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Energy Intensity Variation Among California Urban Water Supplies

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How are California's water supplies going to shift and what effect will this have on the energy intensity of urban water supplies?

PROJECT COVER PAGE

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Table of Contents

I. INTRODUCTION 3

II. BACKGROUND 9

A. DEFINING THE WATER-ENERGY NEXUS 9
I. THE WATER-ENERGY NEXUS IN THE U.S. 10
II. THE WATER-ENERGY NEXUS IN CALIFORNIA 13
B. CALIFORNIA'S WATER DEMAND AND SUPPLY 16
I. LONG-DISTANCE WATER CONVEYANCE 21

III. METHODOLOGY 24

A. SELECTION OF WATER PROVIDERS 24
B. DATA COLLECTED 29

IV. RESULTS AND ANALYSIS 33

A. THE CITY OF EUREKA 34
B. THE CITY OF MODESTO 37
C. THE CITY OF SAN FRANCISCO 40
D. THE CITY OF LOS ANGELES 41
E. SUMMARY 44

V. RECOMMENDATIONS 46

VI. CONCLUSION 49

VII. LIST OF REFERENCES 50

I. Introduction

In late 2011, California entered into what would become the longest drought in state history. This drought would result in approximately $3.8 billion in statewide economic losses and last almost 8 years (National Geographic Society, 2019). In March 2019, rainfall and snow conditions stabilized to levels at or above normal, correcting the offset balance of water demand and supply throughout the state. California has experienced droughts similar to 2011-2019 in the past (Figure 1). Warmer temperatures and more variable rainfall associated with climate change are anticipated to make drought events more frequent and sever in California (Bedsworth, Cayan, Franco, Fisher, & Ziaja, 2018). Figure 2 shows that California experiences water stress on an annual basis, particularly in the southern and central regions of the state. The water stress indicated in Figure 2, shows areas where the available surface and groundwater supplies are not able to meet the water withdrawals. California has developed management strategies to deal with water resource shortages, such as reusing water, long distance water conveyance, and desalination technologies, enabling California to diversify its supply away from solely local ground and surface water (Department of Water Resources, 2019). However, water supply diversification strategies can have the unintended consequence of increasing the water systems energy use and subsequently the associated greenhouse gas emissions. This study investigates how California's water supply is going to diversify and what effect this will have on the energy intensity of urban water supplies.

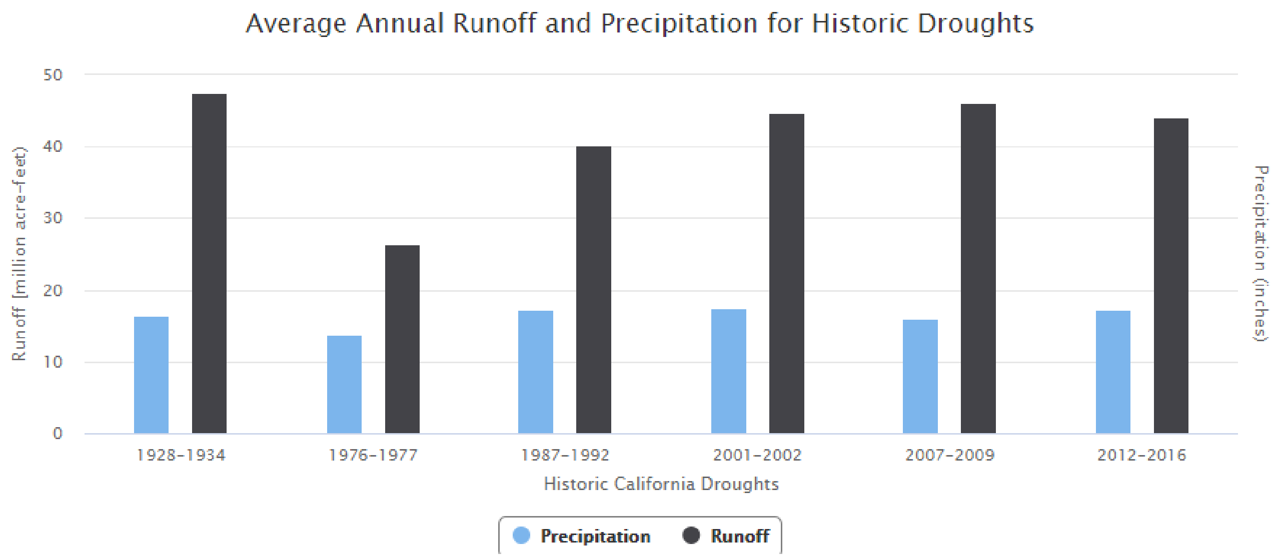


Figure 1. Runoff and precipitation totals for CA drought years. (United States Geological Services, 2020)

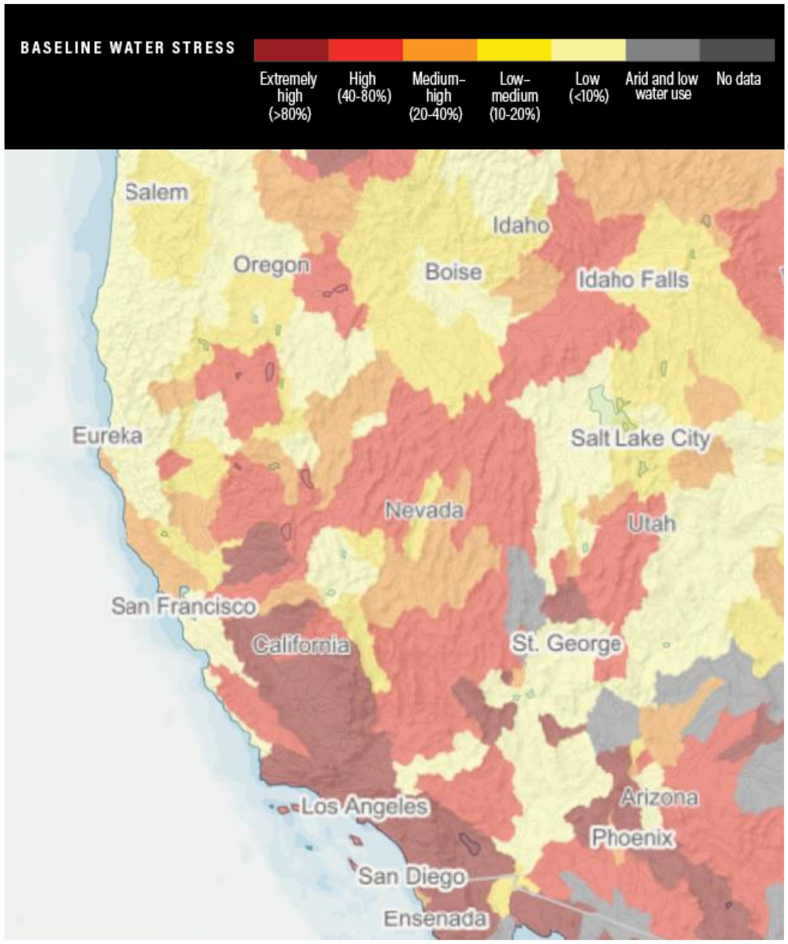


Figure 2. Extreme water stress in the central and southern regions of California. (World Resource Institute, 2019)

The energy requirements of California's water system are one component of a complex web of interconnections between water and energy systems. This web of connections is called the Water-Energy Nexus (WEN) and Figure 3 provides a visual for some of the interconnections and competition that exist within the WEN. The WEN is the idea that water requires energy and energy requires water for both resources to be processed and consumed in modern day society (Chen, Roy, & Goldstein, 2013; Hamiche, Stambouli, & Flazi, 2016; Sanders & Webber, 2012; United States Department of Energy and Water, 2006). Although some aspects of the WEN are more apparent and have been studied in depth, such as the water requirements for energy production, other aspects, like the energy requirements for water production, have only recently been investigated (Badr, Boardman, & Bigger, 2012; Dieter et al., 2018; Escriva-Bou et al., 2018; Klein, Krebs, Hall, & O'Brien, 2005; Sanders & Webber, 2012). The energy demand for water systems across the U.S. is estimated to be 4% of the nation's total, however, in California the water system makes up 20-30% of the state's energy demand (Cooley & Wilkinson, 2012; Copeland, 2014; Klein et al., 2005).

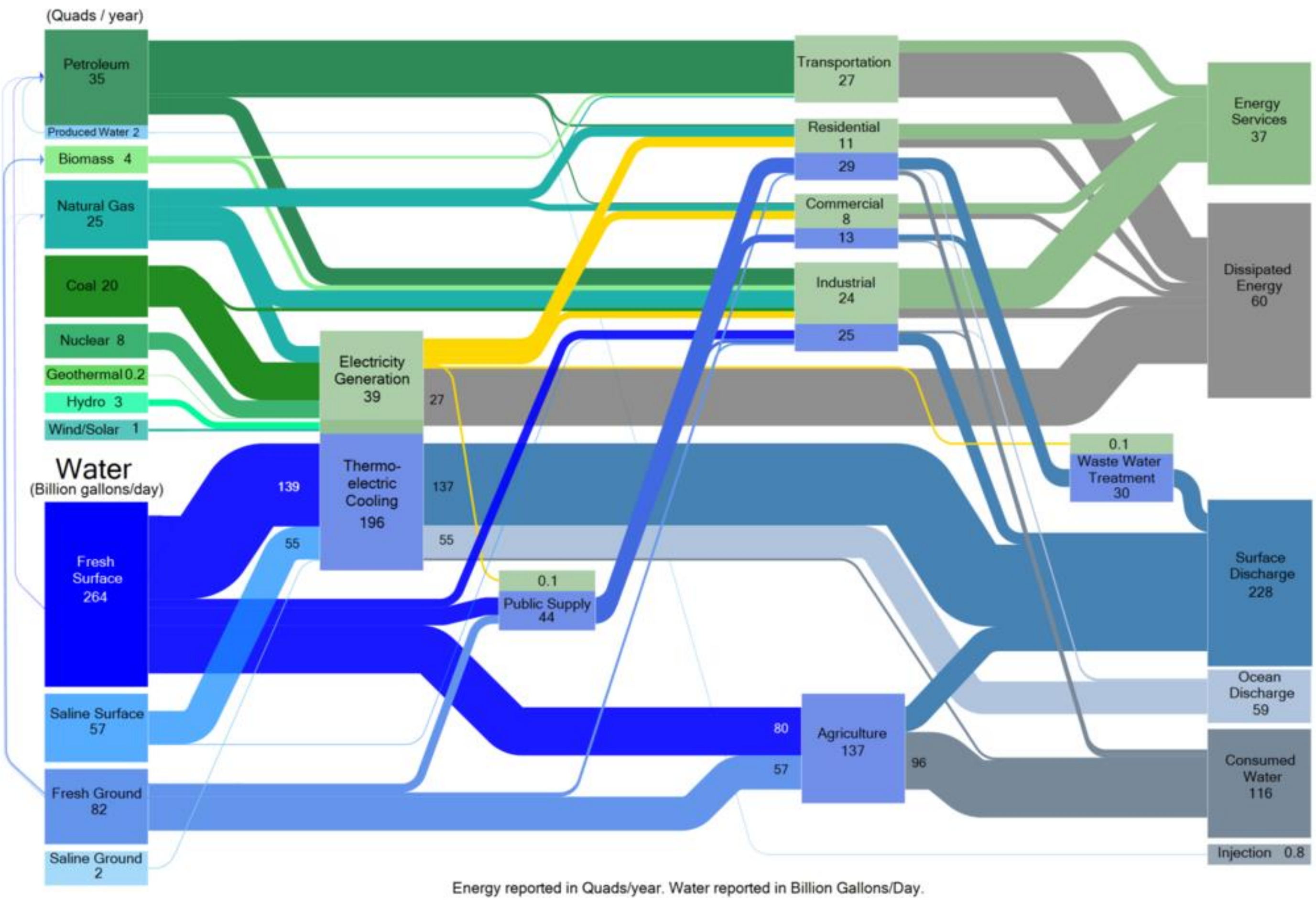


Figure 3. The water-energy nexus of the United States depicted in a Sankey Diagram. (Bauer et al., 2014)

California's water portfolio has developed into a diverse array of supplies as it has faced the challenges of water scarcity (Department of Water Resources, 2019). However, surface water and groundwater still dominate the majority (>50%) of the supply (Figure 4). Urban development in California has often been at odds with available water supply (Los Angeles Department of Water and Power, 2013; J. Null, 2017). As cities continuously develop and populations rise, urban water systems will be challenged to meet the demand. More intense droughts, warmer temperatures, and more variable rainfall will change the hydrology of

California and challenges the ability of urban water supplies to develop sustainable water management strategies (Department of Water Resources, 2019; East Stanislaus Regional Water Management Partnership, 2018; Hendrickson & Bruguera, 2018). This study investigates if and how urban water suppliers are diversifying water supplies to meet projected demands. Solutions range from groundwater recharge and storage, to increased conservation, or to selling water and transporting it to another region (Department of Water Resources, 2019; East Stanislaus Regional Water Management Partnership, 2018; North Coast Resource Partnership, 2020). This study will examine how these solutions compare in terms of energy intensity and how there is significant variation across the regions of California.

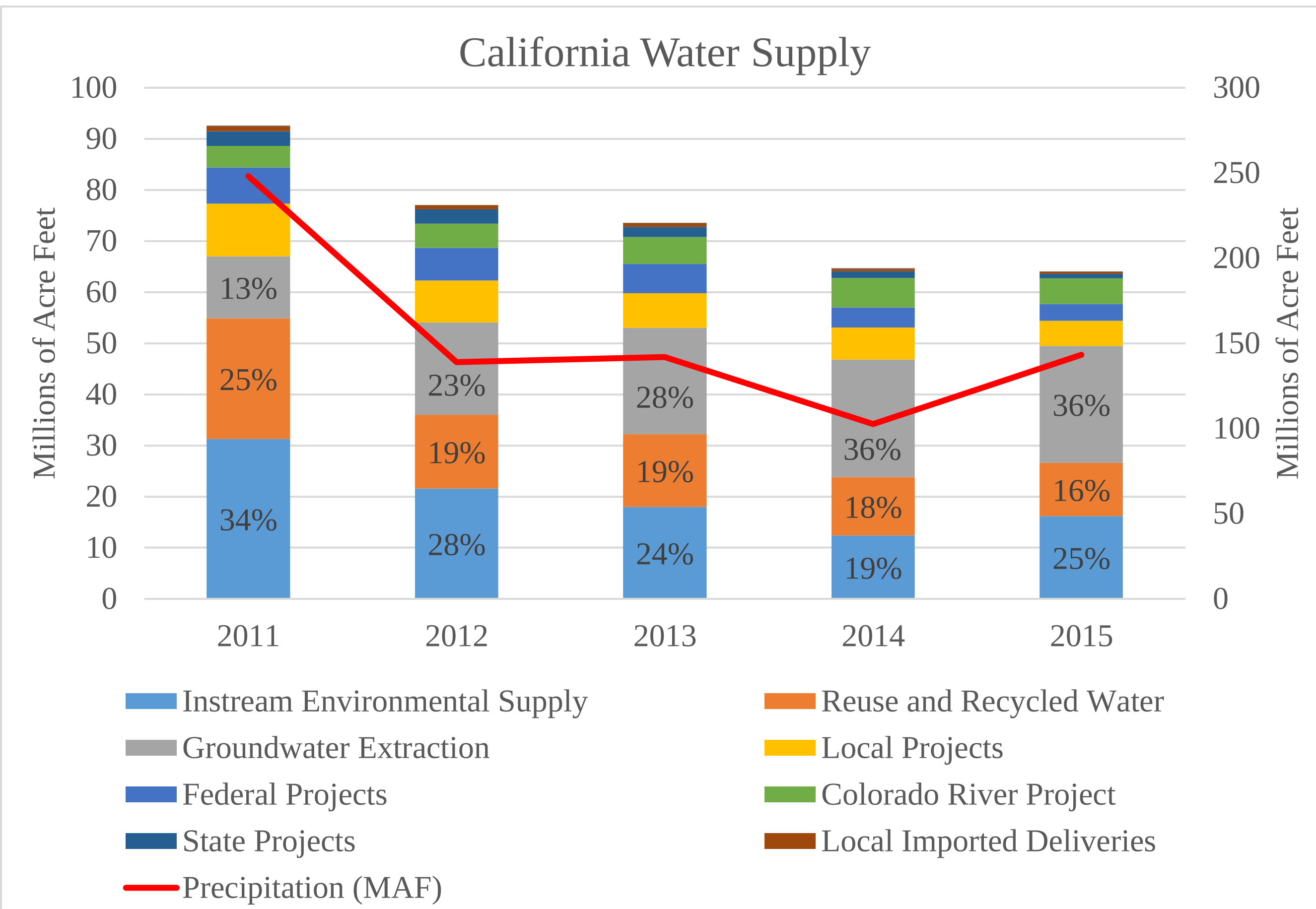


Figure 4. California's diverse water supply portfolio (Department of Water Resources, 2019).

An increase in the energy footprint of California's water system is significant because of the potential greenhouse gas emissions associated with this energy use. It is estimated that

California's water system currently emits 10% of the state's greenhouse gas emissions (Escriva-Bou et al., 2018). As California continues to prioritize climate change mitigation and greenhouse gas reduction in state policy, understanding the high emission factors within water systems will be a key component to compliance (California Air Resources Board, 2014; Weeks, 2020). This paper makes recommendations on how to mitigate increases in energy intensity found within urban water supply systems.

The results of this study found that the variation in California's climate, demographics, and economies greatly affected the development of water supplies throughout the state. The four cities selected for this study did not present a trend or single strategy for preparing their water systems for future availability shifts. Each city's supply was unique to that region and as such, strategies to ensure sustainability varied. The energy intensity of each city's water supply also varied greatly between the cities and while some were predicted to increase others were not. These results highlight the complexity of the California specific WEN and call out the need for further investigation. It also highlights the need for regional level solutions. This is important for policy makers to understand as California endeavors to update its infrastructure and transition to a greenhouse gas free state.

This paper will give an overview of the WEN and how it applies to California's water systems. Included in this will be a description of the research to date on the WEN as well as why California has a higher energy demand associated with its water system. Important to this will be a history of the development of urban centers and water supplies in California's early years. Then a description of the selection process and data gathered using the Urban Water Management Plans from the 4 cities selected for this study will be given. This is followed by a description of the results for how each city's water supply will shift and what the expected change in energy intensity associate with that is. Recommendations are made as to how California can mitigate any increases in the energy intensity of water systems.

II. Background

A. Defining the Water-Energy Nexus

The Water-Energy Nexus (WEN) is a critical component to the management of both energy and water as resources. Separately these resources each face challenges of future strain as population growth increases demand and resource scarcity is exacerbated by climate change. The fourth National Climate Assessment for the United States found that anthropogenic driven changes in climate, resulting in more frequent and intense climate events, would impacts the economy, agriculture, water, infrastructure, and people's health (U.S. Global Change Research Program (USGCRP), 2018). Climate related impacts to infrastructure come in the form of both physical damage to the infrastructure as well as resource shortages (Bauer et al., 2014; U.S. Global Change Research Program (USGCRP), 2018). Drought can impact the ability of power plants to operate their cooling systems without access to water and any shortage or disruption to power can prevent water treatment and distribution systems from operating (Bauer et al., 2014). Infrastructure is ranked as the most critical challenge that urban water suppliers face in the U.S. and the energy infrastructure was given a D+ rating due to aged systems (Aubuchon & Roberson, 2014; Phillips, 2019). The short comings and flaws within the aging infrastructure of state municipalities and service providers will be exacerbated by climate change events (Bauer et al., 2014; Bedsworth et al., 2018). As these systems are re-built to be more resilient and to integrate sustainable resource management strategies, the links between them should be used as an opportunity for innovation.

The WEN represents both a challenge and an opportunity to the management of each resource, because the resources are competitive as well as dependent within the nexus. The matrix in Figure 5 gives examples of the co-dependence in the relationship. The upper left corner labeled "Energy for Water" highlights that the water system is a large consumer of electricity. The lower left labeled "Water for Energy" highlights that both electric and water utilities compete for water at its source. The opportunity that this matrix highlights is shown in the upper right. The "Customer End Use" box highlights that when consumers reduce their use overall, demand of either resource goes down which reduces the competition for both resources (Aubuchon & Roberson, 2014). Less energy being used to produce less water and less water being consumed so less competition for electric utilities to obtain water.

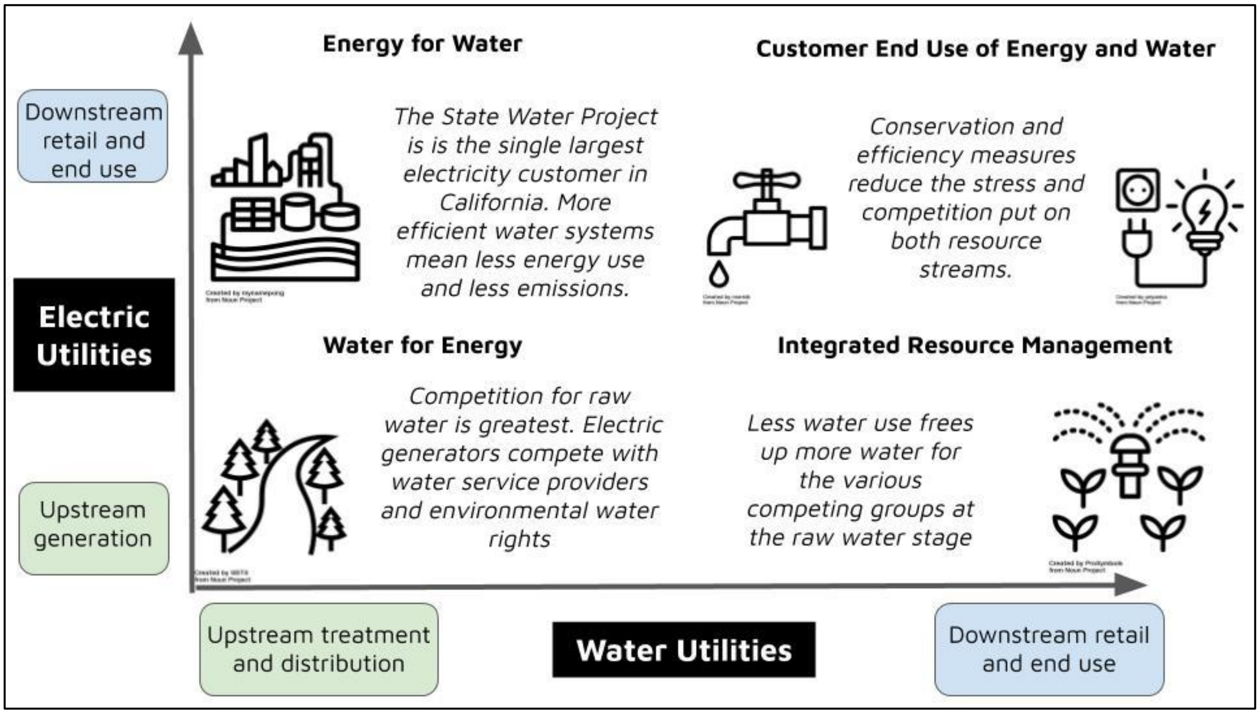


Figure 5. Water and electric utility codependent relationship. Recreated from (Aubuchon & Roberson, 2014)

i. The Water-Energy Nexus in the U.S.

Efforts to research and actually quantify the water-energy nexus began in the early 2000's and were motivated by a need to understand the amount of water used in the energy sector (Electric Power Research Institute, 2002; Hamiche et al., 2016; Murkowski, 2014; United States Department of Energy and Water, 2006). Thermoelectric power generation has accounted for anywhere from 30-50% of freshwater withdrawals in the United States as early as the 1950's (Maupin, 2018). Figure 6 below shows that thermoelectric power accounted for more than 40% of the total water withdrawals in the United States in 2015. Although thermoelectric power accounts for such a great percentage of withdrawals, the actual consumption is estimated to be only 10%, and this is largely due to the recent transition of cooling systems to more efficient models (Badr et al., 2012; Dieter et al., 2018).

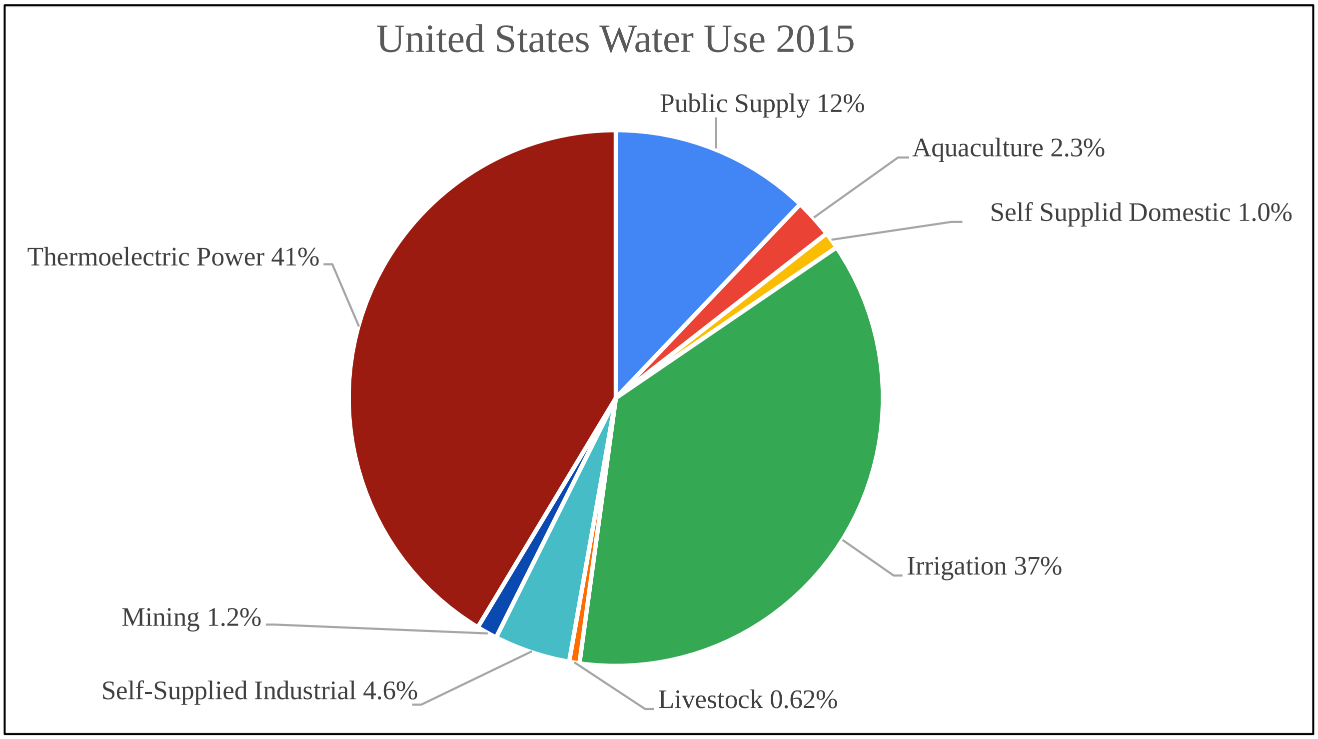


Figure 6. End use of water in the U.S. in 2015. (Maupin, 2018)

To understand the WEN from the water systems perspective, it is important to understand that thermoelectric power generation is such a significant use of water. This relationship highlights how the WEN involves both competition between energy and water as well as interdependence. Just as power generation requires water, water extraction, conveyance, and treatment require power. The first time that a unit of electricity was quantified for a unit of water to be supplied or treated was done by the Electric Power Research Institute (EPRI) in a 2002 report (Electric Power Research Institute, 2002). In the report they estimated that approximately 4 % of the United States' electricity was consumed by the water system. The main question this report sought to answer was whether or not energy production in the U.S. could meet the increasing demand required or agriculture and urban water systems (Electric Power Research Institute, 2002). The foundational watt hour per gallon (Wh/g) measurements that the EPRI report established have been built upon to better understand the true value of water, economic losses occurring within the systems, how this varies regionally, and to build predictive models of the water-energy relationship (Aubuchon & Roberson, 2014; Bauer et al., 2014; Chini, Schreiber, Barker, & Stillwell, 2016; Obringer, Kumar, & Nateghi, 2019; Sanders & Webber, 2012; Tidwell, Moreland, & Zemlick, 2014).

Energy use occurs within the water systems at every stage. Figure 7 shows a diagram of the different stages within the water system grouped by wholesale, retail, and end use. Research on water system energy demand is often broken up by these 3 categories, and even more often with wastewater treatment separated out (Cohen, Nelson, & Wolff, 2004; Escriva-Bou et al., 2018; Hamiche et al., 2016; Klein et al., 2005). The 2002 EPRI study found that of the energy demand calculated for the water system nationwide, approximately 80% was for moving water through the system. However since this early study, there is research now that quantifies as much as 12.6% of the nation electricity demand accounts for water (Sanders & Webber, 2012). This is largely due to the change in or lack of understanding around what end use energy demands should be considered. Taking into account water heating, for example, can significantly change the calculations (Sanders & Webber, 2012; Wilkinson, 2006). This type of associated energy is considered direct end-use energy while the energy that it takes to pump, convey, and treat water can be seen as the embedded energy (Klein et al., 2005; Sanders & Webber, 2012). Using Figure 7 as a guide, the embedded energy would be wholesale plus retail and wastewater, while direct energy would only be that from the end use. After the work done by EPRI and the paper by Sanders and Webber the majority of the research done in detailing the actual energy requirements of each of the water stages has been done in California (Aubuchon & Roberson, 2014; Copeland, 2014; Tidwell et al., 2014; United States Department of Energy and Water, 2006).

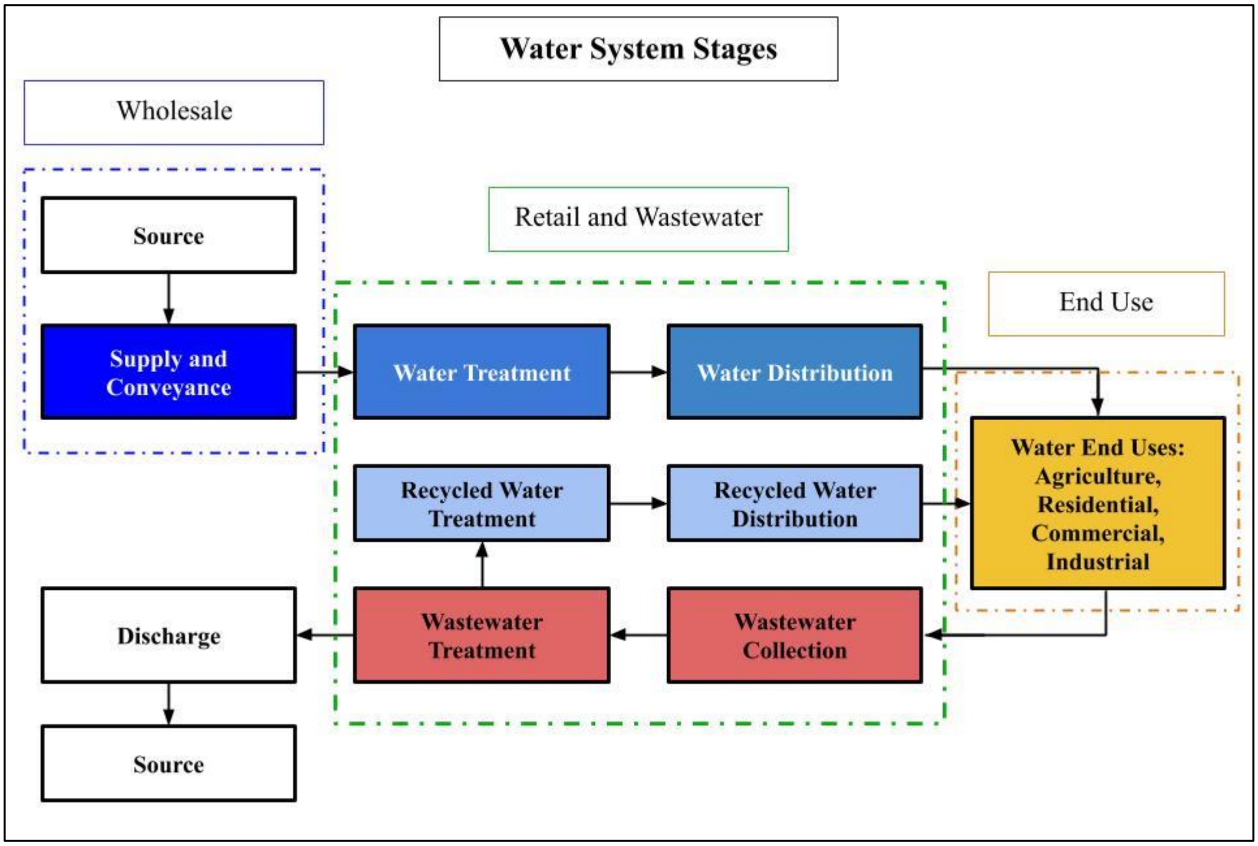


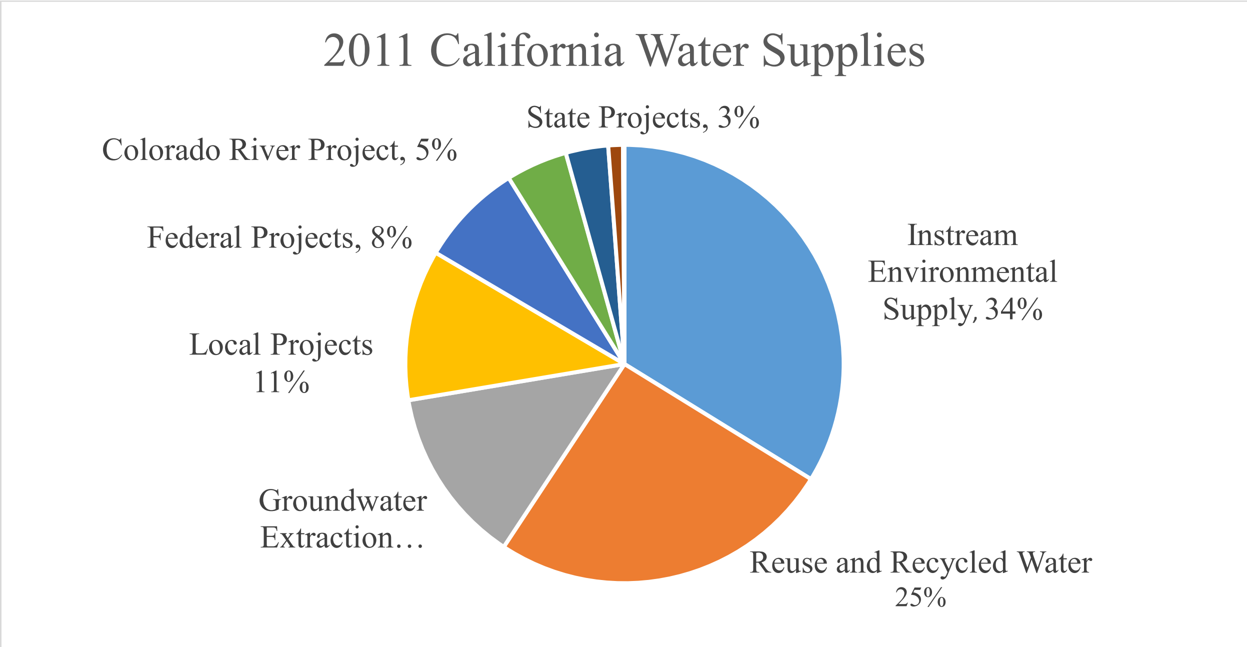
Figure 7. Diagram of Water System Stages. Recreated from Klein et al., 2005

ii. The Water-Energy Nexus in California

After the EPRI report in 2002, the most cited report on the energy intensity of water systems is the California Energy Commission report from 2005. This report further dissected the various stages of the water system and calculated a kilowatt hour per million-gallon (kWh/MG) intensity for subsectors within each of these. The biggest data point that this report illuminated was that 19% of the total electricity and 30% of the natural gas in California is consumed by the water system (Klein et al., 2005).

The relationship between energy and water is more closely dependent in California than in other states mainly due to California's water scarcity (Hanak, Lund, Dinar, Gray, & Howitt, 2011; Klein et al., 2005). After the 2001-2019 drought, approximately 150 million trees were left dead throughout the state of California (Goulden & Bales, 2019). The last 2-3 years have seen some of the most destructive fires in the state due to dry high winds, failing utility infrastructure, and the fuel created by the drought (Crowder, 2019). Because of the intensity and frequency of these fires, utilities in California now shut-off power throughout regions of the state to avoid starting fires (California Public Utilities Comission, 2020). Drought raises risks to the infrastructure and limits the ability of power supply to meet the demand. Not only are power plants capacity's reduced by lack of cooling water, but the energy mix in California usually relies on ~20% from hydroelectric power generation (California Energy Commission, 2019; Hardin et al., 2017). From 2011 to 2014 hydropower capacity decreased by 61% due to water shortages, and, because hydropower is a reliable clean source of power, California's annual emissions increased by 33% over that time frame (Hardin et al., 2017).

Drought can also increase the demand of the water system on energy supply. Figure 8 shows that in 2011, the early onset of California's last drought, surface water (labeled instream environmental) made up a third of the water supply and groundwater only made up 13% (Department of Water Resources, 2019). By 2015, the driest year during the drought, groundwater supply increased to 34% of the water supply and surface water dropped down to 25% (Figure 8). Groundwater supplies have a higher energy intensity than surface water supplies, so this transition from surface to groundwater creates a new energy demand (Hendrickson & Bruguera, 2018; Klein et al., 2005).



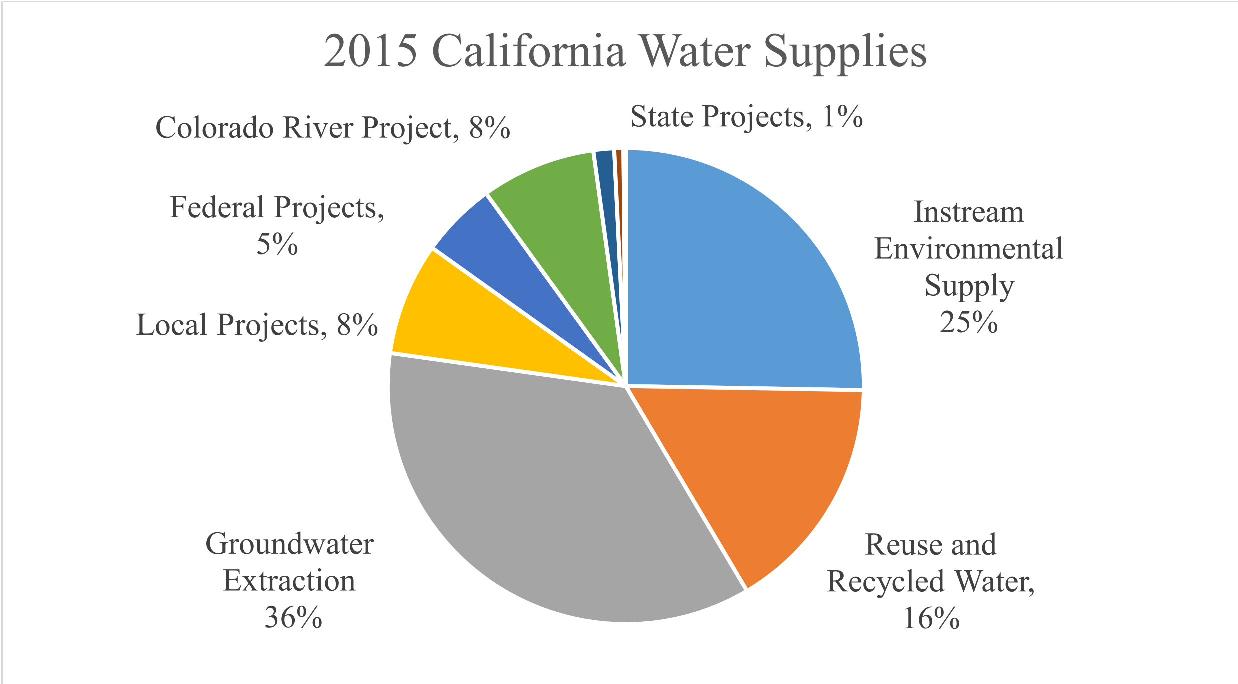


Figure 8. The change in California's water supplies due to drought. (Department of Water Resources, 2019)

The next section of this study will describe why the availability of water has such a great impact on California's water intensity. The development of California is a critical piece to understanding its water infrastructure, and specifically the history of urban development. The 2005 study by the CEC found that urban water had a higher energy intensity than agriculture in California (Table 1). The majority of the energy consumption occurs at the end use of the water cycle and this has been confirmed by multiple studies since this report (Cooley & Wilkinson, 2012; Escriva-Bou et al., 2018; Klein et al., 2005). The CEC report also found that there is significant variation in energy intensity of urban water between Northern California and Southern California (Table 2). Table 2 shows that the majority of this variation is in the supply and conveyance of water in Southern California. This paper will highlight the difference in water supply and conveyance between the different regions of the state.

Table 1. Water related energy use in California in 2001.Recreated from: (Klein et al., 2005)

	Electricity (GWh)	**Natural Gas (Million Therms)**
Water Supply and Treatment		
Urban	7,554	19
Agricultural	3,188	
End Uses		
Agricultural	7,372	18
Residential	27,887	4,220
Commercial		
Industrial		
Wastewater Treatment	2,012	27
Total Water Related Energy Use	48,012	4,284
Total California Energy Use	25,494	13,571
Percent of Energy Use from Water	**19%**	**32%**

Table 2. Electricity use in typical urban water systems in California. Recreated from: (Klein et al., 2005)

	Northern California (kWh/MG)	**Southern California (kWh/MG)**
Water Supply and Conveyance	150	8,900
Water Treatment	100	100
Water Distribution	1,200	1,200
Wastewater Treatment	2,500	2,500
Total	**3,950**	**12,700**

B. California's Water Demand and Supply

California is characterized by a Mediterranean climate, meaning it usually experiences wet winters and warm dry summers (Bedsworth et al., 2018; Department of Water Resources, 2019). However, throughout California there is great variation between rainfall, snowfall, and water use regionally and seasonally. This study highlights this regional variance and stresses the importance that management strategies should vary for different regions. Figure 9 shows the difference between the northern, central, and southern regions of the state in surface water availability. The northern part of the state is characterized by higher rainfall and snowfall (North Coast Resource Partnership, 2020). The central portion of the state can be characterized by a hotter drier climate, with some rainfall and snow along the eastern mountain range (East Stanislaus Regional Water Management Partnership, 2018). The southern part of the state is primarily desert with dry climate (Los Angeles Department of Water and Power, 2016; The Metropolitan Water District of Southern California, 2016). Figure 9 also highlights the disproportion between land area and water availability. Over 70% of California's precipitation falls north of Sacramento while 75% of the state's water demand is south of Sacramento (Hanak et al., 2011). The discrepancy between where water availability is greatest versus where water demand is greatest is critical to how California has developed its unique water system as well as why there is significant variation in energy intensity of water supplies (Ashoori, Dzombak, & Small, 2015; Hanak et al., 2011; J. Null, 2017).

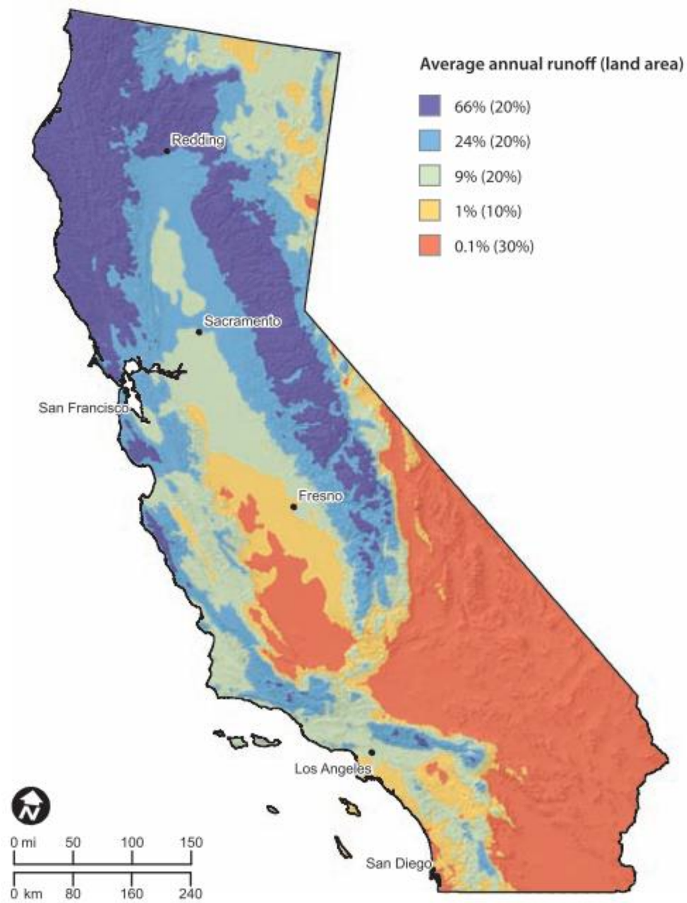


Figure 9. California precipitation and runoff versus land area (Hanak et al., 2011).

Not only is there variation in the water availability throughout California, but there is variation in the water demand (Figure 10). The northern parts of the state primarily apply water to maintaining environmental systems as they are less populated, the central part of the state heavily diverts water for agriculture, and the southern portion has the highest urban demand (Department of Water Resources, 2019; Escriva-Bou et al., 2018; North Coast Resource Partnership, 2020).

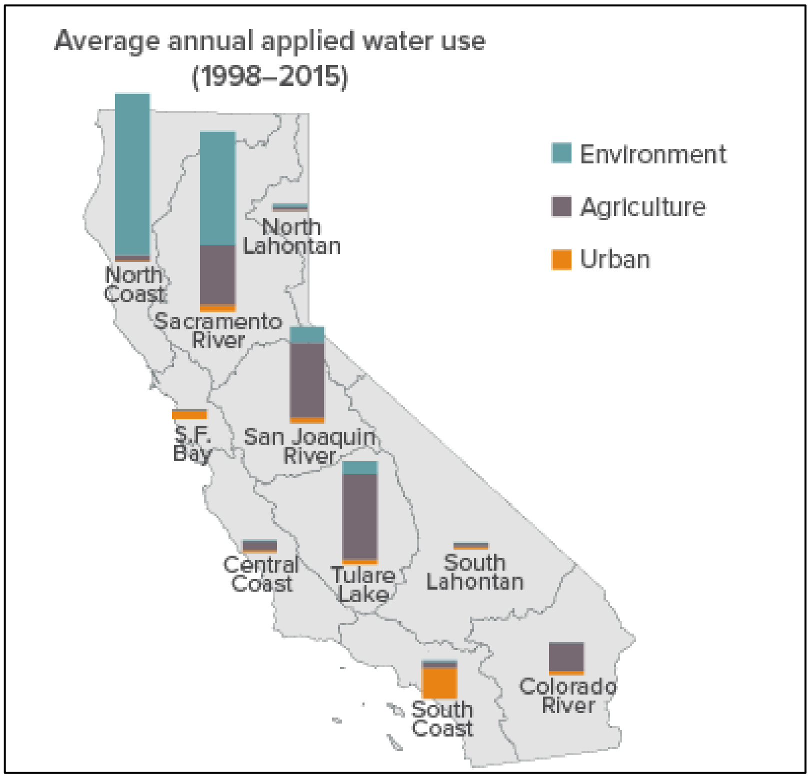


Figure 10. California's variation in water use by hydrological region. (Department of Water Resources, 2019)

Competition throughout the state among the environmental, agriculture, and urban water demand is high, as California is a water-stressed state. During drought years, the water use profile of the state shifts significantly showing which end use California must prioritize (Figure 10.) In 2011 57% of the water supply in California was used for environmental purposes which mainly goes to maintaining stream, rivers, and their ecosystems (Department of Water Resources, 2019). Specifically, the protection of endangered salmonid species habitat is a critical component of maintaining environmental water demand levels (Department of Water Resources, 2019; East Stanislaus Regional Water Management Partnership, 2018; North Coast Resource Partnership, 2020). By 2015 however, 51% of water was used for agriculture purposes, mainly crop production (Figure 11). The water normally diverted for environmental purposes was reduced significantly to maintain the demand levels for both agriculture and urban water (Figure 11). California's agricultural economy leads the nation in revenue and makes up 2/3 of the fruit and nut supply in the United States (California Department of Food and Agriculture, 2018; Jeanne, Farr, Rutqvist, & Vasco, 2019). Over the last 10 years, the central valley agricultural industry has experienced a shift to high yield crop such as almonds that require more water per acre to grow (Jeanne et al., 2019).

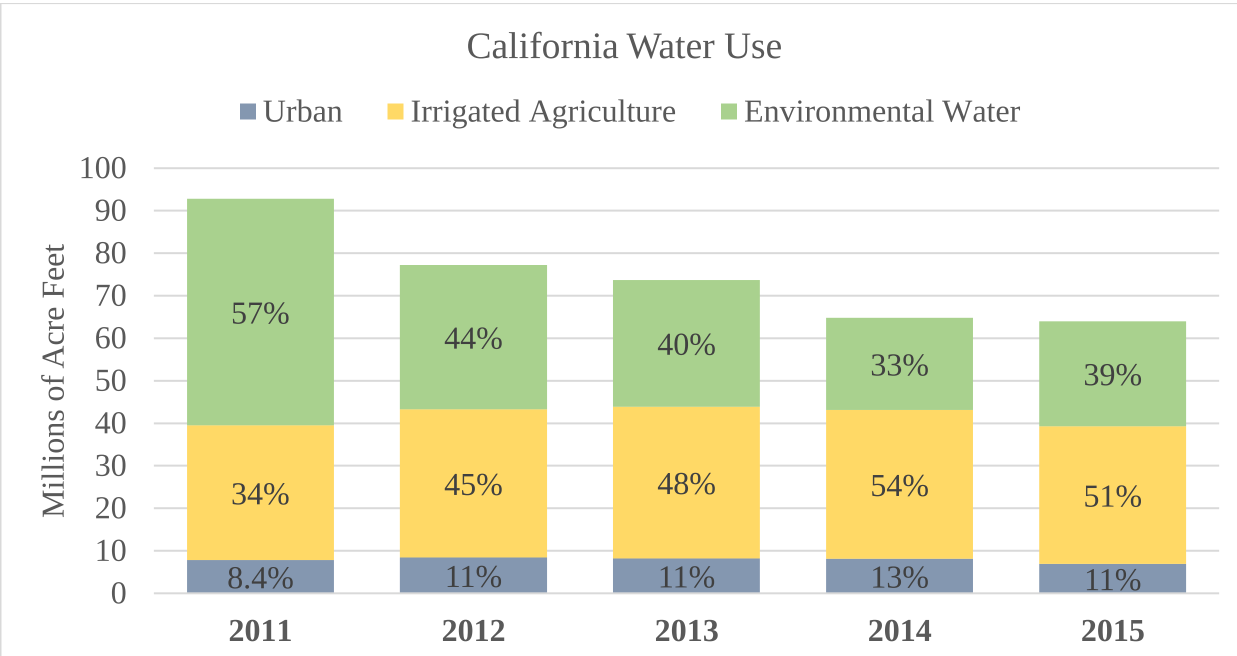


Figure 11. Water Use in California during the most recent drought. (Department of Water Resources, 2019)

In order for California to meet the regional variation in water demand with its dispersed water availability, California developed a unique water infrastructure based on water transport. How California was settled in its early years, greatly influenced the design of the state's water infrastructure. From the beginning of California's development, water laws and rights were a major factor in settlement. Water laws associated with the Spanish and Mexican settlements coupled with the laws developed during the Gold Rush, made water law in California irregular and conflicting (J. Null, 2017). During the Gold Rush, appropriative water rights made it possible for a person to claim rights to water at the source (e.g. a river), even though they were transporting it to be used possibly miles away (State Water Resource Control Board, 2010; The San Francisco Public Utilities Commision, 2015). By the late 1800's and early 1900's areas of California, such as the San Francisco Bay Area and Los Angeles, were developed at or near the capacity that local water systems could supply (J. Null, 2017). Large cities like Los Angeles would then procure water rights miles away from the city's center and build large conveyance systems such as the Los Angeles and Colorado River Aqueduct (J. Null, 2017). Flood prone areas like the Central Valley created dam and levy systems to manage the seasonal wetlands and inundations from the delta (Hanak et al., 2011). From this first come first serve attitude and the ability to manipulate water systems, California's water infrastructure was born. California now has over 1,000 dams and thousands of miles of canals, aqueducts, and levees that make up the state's water system.

i. Long-Distance Water Conveyance

The development of large urban centers far removed from that state's water supplies required the development of long-distance water conveyance systems. These systems are one reason that California's energy demand from its water supply is larger than the national average (Averyt, 2016). States that have consistent water availability throughout the state and less need for water conveyance, have lower water supply energy intensities (Averyt, 2016). The 3 largest conveyance systems in California (or that California water demand are met by) are the California Aqueduct, the Los Angeles Aqueduct, and the Colorado River Aqueduct (Ashoori et al., 2015; Department of Water Resources, 2019; Lofman, Petersen, & Bower, 2010). There are large systems of dams, canals, and rivers that also contribute to the transport of water such as the State Water Project and the Central Valley Water Project. As applicable to this study, a description of the State Water Project, the Colorado Aqueduct, the Los Angeles Aqueduct, and the Hecht Hetchy Aqueduct will be provided.

The California State Water Project (SWP) is one of the largest conveyance systems in the world stretching more than 700 miles and lifting water 1,926 feet to Southern California (California Department of Water Resources, 2020c). The SWP is the largest electricity customer in California, requiring anywhere from 6,000 gigawatt hours to 9,500 gigawatt hours to pump water through the aqueducts (California Department of Water Resources, 2020a; Lofman et al., 2010). The California Aqueduct is part of the SWP system and carries water from the central region of California down to the Los Angeles region (Figure 12). The California Aqueduct is owned by the State of California (DWR) and receives the majority of its supply from the Sacramento and San Joaquin River Basins (Ashoori et al., 2015). The Metropolitan Water District (MWD) of Southern California purchases water from the California Aqueduct to supply urbanized Southern California with water from the SWP, which is about 46% of the total SWP supply and 30% of the urban southern California demand (Ashoori et al., 2015).

Figure 12. Long-distance water conveyance systems in California (Ashoori et al., 2015).

The Colorado River serves one of the largest customer bases of any one water supply, serving between 30-40 million peoples in seven states and across 2 countries (Ashoori et al., 2015; Gautam & Mascaro, 2018). Large urban water demand, irrigation for agriculture, and environmental services all compete for the water supplied by this system (Gautam & Mascaro, 2018; Wildman & Forde, 2012). In 1928 when the Metropolitan Water District of Southern California was formed, it owned rights to the Colorado River water supply and built the Colorado River Aqueduct (CRA) to bring this supply to the residents of Southern California (The Metropolitan Water District of Southern California, 2016). The CRA carries water almost 250 miles to reach Southern California, and is one of the most energy intense water supplies in California (Figure 12) (Ashoori et al., 2015; Wildman & Forde, 2012; Wilkinson, 2006). Drought in the semi-arid region that the Colorado River Basin is located in, has caused reductions of water allotments that California, and the other dependent states, receive (Ashoori et al., 2015; Gautam & Mascaro, 2018).

The Los Angeles Aqueduct (LAA) was built in 1913 to provide the urbanized City of Los Angeles with water that it could not obtain locally (Los Angeles Department of Water and Power, 2013). The LAA brings water from the Eastern Sierra Nevada region from Mono Lake and Owens Valley (Figure 12). The Los Angeles Department of Water and Power (LADWP) owns and operates the two segments of the aqueduct, one built in 1913 running 233 miles, and the second built in 1970 running 137 miles (Los Angeles Department of Water and Power, 2016). The large urban development and lack of local water supplies quickly depleted the Owens Lake supply resulting in the complete disappearance of the lake and the progression of the aqueduct to the Mono Lake supplies (Ashoori et al., 2015). Due to the environmental impacts of the depletion of Owens Lake, as well as the conflict from water competition throughout the state, LADWP must now allocate large amounts of its LAA water supply to environmental restoration (Los Angeles Department of Water and Power, 2016). Although the system travels a significant distance across the state, the water system is entirely gravity fed and is a net positive water conveyance system in regards to energy demand (Los Angeles Department of Water and Power, 2016).

The Hetch Hetchy water system is a series of dams, rivers, and aqueducts built to transport water from the Sierra Nevada's near Yosemite 167 miles to San Francisco (The San Francisco

Public Utilities Commision, 2015). San Francisco was granted the right to build the Hetch Hetchy water system in 1913 to make up for the lack of local freshwater sources (S. E. Null, 2016). Since its establishment the Hetch Hetchy system has been developed to include a system of reservoirs and pipeline that make up what is known as the Regional Water System (RWS) for San Francisco (S. E. Null, 2016; The San Francisco Public Utilities Commision, 2015). The RWS is a gravity fed water conveyance system that generates hydroelectric power through a system of dams, making it a net energy positive water system (produces energy) (Cooley & Wilkinson, 2012; The San Francisco Public Utilities Commision, 2015; Wilkinson, 2006). The water brought in from the RWS supplies water to the entire City of San Francisco as well as many of the cities within the surrounding Bay Area Counties (S. E. Null & Lund, 2006; The San Francisco Public Utilities Commision, 2015).

These long-distance conveyance water systems provide insight into why California has such a high water supply energy intensity. The water availability in California and the water stress issues that the State face, inherently tie energy and water together in an inseparable way. This study will examine how this relationship varies in different regions of the state as well as show how these different cities will prepare water systems for climate change challenges.

III. Methodology

A. Selection of Water Providers

The goal of this study is to examine the current and predicted future regional variability in California's urban water supply with a specific focus on the energy intensity of these supplies. To do this, specific water suppliers were chosen to pull water supply data from for energy intensity analysis. The water supplier had to be representative of their region in both climate and water supplies, as well as serve an urban area. In order to get reliable data that used consistent reporting metrics and parameters, the Urban Water Management Plans (UWMP) for each water provider were used. The UWMPs are required by the California Urban Water Management Act as a way to monitor urban water supply reliability (A.B. 2242, 2018). The UWMP Act is defined in the California Water Code (CWC), Division 6, Part 2.2, Sections 10610 through 10656 where specific instructions on the structure, content, and methodology for calculating the appropriate data is described. This provided consistent and reliable data on water supplier for current and future conditions. The UWMP defines an "urban water supplier" as a public or private entity, regardless of the rights and circumstances, that serves over "3,000 customers or supplies more than 3,000 acre-feet of water annually" (Stats. 1983, Ch. 1009, §1). As such a water supplier can be a private company, a utility, a city, a community service organization, etc. In order to examine urban water supplies, the water suppliers chosen in this study were limited to cities and/or their municipal water providers.

There were 458 water suppliers listed on the California UWMP submittal site. Of those, 438 had submitted a UWMP that was received and reviewed by California Department of Water as of March 2019. The cities selected for this study were chosen because they submitted an UWMP, were representative of the regional microclimate, and the UWMP provided thorough data and analysis. The cities also must use a typical or large-scale water supply within California and/or had been used in previous studies examining the energy intensity of water, to ensure adequate data was available for the energy intensity analysis. During the selection process, cities and municipal supplies were found to have multiple smaller water suppliers serving various end uses within the city, making the water sources hard to trace. For example, Figure 13 shows the red outline of various water suppliers within the Sacramento City region, some served urban populations and others provided irrigation for agriculture. In this case, Sacramento did not qualify for the study as quantifying the city's water services and water sources would have required scanning multiple different UWMPs and untangling the urban versus agriculture bound water. Other cities examined purchase 100% of their water from a wholesale provider and data on the whole sale provider could not be found. After cities were found that represented regional variability in climate and water supply and had a traceable source of water supply, the UWMP's were scanned for thoroughness and data. Some of the UWMP's that were examined were not as thorough or detailed as others and this is often due to a lack of financial or staff resources available in that city (North Coast Resource Partnership, 2020). For the remainder of the paper the term "water suppliers" and "cities" are used interchangeably as the UWMPs examined are for cities only.

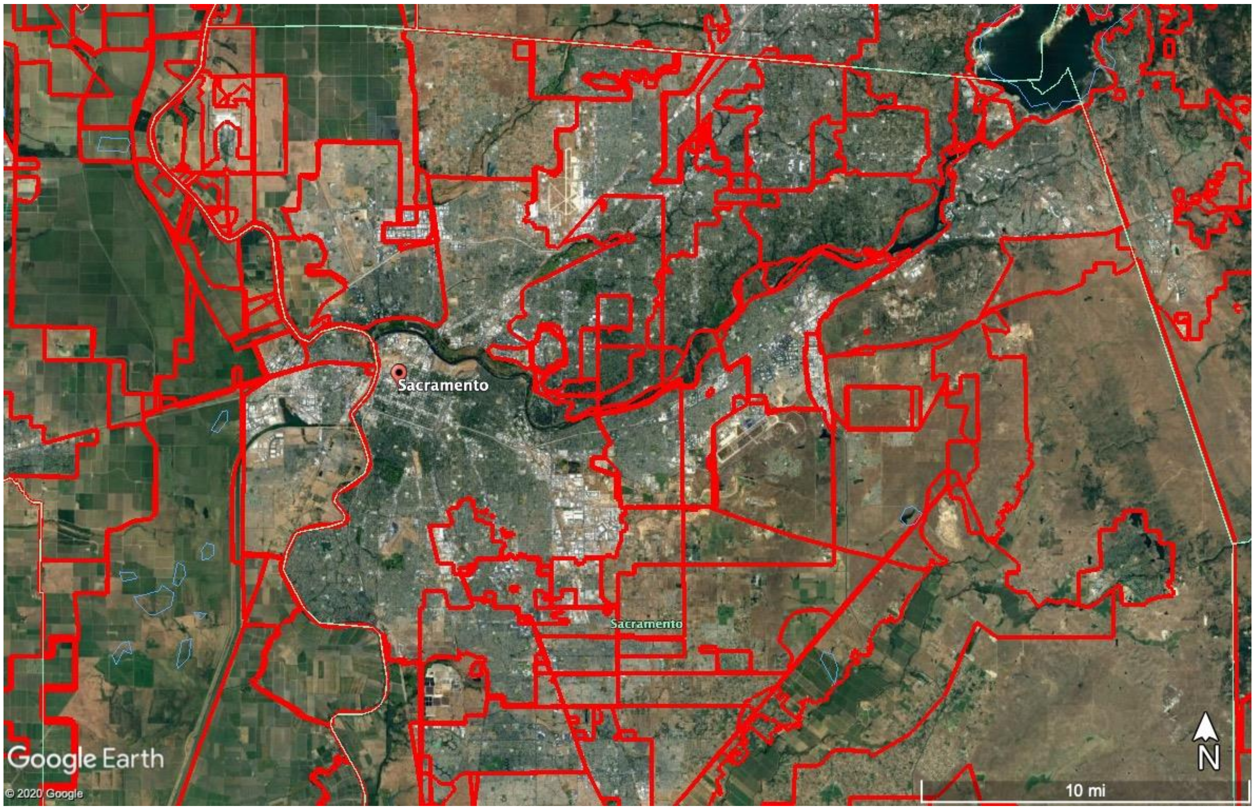


Figure 13. Sacramento water supplier service areas outlined in red. (California Department of Water Resources, 2020d)

Integrated Regional Management Plans (IRMP) were also used to select the cities, as well as confirm projections and regional assumptions. IRMPs were the result of the Regional Water Management Planning Act of 2002 (SB 1672, Costa). The purpose of this bill was to encourage the coordination of local agencies in planning for future resource adequacy and to provide funding to projects and programs developed in this process (SB 1672, Costa). Once cities were identified that met all of the criteria discussed, the IRMP for that region was identified and used to support the selection of that water supplier. Through the above stated process, the following 4 cities were chosen.

- **Los Angeles. Department of Water and Power** (LADWP). LADWP serves the largest number of people of all California Water Agencies (Pacific Institute, 2018). The average annual temperature is 75 degrees Fahrenheit and the average annual precipitation is 14.25 inches per year (Los Angeles Department of Water and Power, 2016). This is representative of the dry arid climate of the Southern California region. LADPW receives the majority of its water supply from the Metropolitan Water District (MWD) of Southern California. MWD had submitted a UWMP as a wholesale provider and included enough data to calculate LADPW's supply energy intensity. Both the LADWP supply and MWD supply pull from the long-distance water conveyance systems in California. MWD serves nearly 85% of the population within its service area and has provided over 50% of the municipal, industrial, and agricultural water demands (The Metropolitan Water District of Southern California, 2016). Because MWD is such a large part of the southern Californian water system, the LADPW and MWD show representation of the region.

- **The City of San Francisco**. The City of San Francisco is served by San Francisco Public Utilities (SFPU) for water. SFPUC serves the fourth largest population of people as a retail providers, but also provides water for a majority of the Bay Area of California as a wholesale provider (Pacific Institute, 2018). San Francisco averages 57 degrees Fahrenheit annually with approximately 22 inches average per year in precipitation, which is representative of the mild climate in this region (The San Francisco Public Utilities Commision, 2015). The UWMP was developed by SFPUC and submitted on behalf of the City of San Francisco. Within the UWMP the City of San Francisco data is separated out from the whole sale data. Because SFPUC serves a large retail base as well as provides water to the region at large, it is representative of the water system for this region of California. The San Francisco water system is well studied and referred to in multiple of the papers used in the energy analysis.
- **The City of Modesto**. The City of Modesto purchases its water from the Modesto Irrigation District (MID) which is a large wholesale provider in the Central Valley of California. The Wright Act of 1887 allowed irrigation districts to be formed for a period of 10 years before the Act was amended in 1897 to establish a more governed system for their formation (J. Null, 2017; Stene, 2015). Due to the high agriculture activity in the area there are a number of irrigation districts within the Central Valley region of California that were formed during this period that now serve as whole sale suppliers to urbanized areas (J. Null, 2017; Stene, 2015). MID did not submit a UWMP, but the city UWMP was prepared with details of both the city's and MID's systems. MID has also been referenced in multiple studies used for the analysis therefore there is ample and

reliable data to use for analysis. The City of Modesto is the 18th largest water district in California (Pacific Institute, 2018). Modesto receives 12.2 inches of precipitation annually and has an average temperature of 62 degrees Fahrenheit (City of Modesto, 2016). Modesto depends on groundwater and surface water that compete with large agricultural and environmental demands, which is representative of the Central Valley Region (East Stanislaus Regional Water Management Partnership, 2018).

- **The City of Eureka**. Eureka is the largest city in Humboldt county and in looking at the map of the North Coast Region's population and water system distribution (Figure 14), it is the most concentrated area of water districts and treatment systems. The counties of Sonoma and Marin have a much higher population density however represent a small portion of the North Coast Region geographically and have a drier climate, so do not represent a good sample of the region (North Coast Resource Partnership, 2020). Eureka was chosen to represent the northern region of the state because the region is characterized by small towns often lacking the resources to provide adequate UWMP's and data (North Coast Resource Partnership, 2020). Eureka purchases 100% of its water from HBMWD and HBMWD also submitted an UWMP. Eureka experiences climate typical of the region, with an average rainfall of 49 inches over the last 30 years which is 99% more than the average in California (Plocher & Thiesen, 2016). HBMWD provides water to 6 other city and water service agencies. HBMWD and the City of Eureka water systems exemplify the overabundance of water that is characteristic of the northern region of California.

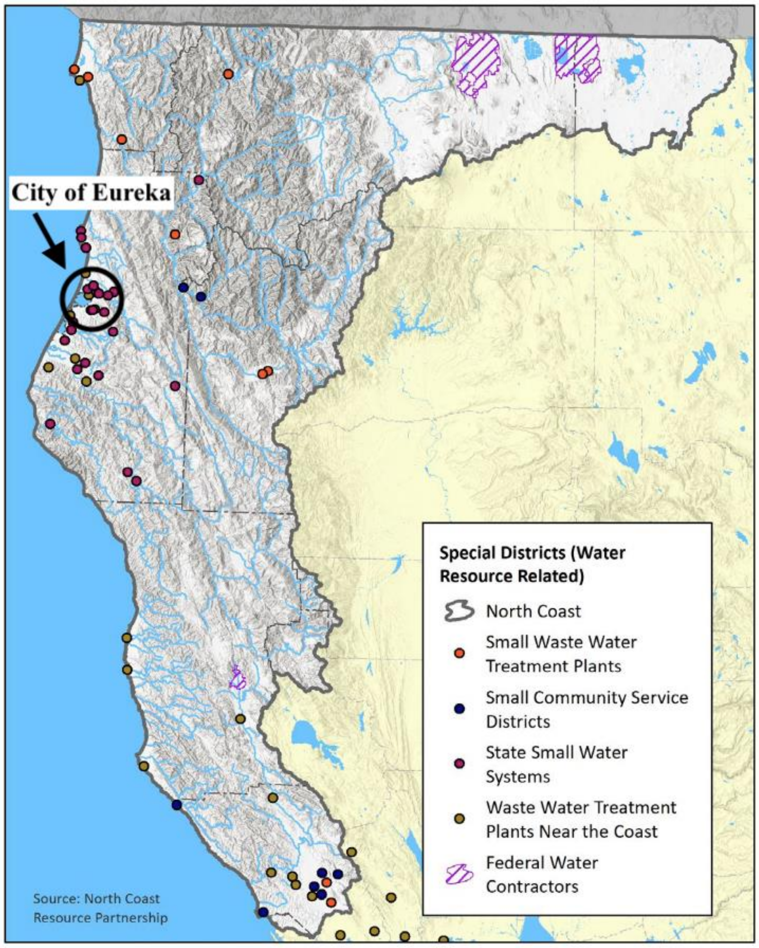


Figure 14. Water resources within Humboldt County. (North Coast Resource Partnership, 2020)

B. Data Collected

In the UWMPs, the water suppliers are required to report on their current supply and demand for water, project what their future demand will be, and assess whether their water supplies will meet that future demand. Following the California Water Code and the Department of Water Resources guideline, each UWMP included a supply forecast modeled using average, single-year, and multi-year drought conditions. The multi-year conditions had to be based on the three driest consecutive years in that district or regions history. For the purposes of this study only the multi-year results were used, as California predicts an increase in the frequency and intensity of droughts (Department of Water Resources, 2019). The projections were calculated for every five years out until 2035 and 2040. Due to inconsistency in the end year of these projections, the data on the water supply mix for 2030 was used for each city. The following criteria were examined within the UWMPs and IRWMs

1. The gallon per capita per day (gpcd) measurement is required in the UWMP's and each city is required to set baselines and reduction goals. The gpcd is required by Senate Bill (SB) X7-7, which requires cities to reduce water use by 20% by 2020. The gpcd is compared to the average gpcd of the region using the Pacific Institute Urban Water Use Portal. The actual gpcd is also compared to the goals set in the UWMP to show that the city has been able to meet its water conservation goals. Conservation is an important method for water reliability in California, per the California Water Plan (2018), and some cities use it as a supply for future conditions in their UWMPs.
2. The 2015 actual water supply in million gallons for each city was found for each supply in the city's UWMP. Then the 2030 water supply in million gallons for each water supply was found and compared to the 2015 water supply. Additional supply sources, changes in total supply, shifts in the percentage of each supply were all examined to understand how that city's urban water supply was projected to shift from 2015 to 2030.
3. Each water supplier is also required to complete a Water Supply Capability and Projected Demand table. This analysis uses projections on population growth, environmental requirements, and development of future water projects to estimate how the supply capacity will be able to reach projected demands. This study examines the supply capability projections for 2030 and examines whether or not they align with regional supply projections in the IRWMs. If the UWMP's projections do not align well with the IRWM, there could be miscalculated energy intensity factors for that water supplier.

After completing the analysis on the gpcd and water supply capability, the final numbers of each city's supply and supply type were used to calculate energy intensity. During the course of research into the water-energy nexus (WEN) within California, papers that included calculations of the water supplies in California were flagged. Seven papers surfaced as the most referenced papers with energy calculations for water supplies. The data in these papers are tabulated in Table 3.

Table 3. Compilation of energy intensity water supplies from various studies.

Source	Water Supply or Source Type	Energy Intensity (kWh/MG)
Tidwell et al., 2014	Surface Water Supply	1,400-1,600
	Groundwater Supply	1,400 – 2,100
	Desalination Supply	12,000
Wilkinson, 2006	Groundwater Supply	2,915
	Desalination Supply	13,503
	State Water Project Supply	8,746
	Colorado River Aqueduct Supply	6,138
Klein et al., 2005	Northern California Water Supply and Conveyance	150
	Southern California Water Supply and Conveyance	8,900
	Northern California Urban Water Supply	2,228
	Southern California Urban Water Supply	9,838
Navigant Consulting, 2006	Northern California Water Supply and Conveyance	2,177
	Southern California Water Supply and Conveyance	9,727
	Recycled Water	1,200 – 3,000
	Brackish Groundwater Supply	1,240 – 5,220
	Desalination	13,800
	State Water Project (Southern California)	8,325
	Colorado River Aqueduct	6,140
Cooley & Wilkinson, 2012	Water Supply and Conveyance	110 – 3,000

	Desalination	14,000 – 16,000
	Recycled Water	982 – 8,300
	Brackish Groundwater	3,000 – 8,3000
Webber, 2011	Surface Water	1,400
	Groundwater	1,800
	Desalination	9,780 – 16,500
	Brackish Groundwater	3,000 – 8,300
GEI Consultants/Navigant Consulting, 2010	State Water Project	4,600 – 14,117
	Colorado River Aqueduct	6,064
	Recycled Water	3,465
	Brackish Groundwater	4,965
	Desalination	12,276

Using the various energy intensity ranges and calculations provided Table 3, the average for each water supply source or type were calculated. These averages were used for the analysis in this paper because there is large variation in the energy intensity for certain water supply types (200-300%), and the factors contributing to this range cannot be identified for each water supply examined. The energy intensity of the water supplies were calculated in kilowatt hour (kWh) per million gallon (MG). If kWh per acre-foot (AF) was used, then it was converted to MG using the following equation (Hutson et al., 2004):

$$(AF \times 325{,}851\ G) \div (1{,}000{,}000\ ) = MG$$

In cases where the studies quantified the energy intensity of supplies and cities specifically used in this study, those numbers were used. For the rest of the city's supplies, the average energy intensity obtained across the seven studies was used. However, because there is variation between regional water supplies, some of the studies broke our water supply energy intensity calculations by northern and southern portions of the state. In this case, the energy intensity calculation for a region (northern or southern California) was applied instead of the average overall. The average kWh/MG for each water supply source found by examining the 7 studies, was then multiplied by the total amount of water from that source that a city used or was projected to use. This provided the total amount of energy required for that water supply for that city in kWh. A city's total energy requirements were then summed up in kWh and divided by the total water supply in MG. This provided the average kWh/MG energy intensity for that city's water supply.

IV. Results and Analysis

Using the data presented in Table 3, an average kWh/MG was calculated per water supply. The results of these calculations, presented in Table 4, show that there is a range of varying energy intense water supplies. It shows that surface water is the lowest energy intense water supply while desalination and long-range water transportation are the highest. Surface water generally requires no energy for extraction and minimal pumping for conveyance (Cooley & Wilkinson, 2012). Groundwater requires energy for extraction (pumping the water from the ground) as well as conveyance (Tidwell et al., 2014; Wilkinson, 2006). Recycled water requires energy for additional treatment of water to the standard required for its reuse (Cooley & Wilkinson, 2012; GEI Consultants/Navigant Consulting, 2010a; Navigant Consulting, 2006). Brackish groundwater requires addition treatment to remove salt and other solids from the water (GEI Consultants/Navigant Consulting, 2010a; Webber, 2011). The Colorado River Aqueduct, as discussed in the background of this paper, is a long distance conveyance system that requires energy to pump the water the ~250 miles it needs to go (Wilkinson, 2006). The SWP, being the largest electricity customer in the state, requires more energy to pump water in the more southern branches of its system (Navigant Consulting, 2006; Wilkinson, 2006). Desalination is very energy intensive due to the energy requirements for separating salt from water (Cooley & Wilkinson, 2012; Navigant Consulting, 2006). Brackish groundwater and Desalination are included in this analysis although they are not cited as a supply in any of the cities studied, because they are on the table for consideration by some of the southern cities (Los Angeles Department of Water and Power, 2016; The Metropolitan Water District of Southern California, 2016). Brackish groundwater can be a result of sea level rise, salt water intrusion, or over-pumping of groundwater basins, and was noted as a concern in the IRMPs for some of the cities examined (East Stanislaus Regional Water Management Partnership, 2018; North Coast Resource Partnership, 2020).

Table 4. Average energy intensity values for each water supply source.

Water Supply Source or Use Category	Average kWh/MG calculated using the 7 listed studies in Table 3
Surface Water	1,467
Groundwater	2,054
Recycled Water	3,141
Brackish Groundwater	5,558
Colorado River Aqueduct	6,114
State Water Project (Southern California Specific)	8,947
Desalination	13,414

The average kWh/MG values obtained in Table 4 were then applied to each of the supplies listed in each city's UWMP. This provided a calculation for the current energy intensity of each city's urban water supply as well as the ability to calculate the change in energy intensity with future shifts in water supply sources. Below the results for each city's UWMP and energy analysis are presented and discussed.

A. The City of Eureka

The City of Eureka receives all of its water supply from Humboldt Bay Municipal Water District (HBMWD). HMBWD receives 100% of its water from the Mad River, which flows from Ruth Reservoir. In 2015, the City of Eureka received 1,034 MG total to serve the 27,428 people within the City's service area. The 2015 gallons per capita daily (gpcd) consumption was 107, which is well below the UWMP required goal of 122. Figure 15 below show the statewide and regional averages, of which Eureka is below. Eureka's UWMP only includes water conservation as a strategy in the water shortage contingency plan, so it is not critical to the future water supply conditions.

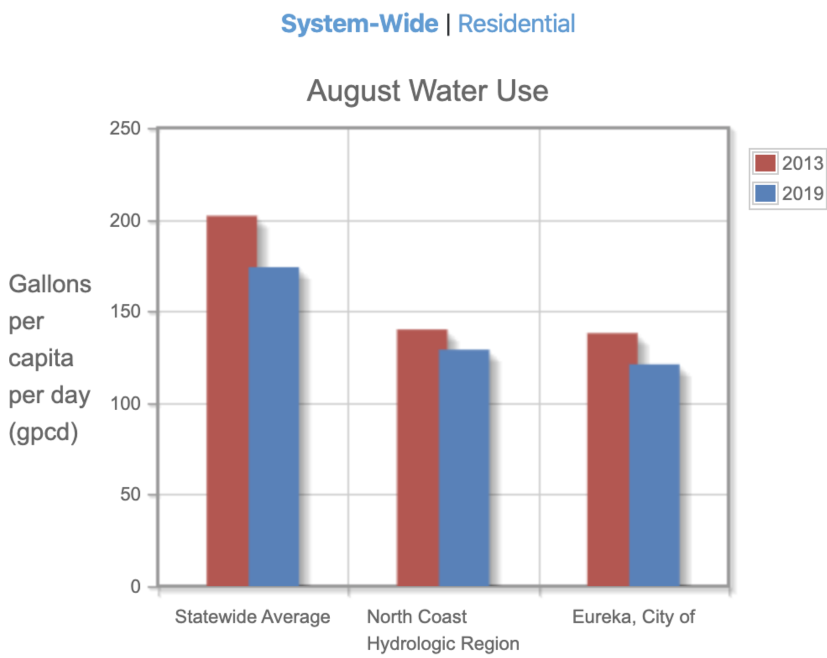


Figure 15. Eureka's system-wide gpcd water use.(Pacific Institute, 2018)

Water conservation is not as critical to Eureka's water supply because the region is experiencing an over-abundance of water. HBMWD reported that they are only using 12% of their water rights to serve their current population (Humboldt Bay Municipal Water District, 2016). This is largely due to the closure of 2 water intensive pulp mills within HBMWD service area (Humboldt Bay Municipal Water District, 2016). With this underutilization of available water HBMWD is looking into water storage, water for cooling, and water transfers as future uses for the extra water (Humboldt Bay Municipal Water District, 2016; North Coast Resource Partnership, 2020). This is not expected to have an impact on the availability of water for the City of Eureka. HBMWD projected a tripling in water demand, with the significant increase coming from potential export or other future use (Humboldt Bay Municipal Water District, 2016). Even with this significant increase in water demand, they would still only be using 54% of their water rights (Humboldt Bay Municipal Water District, 2016). Future storage or export uses that HBMWD utilizes for its water will not have any effect on the energy intensity of Eureka's supply, as it will occur separately to the system that Eureka is supplied by (Humboldt Bay Municipal Water District, 2016; North Coast Resource Partnership, 2020; Plocher & Thiesen, 2016).

Eureka's water supply's total energy consumption is 1,516 MWh and its energy intensity is 1,467 kWh/MG. The City of Eureka supply has the second lowest energy intensity factor of the urban water supplies examined in this study, because it uses a surface water source requiring energy use for pumping stations only (Cooley & Wilkinson, 2012; Plocher & Thiesen, 2016). Eureka is projecting an increase in water demand of 48% by 2030, which does not match the population increase of 13% (Figure 16). This means that Eureka is predicting an increase in the gpcd from the 2015 value of 107 to 136 by 2030. The 2015 goal was 122 gpcd, so the 136 gpcd predicted in 2030 is not in line with the requirements of the UWMP. The projected increase in water demand will not have any effect on the energy intensity of the water supply, only the overall energy demand. Because Eureka's water supply is not expected to change, the only way to reduce the energy demand of Eureka's water supply is by reducing the gpcd. As water conservation is not part of the City of Eureka's water management strategy (due to water stability), conservation will have to be enforced by the state through the UWMP and water code. Because water conservation has no benefits to Eureka's water supply, the state could make the argument that Eureka should conserve water to reduce its energy footprint.

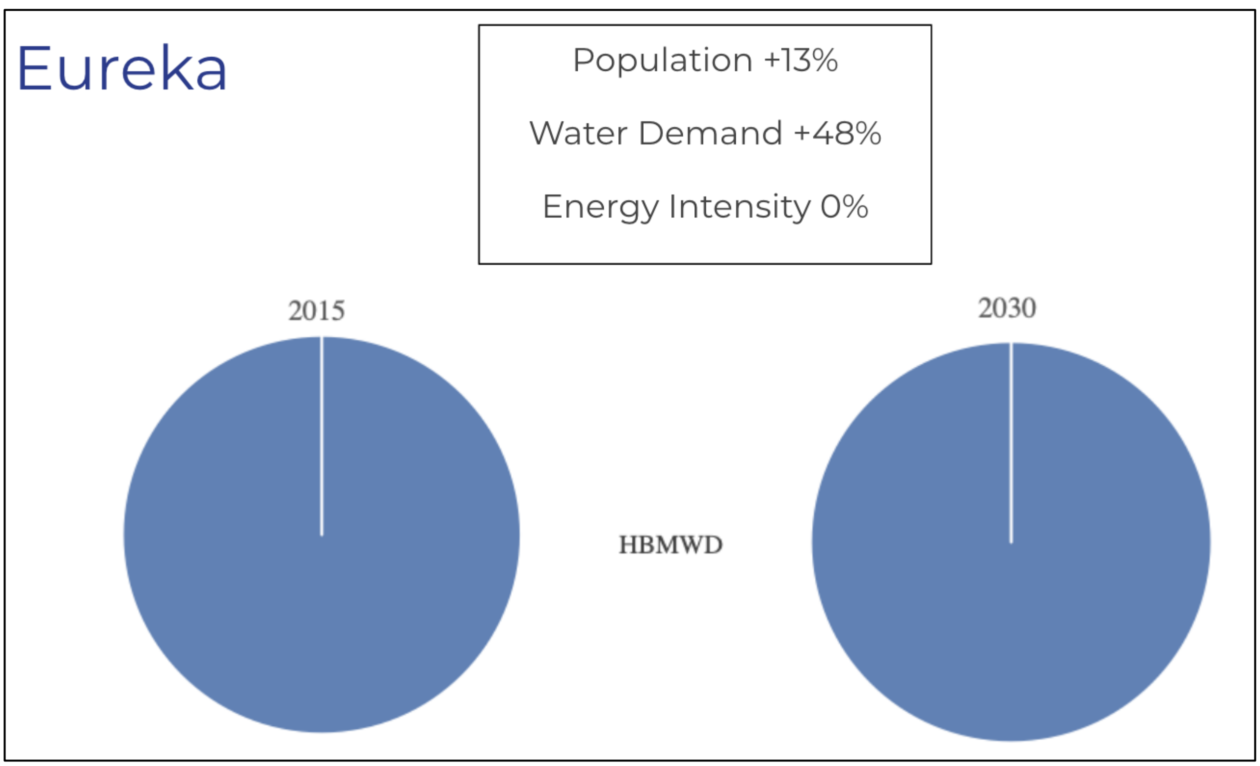


Figure 16. The change in Eureka's water supply and associated energy intensity.

B. The City of Modesto

The City of Modesto receives its water supply from local groundwater sources as well as surface water purchases from the Modesto Irrigation District (MID). Modesto served 259,187 people in the city with 15,465 MG of water in 2015. The gpcd goal for Modesto in 2015 was 257 while the actual gpcd was 163. Figure 17 shows the statewide and regional averages and that Modesto, and its surrounding region, have higher gpcd than the statewide average. Modesto also had the highest gpcd of the 4 cities in this study. The 2015 gpcd for Modesto, however, is well below the it's 2013 and 2019 gpcd shown in Figure 17. In the 2015 UWMP, Modesto noted that due to the extreme drought conditions experience in 2014 and 2015 water demand and use were below average (City of Modesto, 2016). Modesto predicted an increase in gpcd back to more normal levels, which reflects the much higher gpcd numbers reported in Figure 17. In 2030 Modesto projected its population to increase to be 19%, while its water demand would increase 69% (City of Modesto, 2016). This projection would put the 2030 gpcd for Modesto at 232, which is much higher than the statewide averages shown in Figure 17. Modesto mentioned water conservation was strategy for water supply stability, however did to assign any values or goals to this strategy, nor did the UWMP address the projected increase in gpcd (City of Modesto, 2016).

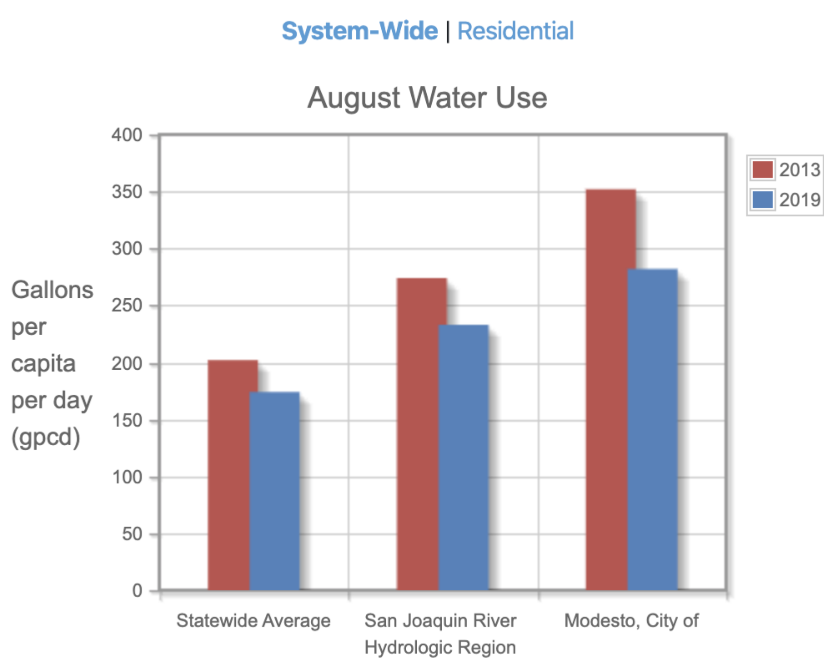


Figure 17. Modesto's system wide gpcd water use. (Pacific Institute, 2018)

The MID supply that the City of Modesto receives, is gravity fed and does not have an associated energy footprint (Cooley & Wilkinson, 2012). The average energy intensity calculated for groundwater supply was applied to Modesto's groundwater source to calculate the energy demand for Modesto's water supply. In 2015, 68% of the water for the City of Modesto was supplied by local groundwater and the remaining 32% was supplied by MID (Figure 18). Modesto's water supply's energy intensity was calculated as 1,387 kWh/MG and the overall energy required for the 2015 water supply was 21,456 MWh. The City of Modesto projects importing 65% of their water supply from MID in 2030 and getting 35% of their supply from groundwater (Figure 18). This change is projected to drop the energy footprint to 718 kWh/MG and the total energy required to 18, 789 MWh/yr (Figure 18).

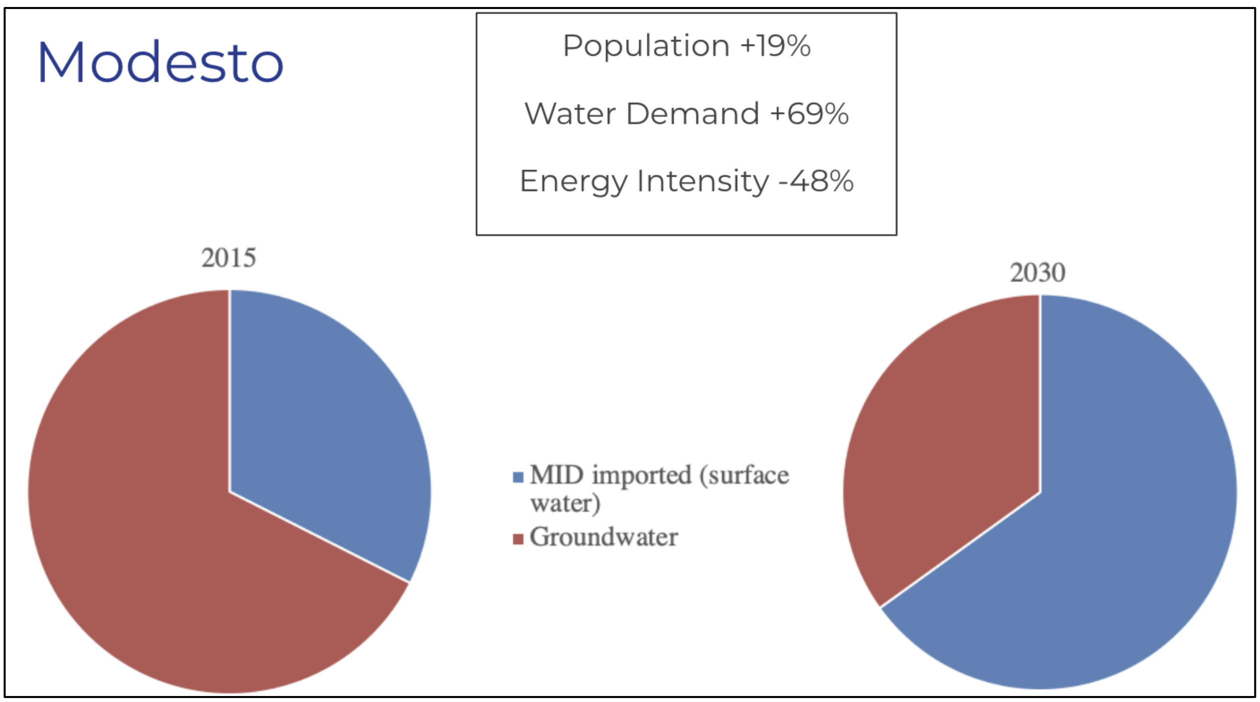


Figure 18. The change in Modesto's water supply and associated energy intensity.

Modesto's shift to a larger dependence on groundwater in 2015, is typical of a drought year for this region (Department of Water Resources, 2019; East Stanislaus Regional Water Management Partnership, 2018). While Modesto is able to supplement groundwater supplies with surface water supplies, the neighboring cities rely solely on groundwater (East Stanislaus Regional Water Management Partnership, 2018). Modesto does not have a well-diversified water supply portfolio, nor did they project expanding it in the future. The IRMP for the East Stanislaus region cites this lack of diversification in water supply as a regional issue. Modesto and its region have a higher than average project population growth(East Stanislaus Regional Water Management Partnership, 2018). The combination of an increased demand, lack of diversification, and increased drought conditions bring the projections of Modesto's water supply stability into question. The UWMP was submitted in 2015, which was in the middle of the California's longest drought, the heavy dependence on groundwater in the UWMP is as a result of decreased surface water availability. The multi-dry year projections of supply do not seem to align with how Modesto responded to drought in 2015. If Modesto continue to rely heavily on groundwater, its energy demand will not decrease as expected, but increase.

The ability of Modesto to rely on groundwater as a source in drought conditions (as it did in 2015), is not guaranteed. In 2014, a three-bill package was passed called the Sustainable Groundwater Management Act (SGMA). This policy put more stringent requirements on the management of groundwater basins, including limitations requirements on water extraction, while also developing a rating system for the basins to identify high needs (California Department of Water Resources, 2020b; City of Modesto, 2016; Hendrickson & Bruguera, 2018). As the policy was just passed when the UWMP was published, only initial understandings of the implications of the SGMA were included. All three basins surrounding the City of Modesto were listed as high priority and one as critically over drafted (City of Modesto, 2016). These basins will have more strict limitations on over drafting of groundwater and a management plan will be required within the next 2 years. The East Stanislaus IRMP was published in 2018, so impacts of the drought and SGMA implications for the region were better understood. The IRMP included diversification of water supply as a critical goal to ensuring water supply reliability and adaptation to climate change (East Stanislaus Regional Water Management Partnership, 2018). Methods for supply diversification in Modesto could include recycled water and groundwater banking, which is the storage and later extraction of water in groundwater basins mirroring the availability of water (City of Modesto, 2016; East Stanislaus Regional Water Management Partnership, 2018). Both of these methods would result in an increase to the energy intensity and total demand for the City of Modesto.

C. The City of San Francisco

The City of San Francisco's water system is operated by San Francisco Public Utiltiies Commission (SFPUC). SFPUC receives the majority of its water from the Hetch Hetchy Regional Water System (RWS). San Francisco acts as both a retail provider to the residents of San Francisco as well as the wholesale provider to cities throughout the Bay Area. In 2015 San Francisco served 859,276 retail customers a total of 25,586 MG of water. The gpcd in 2015 was 81 while the goal was 102. San Francisco's gpcd is the smallest out of the cities examined in this study and is well below the statewide average (Figure 19). San Francisco predicts that this gpcd will increase after the drought ends, as indicated by the slightly higher water demand increase versus population increase (Figure 20). San Francisco does not include water conservation in the supply projections but outlines the conservation program in effect as well as the future program plans. The success of San Francisco's conservation program to date are evident in the low gpcd relative to other regions in this study.

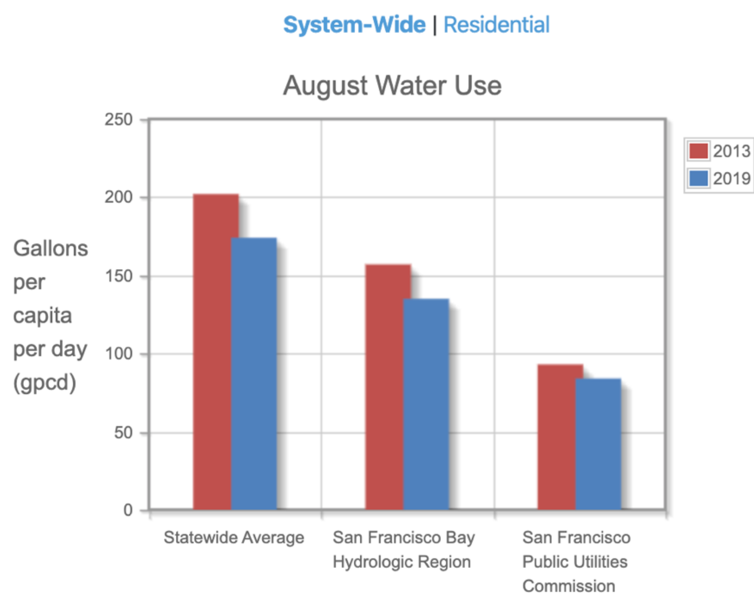


Figure 19. San Francisco's system-wide gpcd water use.(Pacific Institute, 2018)

San Francisco received 97% of their water from the RWS and 3% from groundwater in 2015. The RWS is a net positive, energy producing system (Cooley & Wilkinson, 2012; S. E. Null, 2016; The San Francisco Public Utilities Commision, 2015; Wilkinson, 2006). Although the energy production from this system was not taken into account in this study, the RWS supplied water has zero energy intensity associated. As the RWS supply makes up the majority of the water supply, San Francisco's water supply's energy intensity is only 73 kWh/MG, which is the lowest of this study. San Francisco projects to double their groundwater supply in increase their recycled water supply in 2030 (Figure 20). With this increase in alternative supplies, the energy intensity for San Francisco's water system is projected to triple by 2030. Even with this large increase in their energy footprint, San Francisco still has the smallest energy intensity in this study.

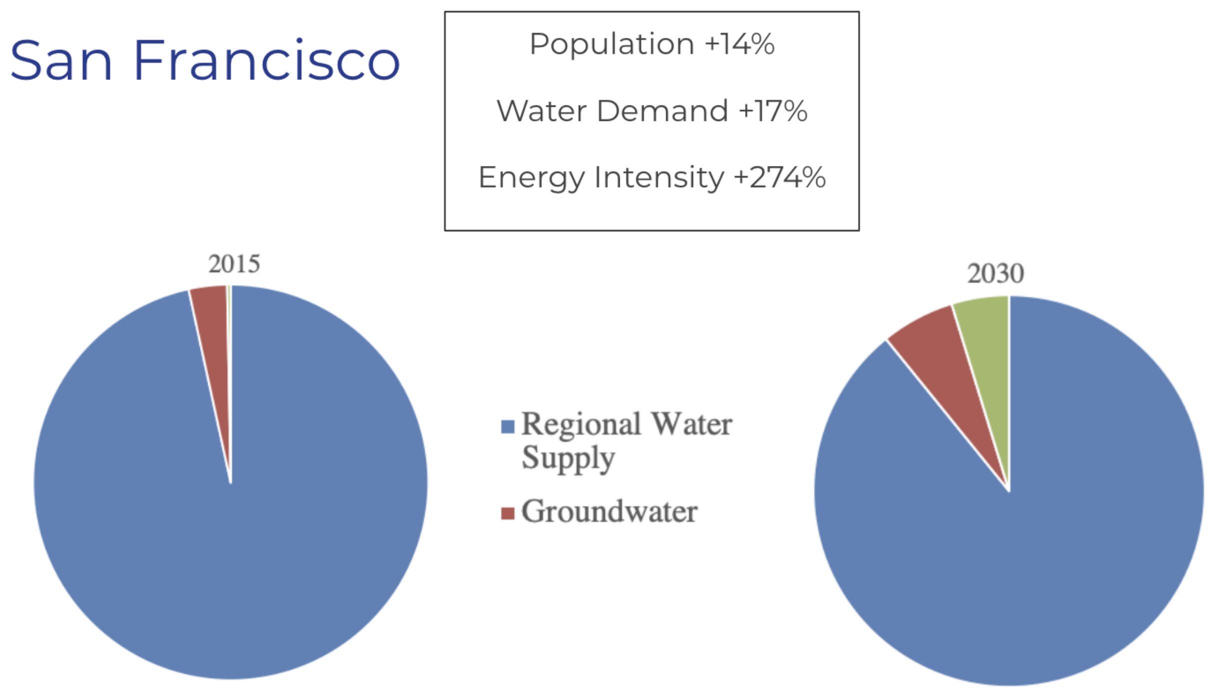


Figure 20. The change in San Francisco's water supply and associated energy intensity.

D. The City of Los Angeles

The City of Los Angeles' water system is operated by the Los Angeles Department of Water and Power (LADWP). LADWP receives the majority of its water from the Metropolitan Water District (MWD) of Southern California. In 2015 LADPW supplied 167,338 MG of water to its 3,987,622 residents. The gpcd goal in 2015 was 148 but the actual gpcd was 114. This is lower than both the regional and statewide average as shown in Figure 21. The success of their conservations programs, as proven with their low gpcd, is critical to the management of their water supply because Los Angeles incorporates predicted water savings in their water supply balance for future years (Los Angeles Department of Water and Power, 2016). Los Angeles projects that even with population growth and increased development of conservation programs for the gpcd to stay at 114 in 2030. To calculate the 2030 gpcd, however the projected supply to be gained from water conservation is not included in the total water demand.

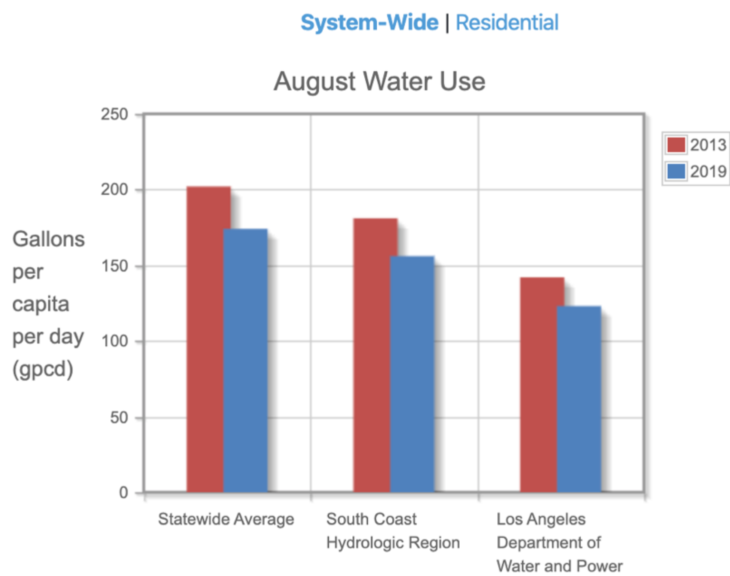


Figure 21. Los Angeles's system-wide gpcd water use. (Pacific Institute, 2018)

Of the 167,338 MG supplied in 2015 to LADPW, 71% of the water came from MWD (Figure 22). To calculate the energy intensity of MWD supply, the MWD water supply mix was also analyzed. MWD supplies water to cities and districts that support 18,740,000 customers (The Metropolitan Water District of Southern California, 2016). In 2015, MWD received 49% of its supply from what they labeled "local regional sources" in their UWMP (The Metropolitan Water District of Southern California, 2016). Included in the "local regional sources" are water supplies from the Los Angeles Aqueduct, groundwater, and recycled water (The Metropolitan Water District of Southern California, 2016). MWD did not divide its local regional supply into portions, limiting the true energy assumption of this source. The average calculated for Southern California supply and conveyance was used as the energy factor for this MWD source. The remaining supply was split between the California Aqueduct, also referred to as the State Water Project (SWP) (35%), and Colorado River Aqueduct (CRA) (16%). These sources had the highest energy intensity factors within the water supplies examined at 8,947 and 6,114 kWh/MG respectively (Table 4). The MWD energy intensity was calculated to be 6,732 kWh/MG for the 2015 mix with a total energy consumption of 6,767,308,108 MWh. In 2030, MWD projects that the CRA will make up 64% of the supply, SWP will make up 41%, and local supplies 22%. The energy intensity for the water supply in 2030 for MWD increases to 6,853 kWh/MG with the higher reliance on the long-distance conveyance supplies. The overall demand of MWD is projected to decrease by 30% in 2030 so the total energy demand will decrease to 5,345,984,822 kWh.

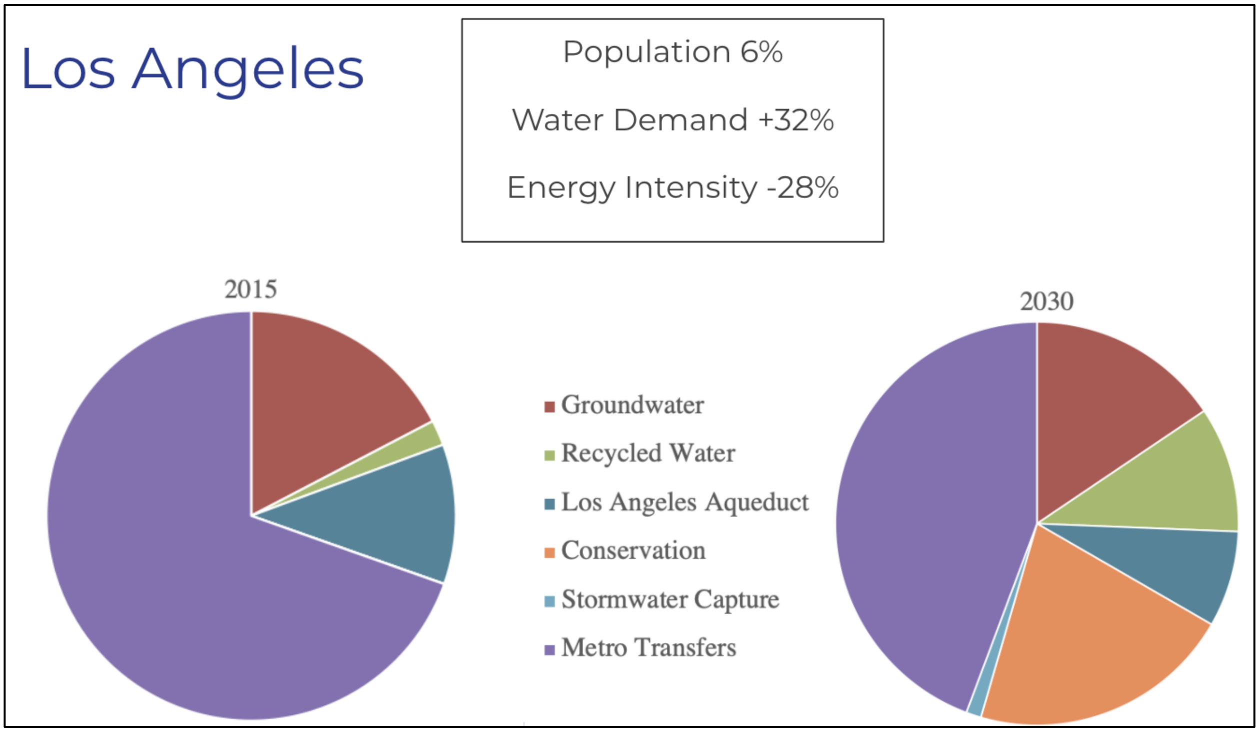


Figure 22. The change Los Angeles's water supply and associated energy intensity.

The energy intensity calculated for the MWD 2015 mix was applied to the total water supplied to LADPW from MWD. LADPW water supplies consisted of 71% MWD purchases, 17% groundwater, 11% Los Angeles Aqueduct supplied water, and 2% recycled water in 2015 (Figure 22). The Los Angeles Aqueduct is a net positive conveyance system and as such does not have an associated energy intensity (GEI Consultants/Navigant Consulting, 2010b; Wilkinson, 2006). The averages calculated for each supply in Table 4 were applied to Los Angeles's supplies and the energy intensity was calculated to be 5,119 kWh/MG for 2015. LADPW projected that they will rely less on the MWD supply and more on locally supplied recycled water and groundwater, which brings their projected energy intensity to 3,941 kWh/MG in 2030, 28% below its 2015 intensity. The 2030 MWD energy intensity calculated was used in this calculation, which is a higher intensity, but because of the higher reliance on local supplies and conservation Los Angeles will have a lower energy intense water supply. LADPW projected that water conservation will make up 21% of their supply in 2030 (Figure 22). The water conserved is calculated in the total water supplied and as no energy required, however by planning on reducing water use by that much the energy calculation should be negative (energy saved). By multiplying the LADWP projected energy footprint for the 2030 water supply, by the projected water conserved, the amount of energy that can potentially be saved through conservation in 2030 is 186,352,797 kWh.

E. Summary

The results presented show 4 very different city water providers, selected to highlight the regional variation of California's water supply and management. The drastic variation in climate and available water supplies throughout California is highlighted by the variation in the results presented. Each city is predicted to experience a different shift in water supply, based on the local and regional availability of water. One over-arching theme that was highlighted in most of the UWMPs, all of the IRMPs, and the California Water Plan Update was water supply diversification. The 2011-2019 drought highlighted the instability of relying on surface water for many of the water suppliers in California (Department of Water Resources, 2019; East Stanislaus Regional Water Management Partnership, 2018; Los Angeles Department of Water and Power, 2016).

Table 5 summarizes the expected change in population, water demand, water supply, energy intensity, and energy demand for each city. All cities expect to see an increase in population growth and water demand. Each city does not anticipate the water demand to mirror the increase in population, rather they anticipate the water demand to increase by a larger factor than the population, meaning the gpcd will increase. The only city where the water demand is projected to increase more than the population and the gpcd is not going to increase is Los Angeles, and this is due to the total water demand including the water conserved.

Table 5. Projected changes between 2015 to 2030.

City	Population change	Change in Total Water Supplied	Changes in Water Supply	Energy Intensity Change kWh/MG	Change in Total Energy Required
Eureka	+13%	+48%	No new supplies	0	+48%
San Francisco	+14%	+17%	Increase in groundwater and recycled water supplies	+274%	+338%
Modesto	+19%	+69%	Increase in surface water supplied purchases	-48%	-12%
Los Angeles	+5.6%	+32%	Added conservation estimates and decreased MWD purchase projections	-23%	+1.3%

The greatest overall change in energy intensity is seen in San Francisco's water supply (Table 5). This is largely due to the water system having such little energy requirements to begin with as the RWS is an energy producing system. Because the total energy required in 2030 is only expected to be 8,223,248 kWh and the SFPUC acts as an energy provider as well as water provider, much of this demand can be met with the carbon free energy produced through the transport of the RWS water (The San Francisco Public Utilities Commision, 2015).

Modesto's projections were mis-aligned with their regional IRMP's. Studies done in the Central Valley since the 2011-2019 drought highlight that the heavy reliance on groundwater that occurred in that region during the drought resulted in the subsidence of some of the groundwater basins, which results in the permanent loss of aquifer capacity (Alam, Gebremichael, Li, Dozier, & Lettenmaier, 2019; Faunt, Sneed, Traum, & Brandt, 2016; Jeanne et al., 2019). As the groundwater basins become depleted, deeper wells must be installed to maintain water quality and supply (Jeanne et al., 2019). Over drafted wells can result in lower water quality, requiring additional treatment which requires more energy and deeper wells require more energy for pumping (Cooley & Wilkinson, 2012; Wilkinson, 2006). Modesto and the Central Valley region will therefore see an increase in energy intensity as water becomes harder to reach and of lesser quality. Water diversification methods that were not highlighted in the UWMP will need to be implemented in Modesto to avoid these water supply issues.

The energy intensity of the Los Angeles water supply is the greatest due to its reliance on long-distance conveyance water systems that do not generate electricity (Table 6). Because Los Angles plans to rely more on local supplies of water, it will see a decrease in its associated energy intensity. San Francisco also plans to increase its reliance on local water supplies, however, will see a large increase in the energy intensity of its water supply (Table 6). This highlights the variation in energy intensity for water systems throughout California. There was not a trend among the 4 cities that could be identified in this study to lend to a single recommendation that would apply to all 4 cities.

Table 6. Changes in energy intensity for cities between 2015 and 2030.

City	Energy Intensity (kWh/MG) for 2015	Energy Intensity (kWh/MG) for 2030
Eureka	1,467	1,467
San Francisco	73	274
Modesto	1,387	718
Los Angeles	5,119	3,941

V. Recommendations

Based on the findings in this study water supplies in California will be shifting in a variety of ways to deal with drought, decreased surface water supply, more stringent groundwater regulations, and the costliness of long-distance water conveyance. There is not one definitive way that California's water supply will shift other than water suppliers are endeavoring to diversify their supply more. San Francisco, Modesto, and Los Angeles all experienced a shortage in surface water in 2015 due to drought that caused a decrease in their water demand. The UWMPs are a useful tool that encourages water suppliers are looking to the future to ensure their supplies are sustainable. Because the water supplies are so interconnected, with multiple conveyance systems supplying a number of different entities, it is important to consider how the region at large is planning for water supplies. In order to successfully plan for sustainable water supplies, the IRMPs should be developed during the same time period as UWMPs or the UWMPs should be developed in close collaboration with the IRMPs developers. Specifically, in the case of Modesto, there was disconnect between the UWMP goals and considerations and the IRMP. The IRMP was developed in 2018 and as such had a better grasp of the impact that the 2011-2019 drought had on the region, while the UWMP was developed in 2015. This is could explain why the IRMP focused more on diversifying from the surface water and groundwater supplies than the Modesto UWMP did. In the case of the North Coast IRMP, the information provided was very well aligned with the UWMP and provide helpful insights to the projections that both the City of Eureka and HBWMD provided in their UWMP. This is a good example of a cohesive approach to water management from a regional level.

Similarly, the results of how the water supply will shift, the energy intensity shift was also found to be different for each city. The energy intensity of each city's water systems varied, did not follow a similar trend across the state, and represents an understudied threat to the water supply reliability. This threat is both an economic and environmental threat to urban water supplies.

As more energy is required to extract and convey water, the water becomes more expensive mainly due to the increased electricity and energy costs. Energy and electricity costs can range anywhere from 30-75% of a water suppliers operating costs (Aubuchon & Roberson, 2014; Copeland, 2014; Sokolow, Godwin, & Cole, 2016). As water suppliers look to diversify their water supply there will be upfront capital costs associated with construction, and if they do not plan carefully, and large increase in operating costs can incur from energy intense systems (Cohen et al., 2004; Cooley & Wilkinson, 2012; Copeland, 2014). The electrical grid within California experiences supply management issues, impacts from heat waves and droughts, as well as issues from aging infrastructure that are predicted to cause the cost of electricity to increase over the coming years (Escriva-Bou et al., 2018; Sokolow et al., 2016). Because surface water and groundwater are the two least energy intense options, when cities are diversifying their supply, they will likely be increasing the energy intensity. In these cases, it is critical for the water supplier to examine onsite energy generation and invest in high efficiency technology.

How are California's water supplies going to shift and what effect will this have on the energy intensity of urban water supplies?

As presented in the background, the infrastructure of the United States for both energy and water is aging and failing (Bedsworth et al., 2018). The top solution to fight the economic loss associated with these aging systems is efficiency, by reducing demand the strain on these systems is reduced (Aubuchon & Roberson, 2014; Pinzon, 2013). While there have been significant advancements in technology to improve efficiency, infrastructure upgrades, remodels, and new facilities are still necessary to ensure water system resiliency (Aubuchon & Roberson, 2014; Bedsworth et al., 2018; Pinzon, 2013). As these new construction projects move forward, it is imperative for energy efficiency and renewable energy to be incorporated. Water reuse and desalination are emerging as two top solutions to increase water supply diversity and reliability, however both will result in an increased energy intensity (Cornejo, Santana, Hokanson, Mihelcic, & Zhang, 2014; Pinzon, 2013). By building renewable energy generation and storage onsite, these water systems reduce the operational cost, reduce the greenhouse gas emission footprint, reduce the demand on the grid, and with storage have a component resiliency built in (Cornejo et al., 2014; Pinzon, 2013; Tarroja et al., 2014).

The impacts that climate change might have on the water and energy system both, have been presented in this paper. If energy intensity from water systems are not taken into consideration, this can be a significant source of greenhouse gas emissions that only further perpetuates the cycle of water and energy scarcity. Greenhouse gas emissions from water systems in the United States are estimate to make up 5% of the Unites States' greenhouse emissions (Copeland, 2014). In California it is estimated that the water system makes up closer to 10% of the state's greenhouse gas emissions (Escriva-Bou et al., 2018).

Due to these two threats to water suppliers, the UWMP guidelines and rules should be updated to include an energy and greenhouse gas assessment. Currently the UWMP encourages, but does not require, the water suppliers to report on energy and emissions associated with their water supplies (Los Angeles Department of Water and Power, 2016). If the goal of the UWMP is to ensure that the urban water supplies of California are being managed sustainably then it is evident, based on the results of this study, that energy and emissions reporting should be included to achieve this goal.

VI. Conclusion

The last drought that California experienced, resulted in the understanding that groundwater and surface water supplies were not going to be able to sustain the growing urban centers and their associated water demands. California's water suppliers will begin to rely on alternative methods of water supply to ensure water sustainability, and this could result in an increased energy demand from these systems. This study presented 4 different cities as case studies to examine how different regions of California are planning to ensure water security. The results showed that there were different water management strategies each city is planning to take as well as different energy impacts as a result. Southern California experiences a high energy intensity due to the scarcity of water in the region, while Northern California is positioned to begin exporting water from the region and generate carbon free electricity.

California has passed greenhouse gas reduction, water conservation, and energy efficiency policies within the last 10 years that emphasize resource conservation and climate mitigation as top priorities for the state. The simultaneously interdependent and competitive nature of energy and water as resources utilized by urban areas, make the relationship complicated to study. However, understanding the WEN will be critical to ensuring water and energy resiliency in the future. The variations of California's climates, economies, and geography will require the solutions to be regional. As California prepares to undergo infrastructure upgrades and undertake climate mitigation and resiliency projects, regional examination of the connections between water and energy will be key. Capitalizing on the construction and upgrades that both the energy and water infrastructure in California need, will help ensure that sustainable solutions are developed that utilize the benefits of the WEN.

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