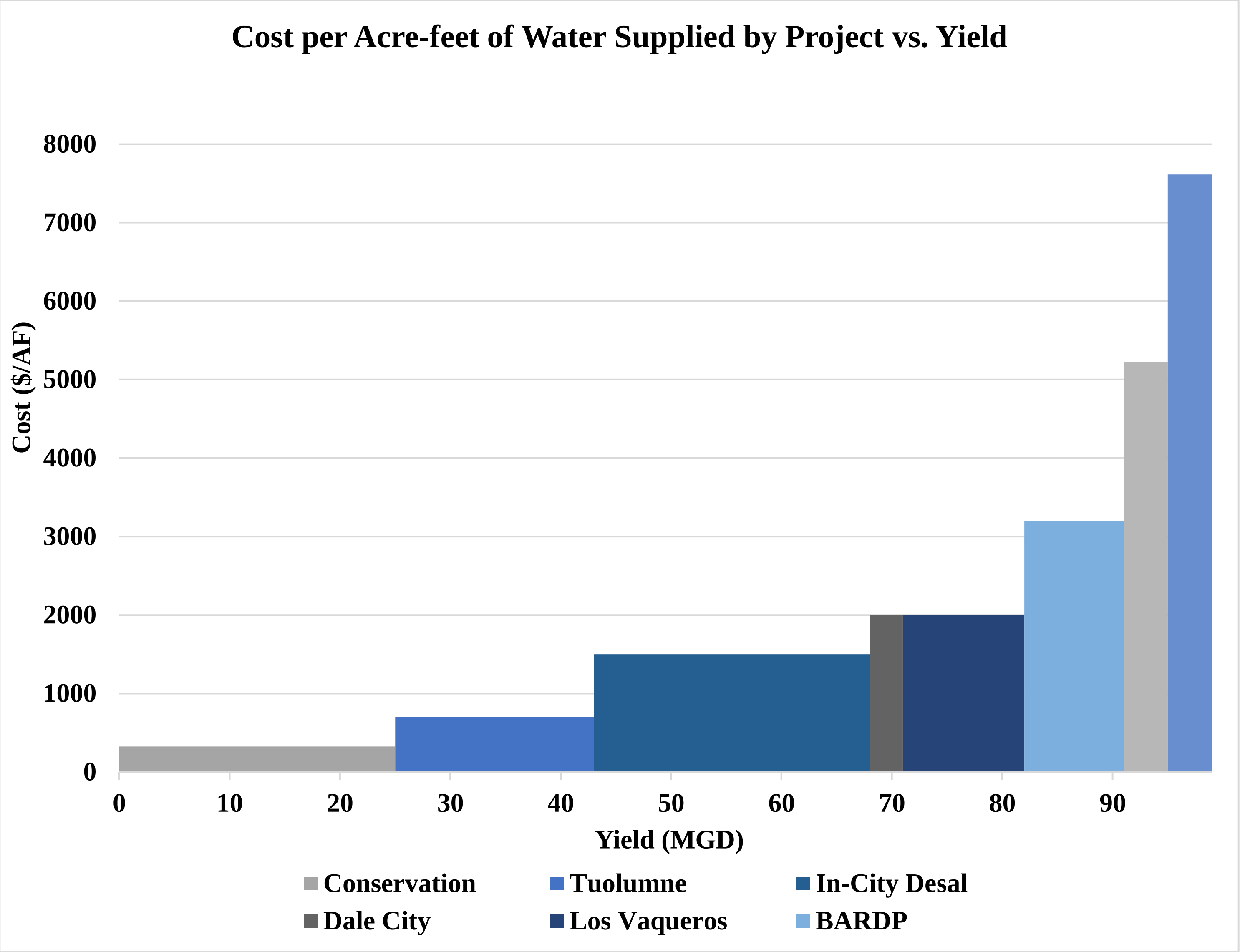

Figure 23. The yield and cost for each alternative water supply project.

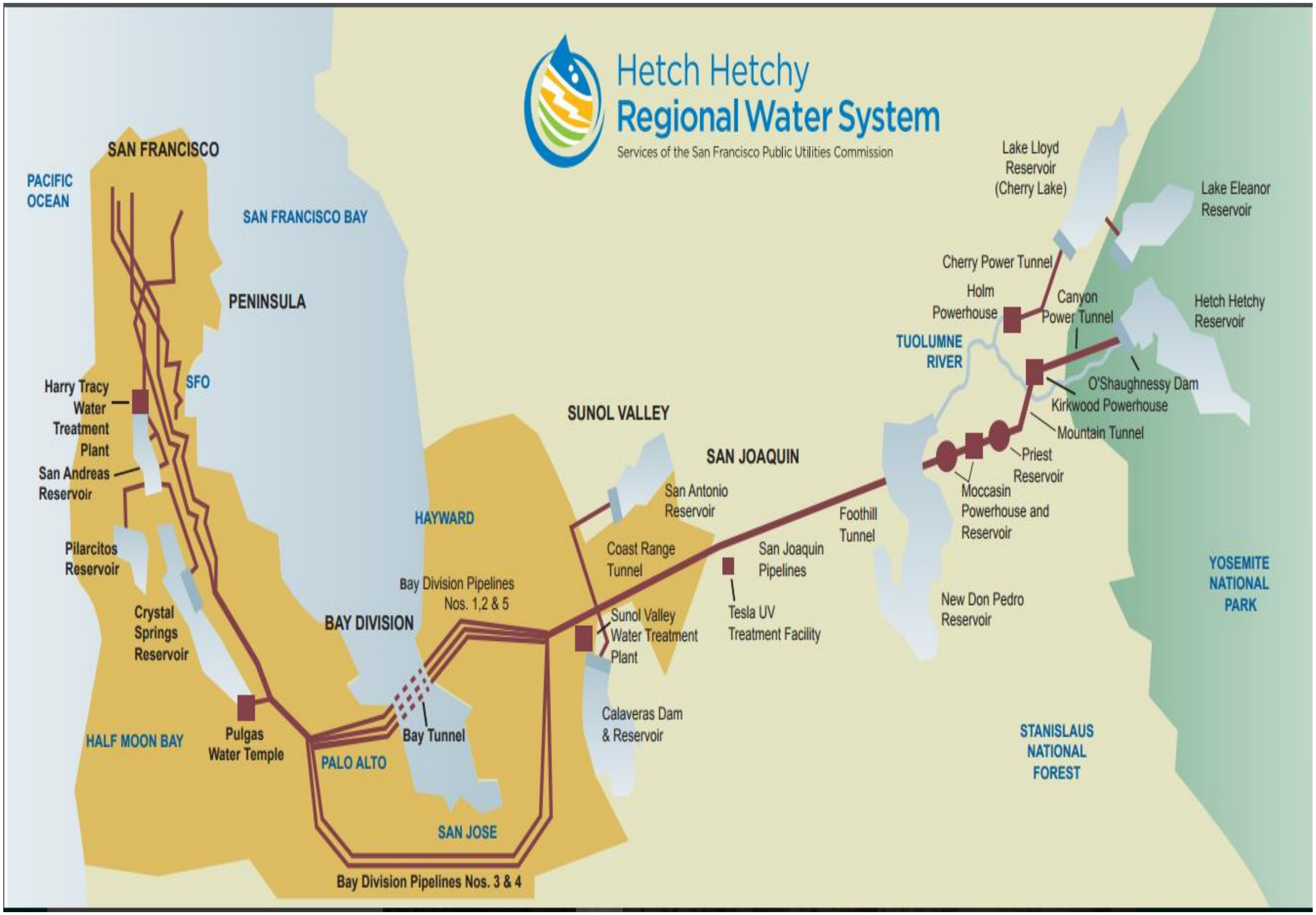

Figure 1. The Regional Water System Configuration. The water distribution system for San Francisco Public Utilities Commission Customers. Source: SFPUC, 2016. https://sfwater.org/index.aspx?page=355

Table 1. Assumptions and descriptions of drought resilience metrics, which are related are partially adapted from the National Academy of Science definition of resilience and (Connelly et al., 2017) Table 1.

Metric (NAS resilience features)	**Description**	**Associated Factors**	**Possible Score out of 55 points**	**Score Breakdown (per associated factor)**
Plan	Focuses on the critical water distribution system functions (conveyance of water to customers)	Institutional aspects	10	2
		Water distribution system reliability		2
		Cost		2
		Water yield		2
		Implementation Time		1
		Project location		1
Absorb	Focuses on thresholds, positive and negative feedbacks, intrinsic threshold of water supply alternatives to disturbance	Redundancy	15	3
		Drought frequency threshold		4
		Demand site coverage		5
		Supply stress[a]		3
Recover	Focuses on time and scale of drought disturbance and how long the performance of the urban water system is degraded.	Degradation time (years)	20	7
		Max water supply degraded		8
		Supply diversity[b]		5
Adapt	Focuses on adaptive management and re-organization of water distribution system after drought. Re-evaluating or re-defining plans, policies, and approaches.	Capacity augmentation[c]	10	5
		Diversity of structures sizes		2
		Connectivity to Regional Water System		3

[a, b, c] Terms/concepts adapted from the (Gonzales and Ajami, 2017) study, Table 2 that focused on quantitative metrics used in Bay Area Water Supply and Conservation resilience assessment. The characteristics of these terms were altered for this study.

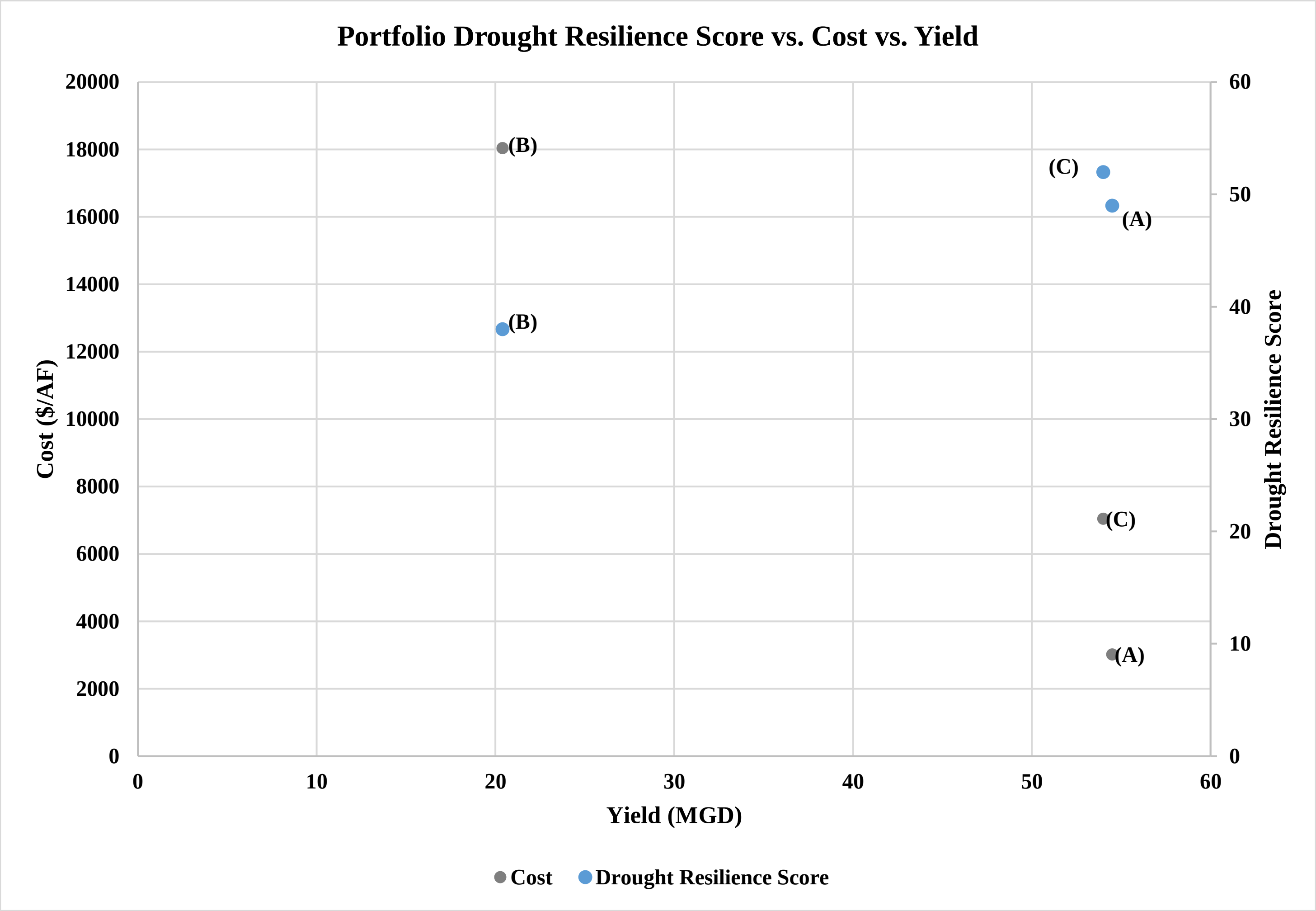

Figure 2. Comparison of portfolio drought resilience scores with each portfolio's associated cost and yield. The portfolios labeled in graph: (A) Modifying Existing Supply, (B) Recycling and Desalination, and (C) Local Approaches.

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