Exploring Advanced Treatment Options for California Water Security

A Management Plan for Three Sites Across California

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Client

Jing-Tying Chao, State Water Resource Control Board

Project Advisor

Dr. Arturo Keller, UCSB Bren School

Prepared by the Water Resourcerers

Savana Gonzales, MESM '23

Renee LaManna, MESM '23

Thomas Lenihan, MESM '23

Trevor Maggart, MESM '23

Matt McCafferty, MESM '23

Taylor Medina, MESM '23

Signature Page

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Taylor Medina	Renee LaManna	Thomas Lenihan
Trevor Maggart	Matt McCafferty	Savana Gonzales

The Bren School of Environmental Science & Management produces professionals with unrivaled training in environmental science and management who will devote their unique skills to the diagnosis, assessment, mitigation, prevention, and remedy of the environmental problems of today and the future. A guiding principle of the School is that the analysis of environmental problems requires quantitative training in more than one discipline and an awareness of the physical, biological, social, political, and economic consequences that arise from scientific or technological decisions. The Group Project is required of all students in the Master of Environmental Science and Management (MESM) Program. The project is a year-long activity in which small groups of students conduct focused, interdisciplinary research on the scientific, management, and policy dimensions of a specific environmental issue. This Group Project Final Report is authored by MESM students and has been reviewed and approved by:

Dr. Arturo Keller	Date

1 Introduction

California faces immense challenges as climate change and the rising demand for water continue to strain the state's available resources. Multi-year droughts have occurred throughout California's history and evidence shows they have worsened in recent decades (Medellin et al., 2022). The past 20 years have been exceptionally arid and included the hottest drought (2012–16) in the state's recorded history (Mount et al., 2021). According to the US Drought Monitor, most of the state is experiencing severe or extreme drought; however, driving factors extend beyond low precipitation numbers. Over the next 20 years, California could lose an estimated 10 percent of its water supply (CA Natural Resource Agency, 2022). Increased evaporation from rising temperatures, groundwater depletion—particularly severe throughout the Central Valley—and a shrinking Colorado River further contribute to water shortages throughout much of the state. With worsening water quality issues, aging infrastructure, and reservoirs at critical lows, Californian communities must employ supply-side and demand-side solutions to ensure an affordable, safe, and secure water supply in future years.

1.1 California Water Issues

California's demographic and geographic diversity has contributed to the array of water quality challenges the state is now facing. Groundwater basins that smaller rural communities rely on for their water have increasingly high levels of nitrate—caused by fertilizer and manure—polluting local drinking water supplies (Hanak et al., 2017). High nitrate concentrations in drinking water have been linked to methemoglobinemia and thyroid cancer (Tariqi & Naughton, 2021). Throughout the early 1900s, technology for treating water pollution did not advance at the same speed as agricultural growth (Olmstead & Rhode, 2018). Finding solutions for these conditions has become complex and expensive, involving divergent economic, environmental, and political groups (Kelley & Nye, 1984). Treatment to remove contaminants from drinking water is costly, especially for small rural systems (Hanak et al., 2017). Low-income and minority communities often face disproportionate burdens of exposure to contamination and pollution, and associations with race and ethnicity persist even after accounting for differences in income (Bullard & Johnson, 2002).

Elevated salinity levels in surface and groundwater have also become an emerging water quality issue, primarily from California's allotment of the Colorado River water supply, which is more saline than State Water Project water; the reuse of water for irrigation; and seawater intrusion—all of which contribute to an increased concentration of salts in water supplies (Pauloo et al., 2021; Hansen et al., 2018). Highly populated coastal areas suffer the greatest from seawater intrusion, in which saline ocean water seeps into underground basins that have been depleted through intensive groundwater pumping (Chappelle et al., 2015). Excess nutrients in the soil such as nitrate-nitrogen can also be mobilized by high salinity, thereby exacerbating nutrient pollution, which contributes to harmful algal blooms and low dissolved oxygen levels in lakes and rivers (U.S. EPA, n.d.). Taken together, excess salts can make water undrinkable, increase the cost of treating water and harm freshwater fish and wildlife (U.S. EPA, n.d.).

Approximately 10% of California's public drinking water systems are currently out of compliance with state drinking water quality standards. An estimated six million Californians are served by systems that have been in violation since 2012 (Pace et al., 2022). Further, the state spends nearly $10 billion on water pollution control annually, with most expenditures being point sources of pollution such as wastewater treatment (Chappelle et al., 2015). In addition to pollution, droughts also result in significant changes in water quality (Mosely, 2015). Reduced stream and river flows can increase the concentration of pollutants in water and cause stagnation. Runoff from drought-related wildfires can carry extra sediment, ash, charcoal, and woody debris to surface waters, killing fish and other aquatic life by decreasing oxygen levels in the water (CDC, 2020). However, effects can vary depending on the characteristics of the water body and its catchment (Mosely, 2015).

Climate change factors have also increased the drought risk in California. Anthropogenic warming is increasing the probability of co-occurring warm-dry conditions like those that have created the acute human and ecosystem impacts associated with the "exceptional" 2012–2014 drought in California (Diffenbaugh et al., 2015). As the climate crisis intensifies, California droughts have the potential to become more severe. California water supply issues are amplified by five climate pressures: warming temperatures, shrinking snowpack, shorter and more intense wet seasons, more volatile precipitation, and rising seas (Mount et al., 2019). These factors affect all aspects of water management. Average temperatures in the state have been rising for the last 40 years creating complex and interrelated effects. Specifically, this rise reduces the share of precipitation falling as snow, causes earlier snowpack melting and higher winter runoff, raises water temperatures, and amplifies the severity of droughts and floods (Mount et al., 2019).

At the beginning of water year 2022, based on measurements from the California Department of Water Resources (DWR), all major California water reservoirs were well below the historical averages, and some were experiencing critically low levels. The two largest reservoirs, Oroville and Shasta, were at 31% of the total capacity (California Department of Water Resources, 2022). Both reservoirs are pivotal to California's largest water storage and delivery systems—the State Water Project and Central Valley Project—that provide water for millions of California residents and farmlands. Historically, drought has always been a regular part of California's landscape, but a dry period as extended and severe as this recent period severely challenged California's reservoirs and capacity to meet water demand (Ullrich et al., 2018).

California further relies on importing water from the Colorado River Basin. The Colorado River has been an essential component of Southern California's imported water supply for 80 years (Metropolitan Water District, 2021). Relying on the Colorado River is becoming increasingly tenuous. States in the Colorado River basin are scrambling to propose steep cuts in water use from the river in response to a call by the federal government for immediate, drastic efforts to keep the river's main storage reservoirs from reaching critically low levels (Fountain, 2022).

1.2 Potential Solutions

One potential solution to mitigate these issues is through water markets, which transfer or sell water or water rights from one user to another. If properly regulated, water markets can be a powerful mechanism for improving water scarcity, restoring ecosystems, and driving sustainable water management. However, water markets and privatization threaten to exacerbate existing water injustices as low-income communities and communities of color cannot access these markets (Gibler, 2005). While these solutions have the potential to alleviate some burden, there are serious limitations that must be considered and addressed, and any market-based approaches must be complemented with conservation efforts and technology-based solutions.

Historically, the State Water Resource Control Board (SWRCB) and Department of Water Resources (DWR) have used regulation to manage water demand and increase supply. The passing of the 2014 Sustainable Groundwater Management Act (SGMA) is the most recent package of state legislation aiming to address groundwater demand in critically overdrafted basins across the state. The legislation provides a framework for long-term sustainable groundwater management with the goal of achieving groundwater sustainability by 2040. Since 1983 urban water suppliers have also been required to develop and report Urban Water Management Plans (UWMPs) which have helped to improve water use, by requiring an emphasis on water use efficiency and better long-term planning. The list of requirements in the UWMPs has been updated numerous times, with each revision attempting to reinforce its core purpose: assessing the extent to which current and future water supply sources will meet water demand at an appropriate level of reliability for years with normal levels of precipitation as well as during single or multi-year droughts (Hanak, 2010). These plans are useful tools to aid with goal-setting, accountability, and transparency, but alone are not enough to secure a reliable water supply during extensive drought years. Water conservation measures are another tool that California policymakers can utilize to curb demand. California's changing climate requires residents to move beyond temporary emergency drought measures and adopt permanent changes to use water more sparingly and prepare for more frequent and persistent periods of limited water supply (Cal Water Board, 2023). Water conservation can be effective, as evidenced by the decoupling of California's population growth and the state's overall water consumption over the past two decades (Figure 1-1); however, conservation measures are not always popular among segments of the public, and efforts to hit reduction targets over the past few years have fallen short (Cal Water Boards, 2023).

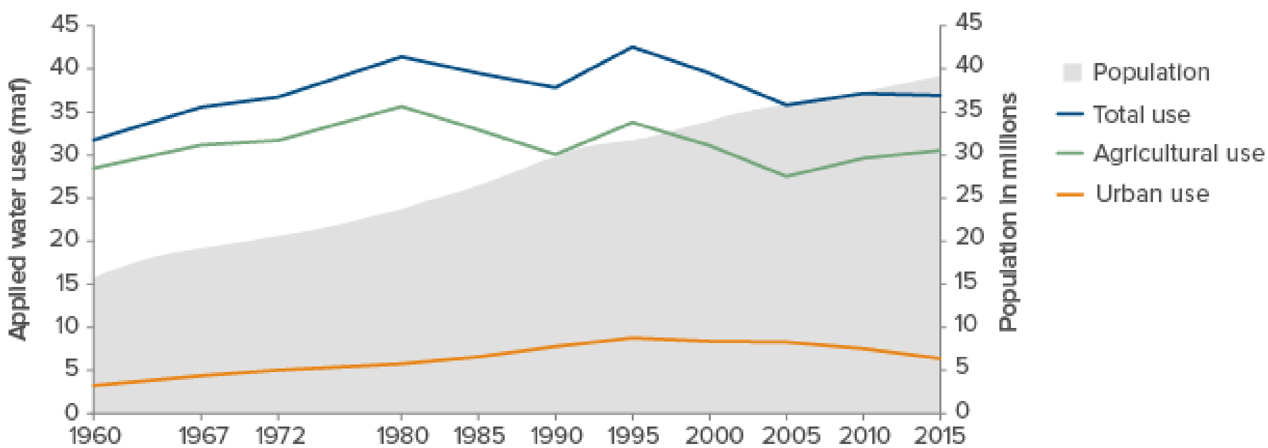

Figure 1-1. *California Water Use 1960-2016 (Cooley, 2020).*

The state has also employed other supply-side strategies and water resource management tools to address this issue. With California projected to lose around ten percent of its water supply by 2040, securing sustainable water supplies is crucial for the state (CA Water Supply Strategy, 2022). In addition to expanding reservoir storage capacity and freeing up existing water supply through conservation measures, California's new Water Supply Strategy Plan calls for the state to use at least 800,000 acre-feet of recycled or reused water per year and to secure new water supplies through desalinating ocean water and salty groundwater (CA Water Supply Strategy, 2022). The strategy is part of Gov Newsom's broader water resilience strategy that has already invested $8 billion of state investments to shore up water supplies. The plan outlines a strategy to capture, recycle, desalinate, and conserve enough water over the next two decades to provide additional supply for nearly 8.4 million households. This is a significant investment; however, much more is still needed to address the worsening California's water supply problem. If the state moves to implement this plan, three water treatment technologies will be critical for accomplishing these goals: Indirect Potable Reuse, Direct Potable Reuse, and Desalination. Indirect potable reuse (IPR) takes treated wastewater which would otherwise be released into local waterways and treats it further to reach a level of water safety sufficient to release it into an environmental buffer, typically a groundwater basin or reservoir (Keller et al., 2022). Once the water is deposited into the basin or reservoir, it becomes part of the water supply and can be drawn upon by existing infrastructure.

Using an environmental buffer means that IPR can function as a water recycling method, a means of supplementing existing groundwater supplies, or a way to address land subsidence and seawater intrusion. Direct Potable Reuse (DPR) uses the same basic water treatment processes as IPR but does not employ an environmental buffer to mediate the final filtration of contaminants/pollutants. Instead, the water undergoing DPR is treated to meet safe drinking water standards before being released directly into the drinking water system (Keller et al., 2022). In addition, emergency planning needs to be considered in terms of emergency buffer reservoir(s) and planning for situations where the treated water does not meet specifications (Keller et al., 2022).

Desalination removes salts, other minerals, and contaminants from seawater, brackish water, and wastewater effluent. It is an increasingly common solution to obtain freshwater for human consumption, and domestic and industrial utilization (Asadollahi et al., 2017). Desalination uses seawater or saline groundwater as input and treats it to remove the salts, leaving freshwater that can then be treated to drinking water standards. As a byproduct, the desalination process produces a highly saline brine solution that is often cited as a potential source of contamination in marine ecosystems (Pistocchi et al., 2020). While these water treatment technologies utilize many of the same unit processes to treat non-potable water, each technology is suited for different communities, economic and political considerations, and geographic conditions.

Despite the promise of each of these three water treatment technologies and California's dire need of additional water supply, there are currently few communities in the state utilizing these technologies. This is particularly true of IPR and DPR, which could alleviate the overwhelming demand for groundwater in many areas by recharging existing groundwater basins. On average, underground aquifers provide nearly 40% of the water used by California's farms and cities, and significantly more in dry years (Chapelle et al., 2017). About

85% of Californians depend on groundwater for some portion of their water supply (Chapelle et al., 2017). California's groundwater basins are depleting at a rate that, if unchecked, could significantly impact the water supply in the near future; as mentioned, California's current goal is to achieve groundwater sustainability by 2040. Without significant investment in groundwater recharge and reducing groundwater pumping—using technologies such as IPR, DPR, and desalination—California's groundwater supply will deplete precipitously before the state can act.

Our work seeks to explore the potential to implement these technologies (i.e., DPR, IPR, desalination) in water districts situated in areas of the state under particularly acute water stress. Using publicly available data from industry, state agencies, and water districts, we evaluated three urban water districts in select Southern and Central California cities that provide a baseline evaluation of the economic viability, environmental impacts, and environmental justice considerations associated with the implementation of IPR, DPR, or desalination in each location. We chose the cities of Bakersfield, Fresno, and Oxnard as the sites of our assessment. The water problems these cities face are representative of those plaguing many communities across Southern California and the Central Valley. Water quality issues from nitrate, salt, phosphate, arsenic, and emerging contaminants; a widening income gap, worsening poverty, and linguistic isolation of marginalized communities straining access to clean water; rising water costs due to shrinking groundwater supplies that require deeper wells to extract; and increased climate risk from droughts and wildfires that affect key infrastructure are all factors contributing to a severe threat to the supply of drinkable and affordable water for these communities.

Using data from CalEnviroScreen 4.0, we evaluated risks to water supply and equitable access to characterize the water-related risks facing our chosen cities. We looked for hotspots or problem areas that may need to be considered when procuring new water sources. We paired this assessment with an economic model, which uses key parameters such as daily water demand, groundwater depth, and other factors to estimate the costs and energy intensity of DPR, IPR, and desalination technologies if implemented in each of these cities. Together, our assessments offer a preliminary picture of how these various water treatment technologies could be applied to regions facing an increasingly scarce water supply. This management plan can aid policymakers in their efforts to secure clean, accessible, and affordable water for all Californians.

2 Technology Overview

2.1 Wastewater Treatment Levels

There are four main stages in California wastewater treatment: preliminary, primary, secondary, and tertiary. The initial step in the wastewater treatment process is called preliminary treatment, which begins with all raw sewage from domestic and commercial sources entering the treatment plant at the plant's head works (Guide to California Wastewater, 2013). This treatment removes large and medium-sized solid waste using screens and sieves. Following preliminary treatment, the wastewater enters primary treatment, which focuses on removing suspended solids and floating particles. This process is primarily physical, as wastewater is piped into primary settling or sedimentation tanks where heavy particles sink to the bottom and light particles float (Nickles, 2013). Chemicals such as coagulants are added during this process to improve the sedimentation of solids. Mechanical arms skim the top and bottom of the channeled wastewater to remove the floating and sunken particles. Once the particles are removed from the water, the water is channeled to secondary treatment, focusing mainly on biological processes.

During the secondary treatment stage of the wastewater treatment process, biological processes are utilized to eliminate contaminants present in the wastewater (Nickles, 2013). This involves the use of bacteria and microorganisms to break down and remove nutrients such as nitrate, phosphate, and organic matter. The wastewater flows through large tanks with air pumped in to facilitate the growth of naturally occurring microorganisms that feed on organic materials. Once the microorganisms have consumed and digested the organic matter, the treated wastewater is sent to secondary sedimentation tanks, where the microorganisms settle to the bottom and are removed (Nickles, 2013).

After undergoing secondary treatment, at least 85 percent of the solids and organic materials present in the wastewater have been eliminated (Nickles, 2013). The next stage in the process is tertiary treatment, which can eliminate over 99 percent of impurities, resulting in water quality that meets potable (drinking water) standards. Advanced treatment options are used for this stage, including the removal of residual nutrients such as phosphorus and nitrogen, as well as suspended solids and micropollutants like pharmaceuticals and chemicals found in personal care products (Nickles, 2013). Some methods used in tertiary treatment include chlorination and activated carbon absorption, which are effective in destroying harmful microorganisms and other contaminants present in the water (Nickles, 2013).

2.2 Advanced Water Treatment Methods

Multiple water treatment methods are considered advanced water treatment, including various types of filtration depending on the technology used. For instance, biofiltration enables microorganisms to colonize water plant filters and remove biodegradable compounds from water. The biofilm, which is the microbial growth attached to the filter media, consumes organic matter that would otherwise flow through the treatment plant and ultimately into the distribution system (Water Research Foundation, n.d.).

There are four types of membrane filtration, namely nanofiltration, ultrafiltration, reverse osmosis, and microfiltration, that can sequentially remove nearly all pathogens and pollutants from water (Keller et al., 2022). The size of materials that can be removed during filtration depends on the size of the filter's pores (Hancock, 2018). Figure 2-1 illustrates which types of particles are removed by each membrane filter.

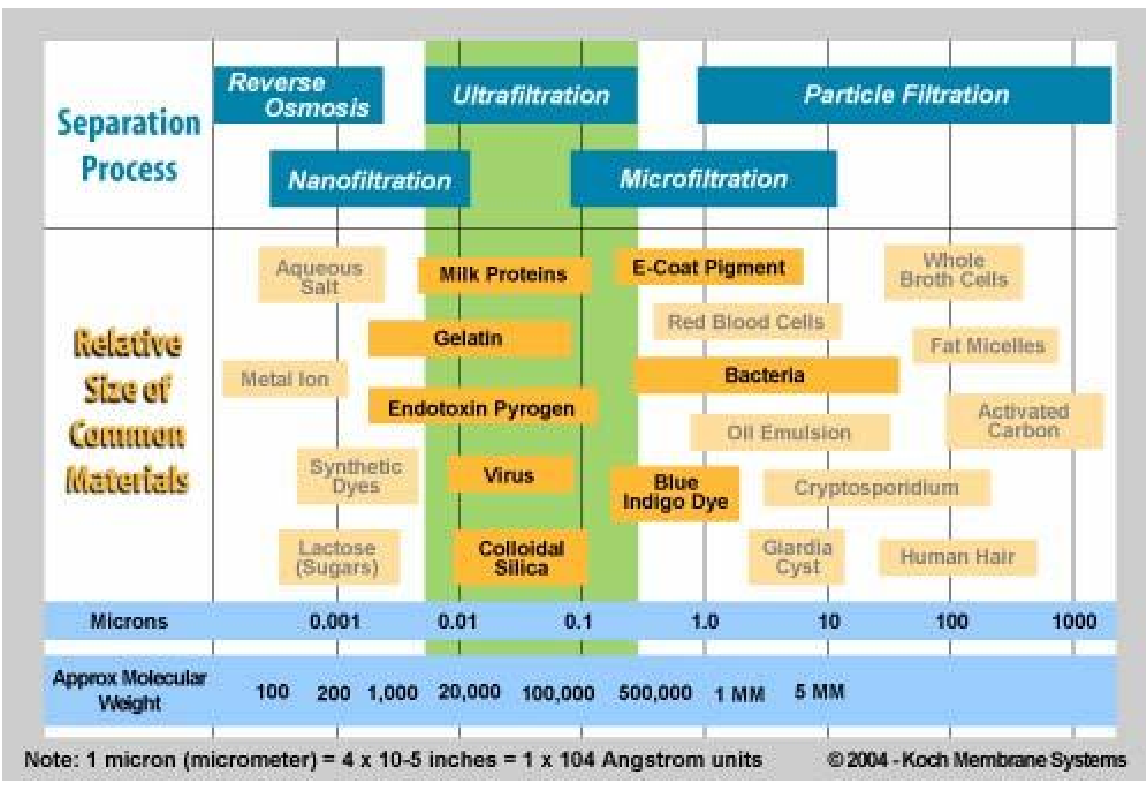

Figure 2-1. *Size of particles removed by various separation processes (Hancock, 2018).*

Reverse osmosis is utilized for the final stage of potable reuse and for ocean desalination processes, removing contaminants or particles from water by pushing only water molecules through a semipermeable membrane under high pressure, leaving behind a brine concentrated with salts and contaminants. In addition to reverse osmosis, other advanced water treatment methods such as UV disinfection and advanced oxidation are also used. These processes eliminate harmful pathogens and bacteria using ultraviolet light or by adding ozone to the water.

2.3 Indirect Potable Reuse

Water reuse (also known as water recycling or reclamation) reclaims water from various sources and then treats and reuses it for beneficial purposes such as agriculture and irrigation, potable water supplies, groundwater replenishment, industrial processes, and environmental restoration (EPA Water Reuse, 2022). Indirect Potable Reuse (IPR) is a water treatment process that takes treated wastewater from a wastewater treatment plant and treats it to drinking water standards to input into an environmental buffer (Figure 4-1; Keller et al., 2022). There are two types of IPR projects in California: Groundwater Replenishment Reuse Projects (GRRP) and Surface Water Source Augmentation Projects (SWSAP) (California DWR, 2021). A GRRP is a project involving the planned use of recycled municipal wastewater that is operated for the purpose of replenishing a groundwater basin designated in the Water Quality Control Plan [as defined in Water Code section 13050(j)] for use as a source of municipal and domestic water supply (California DWR, 2021). A SWSAP is a project involving the planned placement of recycled municipal wastewater into a surface water reservoir that is used as a source of domestic drinking water supply, for the purpose of supplementing the source of domestic drinking water supply (California DWR, 2021). According to California DWR, the recycled municipal wastewater applied by a Groundwater Replenishment Reuse Project (GRRP) and Surface Water Source Augmentation Project (SWSAP) shall be retained for a period of time necessary to allow a project sponsor sufficient response time to identify treatment failures and implement actions, including those required pursuant to section 60320.100(b), necessary for the protection of public health. The California DWR requires there is a minimum of two months. Using an environmental buffer means that IPR can function as either a water recycling method or a means of supplementing existing groundwater supplies and addressing land subsidence and seawater intrusion.

To regulate the use of recycled water, the State Water Resources Control Board published Title 22, Chapter 3, under Social Security in the California Code of Regulations. Title 22, Chapter 3, refers to state guidelines for how treated and recycled water is discharged and used. Title 22 lists 40 specific uses allowed with disinfected tertiary recycled water (such as irrigating parks), 24 specific uses allowed with disinfected secondary recycled water (such as irrigating animal feed and other unprocessed crops), and seven specific uses allowed with non-disinfected secondary recycled water, such industrial uses (Water Education Foundation, 2017). The California State Water Resources Control Board defines environmental buffers in two categories: "groundwater replenishment" (e.g., basins) and "surface water augmentation" (e.g., reservoirs). An environmental buffer provides enough residence time to achieve water quality objectives. From there, the water is extracted and transported to a drinking water facility that treats the water to drinking water standards. The most common tertiary treatment processes in IPR include microfiltration, reverse osmosis, UV light treatment, and oxidation using ozone or hydrogen peroxide. Often, the UV light and oxidation processes are combined into one step. There are many alternative unit processes in IPR, such as using nanofiltration membranes, ultrafiltration membranes, granular activated carbon, and activated sludge. Each of these processes has varying costs and targets differing contaminants in the water. Below is a representation of the indirect water recycling process (Figure 2-2).

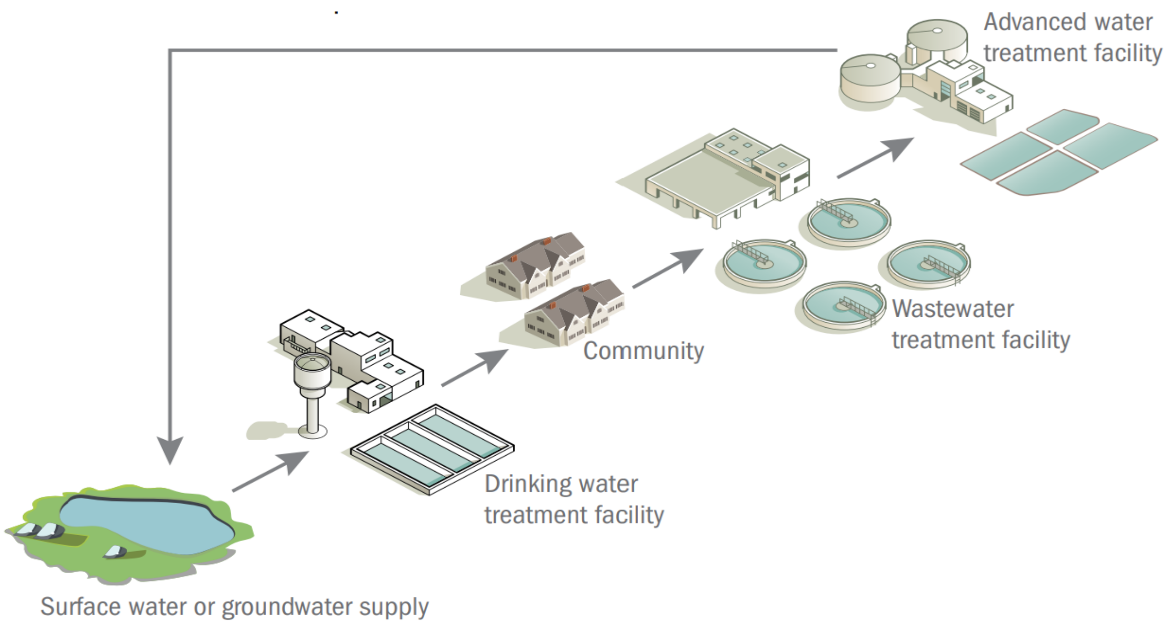

Figure 2-2. *Flow Schematic of indirect potable reuse (AWWA, 2016).*

As of 2022, there are currently 516 reclaimed wastewater facilities in the United States and 117 of those are in California (DOE, 2022). California is home to the largest IPR facility in the world, the Groundwater Replenishment System (GWRS) in Orange County. The maximum capacity for the GWRS is projected at 130 million gallons/day (MGD), after the infrastructure is built to increase wastewater flows from OC San to the GWRS and on average, the facility produces 100 MGD of potable water (GWRS, 2021). About 35 MGD are sent to water injection wells to prevent seawater intrusion while 65 MGD are sent to an aquifer to be utilized by 850,000 Orange County residents in northern and western Orange County (OCSD, 2022). First, the wastewater is treated to a secondary level in the wastewater treatment plant which is considered pretreatment for the IPR process. The first step in the advanced treatment is microfiltration, followed by reverse osmosis, and then finally a combined UV light and oxidation process using hydrogen peroxide (Guo et al., 2014). From there, 65% of the treated water is sent to the aquifer, where it is filtered naturally in the vadose zone of the soils above the aquifer. The system was built in 2008 with a capital cost of $481 million and then expanded in 2015 with a cost of $142 million (OCWD, 2022). The operation costs are $40 million per year and include power, chemicals, membrane and UV lamp replacement, and staffing (OCWD, 2022). According to the GWRS website, this IPR system uses less than half of the energy required to transport water from northern California to southern California. This energy is approximately enough to power 21,000 homes a year (OCWD, 2022). All treated wastewater not injected is released into the ocean five miles off the coast of Huntington Beach, California through the Orange County Sanitation District Ocean Outfall System (OCSD, 2020). The treated wastewater is discharged into the Pacific Ocean in strict and consistent compliance with state and federal requirements as set forth in OCSD's NPDES permit (OCSD, 2020).

Other IPR sites include Singapore's NEWater system composed of five treatment plants situated across the island. Its combined capacity is 20 MGD, 6% of which is used for drinking water (which accounts for 1% of Singapore's potable water requirement), and the rest of the treated water is used for industrial processes (PUB NEWater, 2022; Guo et al., 2014). The IPR unit processes are identical to that of the Groundwater Replenishment System in Orange County. Another important IPR site is the Scottsdale Water Campus in Scottsdale, Arizona. The system is exclusively for groundwater recharge and pumps approximately 1.7 billion gallons a year back into the city's aquifer (Scottsdale Water, 2022). A notable difference in the process is that the pretreated water first undergoes advanced oxidation by ozone, followed by ultrafiltration, then reverse osmosis, and finally ultraviolet disinfection (Scottsdale Water, 2022). As of 2019, the state of Arizona authorized Scottsdale Water Campus a permit for direct potable reuse, but it continues to operate as an indirect potable reuse facility to maintain a diverse water use portfolio (Scottsdale Water, 2022).

2.4 Direct Potable Reuse

Direct Potable Reuse (DPR) is similar to Indirect Potable Reuse, but with the key difference that there is no environmental buffer, and the water is released directly into the drinking water system (Figure 2-3; Keller et al., 2022). As DPR technology lacks an environmental buffer, this type of technology will also need to ensure that multiple treatment barriers are in place to address reduction of constituents of concern (Chan, 2014). Treatment barriers could include an Engineered Storage Buffer (ESB) to handle any flows that are suspected of not meeting drinking water standards. An ESB is a storage facility used to provide retention time—before advanced treated water is introduced into the drinking water treatment facility or distribution system—to (1) conduct testing to evaluate water quality or (2) hold the water in the event that it does not meet specifications (Framework for DPR AWWA, 2020). The need for accurate real-time information on the actual log reduction value provided by individual treatment processes increases with proximity to the drinking water consumer and increases to a maximum for DPR (California SWRCB, 2019). There are a number of instruments (e.g., engineered treatment reliability and redundancy, monitoring, system controls, and required log reduction (LRV specifications) that can be required in a manner that compensates for the diminishing role of the environmental buffer (California SWRCB, 2019). DPR introduces purified water directly into an existing water supply system; there is a requirement for constant online monitoring at critical locations. The figure below demonstrates the direct potable reuse process.

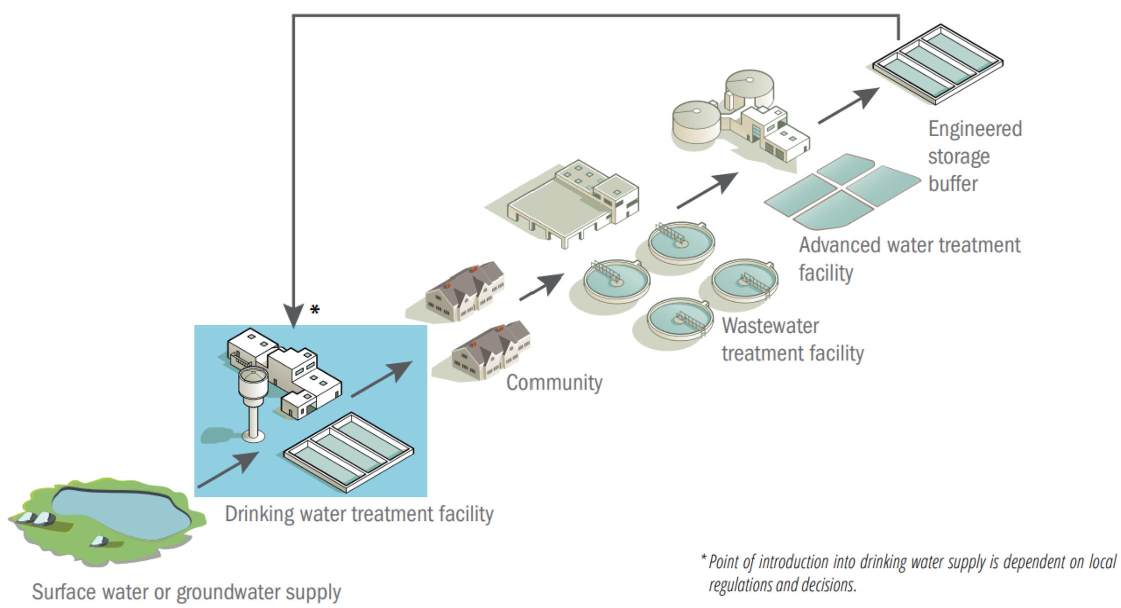

Figure 2-3. *Flow Schematic of direct potable reuse (AWWA, 2016).*

The process must treat the water to safe drinking water standards and utilizes some advanced tertiary treatment process (such as reverse osmosis and UV) followed by disinfection. Other processes such as Biologically Activated Carbon can be added to increase the reliable removal of trace amounts of contaminants not removed by reverse osmosis and UV. After treatment, the water is directly pumped to the water distribution. There are no federal regulations on DPR; thus, state, and local agencies are responsible for setting potable reuse standards. For DPR, the ability to decouple processes at key points throughout the project from a wastewater source to treated drinking water, including decoupling the treatment system from the distribution of safe drinking water, would provide treatment system protection and prevent upstream events from adversely affecting downstream systems (DPR Framework SWRCB, 2019). This could include an emergency buffer reservoir in case there is a malfunction in the

DPR process. There are no direct potable reuse sites, but permits exist, such as that mentioned above for the Scottsdale Water Campus.

2.5 Desalination

Desalination is a process that removes mineral components from saline water and turns it into potable freshwater (Figure 2-4). The process is usually applied to seawater but can also be applied to brackish groundwater. For seawater desalination, water is taken from the ocean and is forced through thousands of tightly wrapped, semipermeable membranes under very high pressure. The membranes allow the smaller water molecules to pass through, leaving salt and other impurities behind. The figure below shows how a seawater desalination facility operates and the order in which the process is applied.

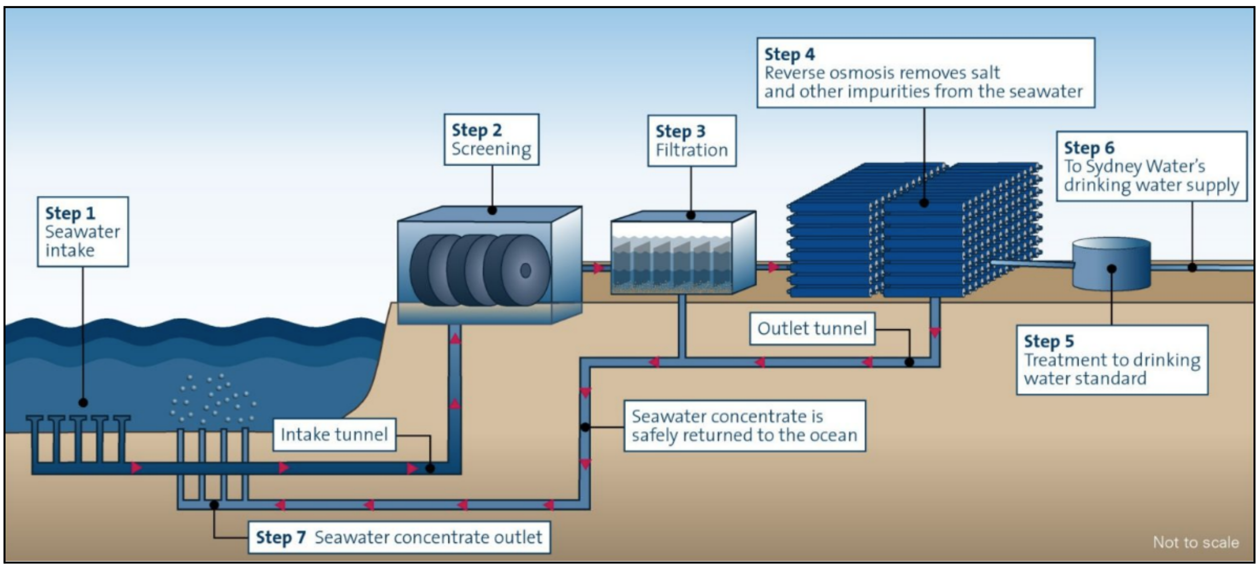

Figure 2-4. *Desalination diagram from a plant in Sydney, Australia (Sydney Desalination Plant, n.d.).*

Many countries have turned to developing desalination plants to help increase water supplies, with the number and size of projects worldwide increasing by approximately 5-6% since 2010 (Voutchkov, 2018). At present, over 150 countries currently utilize desalination to supply daily water to more than 300 million people (Panagopoulos & Haralambous, 2020). There are 19,000 existing desalination plants, which can produce more than 1×10^8 m^3/day of freshwater (Alrowais et al., 2022). With water scarcity issues continuing to worsen around the globe, these numbers will continue to increase.

While many methods of desalination exist, large-scale plants are frequently constructed for seawater reverse osmosis (SWRO). Using high-pressure pumps coupled with energy recovery devices, SWRO plants capture salt and other impurities by extracting seawater and passing it through a semipermeable layer at high pressures (Park et al., 2020). As a byproduct, this process creates a hypersaline brine that is difficult to dispose of safely. It can be returned to the ocean, provided there is adequate natural dispersion and dilution to minimize environmental impacts. The process is highly energy intensive. While technological advancements have lowered the specific energy consumption for SWRO from 20 kWh/m^3 to 2.5 kWh/m^3 within the last 50 years, the energy demand still often remains too great to warrant its implementation in regions with more effective alternatives (Park et al., 2020). However, the concern over decreasing water supplies in California has led to an increase in the creation of desalination facilities across the state. Currently, there are 12 active plants in California, and an additional 5 have been proposed or are currently under construction (California Waterboard, 2022). The largest desalination plant in the United States is the Carlsbad Desalination Plant located in San Diego, California. The plant provides 50 MGD to over 400,000 residents (Carlsbad Plant FAQ Sheet, 2020). There are process alternatives to reverse osmosis in desalination plants, including the use of nanofiltration, coupling nanofiltration and reverse osmosis, forward osmosis, electrodialysis, ion exchange, and membrane distillation (Zhou et al., 2015).

3 Law and Regulations

3.1 Federal Law

3.1.1 Clean Water Act

The Clean Water Act (CWA) is the primary federal statute regulating and protecting the quality of the United States' surface and groundwater sources. The CWA establishes the basic structure for regulating discharges of pollutants into the waters of the United States and regulating quality standards for surface waters (USEPA, 2022). The Clean Water Act sections 303(a) and 303(b) establish state and federal pollutant thresholds for regulated waters, which are based on a particular water body's official designated use: recreation, protection of wildlife, agriculture, public drinking water supply, et cetera. A particular designated use determines the Total Maximum Daily Load (TMDL) of pollutants entering a water body. One of the central tenets of the CWA is the National Pollutant Discharge Elimination System (NPDES), which prevents water pollution by making it unlawful to discharge pollutants from a point source unless official documentation approved by the EPA—called an NPDES permit—is obtained. Point sources are discrete conveyances transferring a pollutant into a regulated body of water, such as pipes or man-made ditches. Since the CWA requires all states to comply with this system, water districts must consider the acceptable levels of pollutants for which the water district can obtain NPDES permits to discharge water sources and wastewater. To comply with the CWA, water reuse projects such as desalination plants, DPR facilities, and water purification plants (that have outflows) must obtain NPDES permits to discharge brine, a common byproduct of these sites.

3.1.2 Safe Drinking Water Act

The Safe Drinking Water Act (SDWA) is the primary federal legislation responsible for ensuring safe drinking water for the US population. The Safe Drinking Water Act (SDWA) authorizes the United States Environmental Protection Agency (USEPA) to set national health-based standards for drinking water to protect against both naturally occurring and man-made contaminants that may be found in drinking water (USEPA, 2004). These National Primary Drinking Water Regulations set enforceable maximum contaminant levels for particular contaminants in drinking water or required ways to treat water to remove contaminants. This law focuses on all waters actually or potentially designed for drinking use, whether from above-ground or underground sources. The SDWA applies to all public water systems but does not include private wells.

3.1.2 Drinking Water State Revolving Funds

The Drinking Water State Revolving Funds program is a federal-state partnership that provides communities with low-cost financing for a wide range of water quality infrastructure projects (USEPA, 2022). The DWSRF financial assistance helps states achieve the health protection objectives of the SDWA. The funds are appropriated through Congress, and the grants are for all 50 states, Puerto Rico, US Virgin Islands, American Samoa, and Guam. The states are overall responsible for contributing an additional 20 percent to match the federal grant and are also responsible for the operation of the DWSRF programs. Loan repayments are used to support new projects, hence the revolving nature of the program (WaterReuse Association, 2022). There are various types of assistance that the grants can be used to include improving drinking water treatment, water supply, piping, and other infrastructure projects needed to enhance water quality. Publicly-owned utilities and privately-owned water reuse facilities are eligible for funding (WaterReuse Association, 2022). Eligible water reuse projects include direct potable reuse, groundwater recharge, and indirect potable water reuse.

3.2 California Regulatory Bodies

3.2.1 Department of Water Resources

The Department of Water Resources (DWR), established in 1956, is the regulatory authority responsible for protecting, developing, and managing most of California's water resources. To this end, the DWR maintains the necessary infrastructure to provide the state with adequate water supplies to sustain California's water needs. This includes maintaining and managing the State Water Project (SWP)—the largest state build water distribution system within the United States. Further, the DWR oversees other responsibilities such as the protection and restoration of the Sacramento-San Joaquin Delta, the development and improvement of the California Water Plan, and providing support to local water agencies through various means (California Department of Water Resources, 2023c).

3.2.2 State Water Resources Control Board

The State Water Resources Control Board (SWRCB)—established in 1967 within the California Environmental Protection Agency—is responsible for ensuring the highest possible standard of water quality throughout California, while also allocating these resources to optimize beneficial uses. The board is composed of five full-time salaried members appointed by the Governor and confirmed through the state senate. Each member fulfills a specialized role and serves a 4-year term. Water allocations and water quality standards are established and enforced under the authority of the SWRCB (California Water Boards, 2018).

3.2.3 Regional Water Quality Control Boards (Regional Boards)

In addition to the SWRCB, California has nine Regional Boards reporting to the SWRCB to manage the state's water resources to optimize beneficial use while taking into account local variables such as topography, climate, etc. Each regional board consists of seven part-time members that, like the SWRCB, are appointed by the Governor and confirmed through the state senate. In practice, the Regional Boards are responsible for the development of water basin plans, issuing discharge permits, monitoring water quality, and enforcing regulations against violators (California Water Boards, 2018).

3.2.4 California Coastal Commission (CCC)

Established in 1972, the CCC plans and regulates the use of land and water in the coastal zone. Under the California Coastal Act, development activities within the coastal zone require a coastal permit from the CCC. Ocean desalination plants require proximity to the ocean, oftentimes within the coastal zone. Therefore, the CCC plays an important role in determining if desalination projects may receive a permit to develop and operate within this zone. In 2022, the CCC rejected a $1.4 billion plant in Huntington Beach but has recently accepted others in Orange County and Monterey Bay.

3.3 California Water Law

3.3.1 Sustainable Groundwater Management Act (SGMA)

The SGMA, passed into law in 2014, is a California-wide framework with the goal of long-term protection of groundwater resources. SGMA requires local agencies to form groundwater sustainability agencies (GSAs) for both high and medium-priority basins. The process of assigning basin prioritization is described in California Water Code Section 10933(b). Our three study districts all source water from high-priority basins that are managed by one or more GSAs. GSAs were required to submit Groundwater Sustainability Plans (GSPs) to the California Department of Water Resources (DWR) for critically overdrafted basins by January 31, 2020, and by January 31, 2022, for basins not considered to be critically overdrafted by the DWR. Within each GSP, the sustainable yield for the groundwater basin must be determined and a management plan that supports the goal of obtaining the sustainable yield within 20 years of submission is required. DWR is responsible for regulatory oversight of SGMA including the evaluation and assessments of GSPs. DWR also provides best management practices and guidance, in addition to planning, technical, and financial assistance (California Department of Water Resources, 2020).

3.3.2 California Water Code

Under California Water Code, every urban water supplier that either supplies more than 3,000 acre-feet of water annually or serves more than 3,000 urban connections is required to submit an UWMP. The requirements outlined in California Water Code, §10610-10656 and §10608 state that UWMPs are submitted every 5 years by qualified urban water suppliers. Within the UWMP, suppliers are required to include the following: assess the reliability of water sources over the sequential 20 years, describe demand management measures and water shortage plans, report progress toward meeting a targeted 20% reduction in per-capita urban water consumption by the year 2020, and consider the use and planned use of recycled water. Where a supplier sources groundwater from a basin regulated under SGMA, the GSA, and GSP of the basin will be considered. DWR reviews submitted UWMPs to ensure the requirements identified within California Water Code have been addressed.

3.3.2 California Coastal Act

Passed into law in 1976, the California Coastal Act (CCA) designates the California coastal zone as a 'distinct and vital' natural resource. It emphasizes that protecting the coastal zone is essential to keep a balanced ecosystem and maintain California's natural and scenic resources. Further, the act maintains that protecting this vital ecosystem is important for promoting the health and well-being of wildlife, marine fisheries, ocean resources, and public and private property. The act acknowledges that economic development may need to occur within the coastal zone to protect the state's inland resources, and it strives to ensure a healthy coastal ecosystem while considering the economic and social needs of the people of California (California Coastal Commission, 2023).

4 Ecological Risks

4.1 Potable Reuse

4.1.1 Hypersaline Brine Disposal

During the desalination process, feed water is separated into two streams, a freshwater product stream and a byproduct stream consisting of brine (Panagopoulos et al., 2019). Like desalination and other water purification methods, both DPR and IPR produce brine as a byproduct which requires proper disposal. Brine is an unavoidable product of seawater desalination and is commonly disposed of in oceans and seas, where it has negative effects on the surrounding marine environment and its biodiversity due to the resultant increased salinity and temperature, as well as the presence of chemicals (Omerspahic et al., 2022). While this disposal method is an option for desalination, DPR, and IPR operations in coastal regions, it is not feasible for operations in arid regions distant from a coastline. Brine is commonly disposed of in the environment with various methods, such as deep-well injection, evaporation ponds, and land application (Mickley, 2018). Each method has associated environmental impacts such as groundwater pollution risk in the case of seismic activity, land use, and impacts on local organisms (Soliman et al., 2021). Brine can be harmful to the environment due to its salinity, temperature, and chemical substances (Panagopoulos et al., 2019). Concerns associated with brine disposal for groundwater and surface water pollution are increased salinity of receiving water bodies and soil, regional impacts of high-TDS brine on marine benthic communities near the discharge point, esthetic problems, disposal of pretreatment and membrane cleaning chemicals, disposal of corrosion-derived metal ions such as copper (Cu), iron (Fe), nickel (Ni), molybdenum (Mo) and chromium (Cr) (Panagopoulos et al., 2019). NPDES permits are required by the RWQCB for desalination, IPR, or DPR plant discharging brine to the environment.

4.1.2 Chemicals of Emerging Concern

Not all chemicals of emerging concern (CECs) are completely removed by current wastewater treatment technology, as it is not required, and therefore remain a concern when purifying recycled water for DPR and IPR. Many CECs such as disinfection byproducts (DBPs), endocrine disrupting chemicals (EDCs), pharmaceuticals and personal care products (PPCPs), per- and polyfluoroalkyl substances (PFAs) have relatively low molecular masses ($\approx 5x10^2$ g/mol), and small sizes (≈ 0.5 nm). The small size and low molecular masses of CECs prevent sufficient removal via primary and secondary treatments. Some advanced tertiary treatment combinations can remove CECs; however, the treatment processes do not fully decontaminate the water (Fanourakis et al., 2020).

The combination of nanofiltration and RO rejects most PPCPs and PFAS (Szczuka et al., 2021 and Keller et al., 2022). Advanced oxidation processes are also considered an effective treatment option for the removal of residual CECs. Ozone-based and UV-based processes showed removal efficiencies of over 80% for a variety of antibiotics, anti-inflammatories, and pesticides, particularly with ciprofloxacin and amoxicillin (Bermúdez et al.). The most effective removal method in wastewater treatment is reverse osmosis with almost 100% removal efficiency of emerging pharmaceutical compounds (Lopera et al., 2019). Despite most CECs being rejected by advanced removal processes, the remaining concentration of CECs presents low-dose long-term exposure to humans and the environment (Vandenberg, 2022).

IPR design incorporates an environmental buffer in which recycled water after being treated to a potable level is injected into a natural water source (the environmental buffer). As a result, natural water may be considered degraded by the addition of reclaimed water that may contain residual levels of CECs. The residual CECs can bioaccumulate and subject aquatic life to low-dose long-term exposure. Research in the release of CECs via treated wastewater effluent is relatively new and the effects are not fully understood. However, there is significant evidence that chronic exposure to low levels of CECs such as pharmaceuticals and hormone-containing substances can have significant effects on aquatic vertebrates that inhabit the water bodies in which CECs are introduced. Depending on the concentrations, potential effects can be severe and result in neurological, reproductive, and developmental defects (Vandenberg, 2012). CECs also present a risk for DPR, but because the loop is closed and the environmental barrier removed, the concern is focused on human health.

In both DPR and IPR, the extent to which CECs may impact humans and aquatic life is not fully developed. However, the current scientific consensus is that there may be negative effects associated with low-dose long-term exposure to CECs (Vandenberg, 2012 & Keller, 2022). The unknowns and current understanding of CECs make constant real-time monitoring to detect low levels of CECs essential to potable reuse (Keller, 2022). Real-time monitoring, especially for DPR and redundant filtration mechanisms is vital to avoid potential system failures that would result in the exposure of the public to CECs.

4.1.3 Reduction in Wastewater Discharges

Reduction in wastewater discharges is a potential environmental concern unique to DPR. DPR reduces wastewater discharges because instead of flow being released into the environment, it is being reused in this closed-loop process. Many inland water bodies in arid regions are supported by WWTP effluent, which often makes up a significant portion of their flow. Some of these water bodies would not have been flowing on a regular basis and the WWTP effluent has allowed them to have a regular flow and support plants and wildlife. Many of these small water bodies supported by WWTP effluent have established communities of aquatic and riparian species which could be negatively impacted if water levels are reduced (Scruggs, 2017). On the positive side, by not discharging treated wastewater to these water bodies that may contain residual CECs, the ecological risk is reduced.

4.2 Desalination

4.2.1 Groundwater Brine Disposal

Brine resulting from groundwater desalination is much less salty compared to brine created from seawater desalination. For reference, brackish groundwater salinity may range from 1,000 ppm to 10,000 ppm, while ocean water is typically found at salinities greater than or equal to 35,000 ppm (NGWA, 2013). Seawater desalination brine is routinely disposed of into the ocean near the location where the water was initially pumped from. Contingent upon the location of the groundwater desalination plant, the brackish water waste disposal methods include sewage discharge, land application, salt processing and evaporation ponds, and deep well injection (NGWA, 2013). Direct well injection and sent to treatment plant

Sewage discharge and land application practices may lead to soil and water contamination. In addition to the evident water resources contamination it may cause, the discharge can reduce soil fertility and inhibit nutrient uptake and plant and crop growth. Large and impervious land space is necessary for the development and use of the evaporation ponds disposal method. Permeable ponds and humid/tropical climates would also allow for the contamination of regional soil and water resources. Deep well injection is not legal in many states, but those that do permit this method risk contaminating freshwater resources (NGWA, 2013). In some locations, the deep wells reach spent oil and gas reservoirs, in which case there is adequate pore space for brine disposal.

4.2.2 Hypersaline Brine Disposal

The disposal of brine into the ocean can bring about physical, chemical, and ecological effects on the receiving environment. The greatest environmental impacts are typically identified around multi-stage flash (MSF) plants that are discharging this hypersaline product into water bodies with little flushing. These MSF plants utilize thermal distillation and can release brine that is 10-15 °C warmer than the receiving waters (Roberts et al., 2010). Brine disposal, or outfall, into any water body can result in substantial increases in salinity, temperature, and the accumulation of heavy metals, hydrocarbons, and toxic antifouling compounds (Roberts et al., 2010). The amount of wave energy, flushing, and tidal movement will influence the extent of these effects. With greater flushing, impacts to benthic communities are diminished and surface waters are typically only affected for a short period of time before the salinity and temperature effects dissipate. Additionally, most environmental effects tend to be limited to within tens of meters of the outfalls (Roberts, Johnston, & Knott, 2010). In California, permitted seawater desalination facilities must have a plan within their NPDES permit to minimize the effect on the receiving ocean water.

In environments with little to no mixing, brine plumes tend to extend the furthest across the seafloor, greatly impacting benthic communities, as opposed to the surface waters because the discharge is denser than the seawater. Some observed effects on the ecological communities include reductions in benthic diatom community richness and abundance, alterations of soft bottom structure and infaunal community diversity, and depletion of plankton and sessile invertebrate abundance (Gacia et al., 2007, Roberts et al., 2010, & Crockett, 1997). Furthermore, seagrasses are exposed to changes in vertical salinities, and desalination outfalls can significantly affect survival. Consequences include, but are not limited to, amplification of leaf necrosis and decreased carbohydrate storage in seagrass tissue, reductions in Echinoderm densities within seagrasses, and increased dominance of nematodes within the community (Ruso et al., 2007).

5 Methodology

5.1 Site Selection

The current California water crisis impacts certain areas differently, and regions of California have diversified its water supplies in response. This happens in wealthier areas like Los Angeles, Orange County, Santa Barbara, and San Diego. For example, the City of Santa Barbara upgraded its long-standing ocean desalination plant in 2017 to supply around 30% or 2 MGD of the city's water needs. Orange County's groundwater replenishment system is the world's most extensive indirect potable reuse system and has just finished an expansion that allows for a capacity of 130 MGD of treated wastewater. Carlsbad, San Diego, opened its desalination plant in 2015, and it is one of the largest and most advanced in the nation, providing 50 MGD of safe drinking water. Only some California cities and municipalities have the luxury of diversifying their water supply portfolios beyond surface and groundwater sources. We used three different selection criteria for selecting the sites for the project.

The first criteria we considered were locations that could or would need this technology in the future that still need to develop it. Developed areas like Orange County, LA, and Santa Barbara have already established the facilities for these treatment methods or have analyzed developing the treatment method sites. We also wanted to focus on two inland California sites and one coastal site to include ocean desalination in our evaluation.

The second of our criteria was the size and location of the water district. Concerning size, we looked at areas that had to submit an Urban Water Management Plan to the California State Water Board. Urban Water Management Plans (UWMPs) are prepared by urban water suppliers every five years. These plans support the suppliers' long-term resource planning to ensure adequate water supplies are available to meet existing and future water needs. This was to ensure that we could use accurately forecasted water supply and demand and contingency plans to meet water needs in these areas. By focusing on urban water areas, we assumed that these areas could afford to build or have the infrastructure to operate one of these treatment methods.

The last criteria were water risk, environmental justice, and socioeconomic factors. For this, we used the CalEnviroScreen 4.0 application to focus on communities disproportionately burdened by multiple sources of pollution. We screened for specific environmental indicators focusing on groundwater threats, drinking water contaminants, and impaired water bodies. Next, we screened for socioeconomic factors, including linguistic isolation, education, poverty, and unemployment. Finally, we compared areas across the state to determine which communities could benefit from one of the treatment methods based on need.

5.2 Water Risk Calculation with CalEnviroScreen

5.2.1 Indicator selection

CalEnviroScreen stands for the California Communities Environmental Health Screening Tool. It was first released in 2017 and has since been updated, the most recent version being CalEnviroScreen 4.0. This version provides 21 different indicators of pollution burdens and population characteristics. Using data from CalEnviroScreen 4.0, we isolated 10 indicators to calculate a water risk score and relative percentiles. We chose the following indicators from the pollution burden category: groundwater threats, drinking water, impaired water bodies, pesticide use, and hazardous wastes (Table 5-1). The population characteristic indicators we considered include linguistic isolation, education, poverty, unemployment, and housing burden. Of the five environmental risk indicators that were relevant to the study sites, we determined three had a direct effect and two had an indirect effect on the water systems in question. The indirect indicators received half the weight as the direct indicators. We weighed the weight of environmental and population indicators equally, with a total weight of 4 for each risk category. This resulted in weights of 0.8 for each of the five population indicators.

Table 5-1. *Indicators included for the water risk score, categorized risk type, and assigned weights.*

Indicator	Risk Type	Weight
Groundwater threats	Direct Environmental	1
Impaired water bodies	Direct Environmental	1
Drinking water contaminants	Direct Environmental	1
Hazardous wastes	Indirect Environmental	0.5
Pesticide use	Indirect Environmental	0.5
Education	Population	0.8
Housing Burden	Population	0.8

Poverty	Population	0.8
Linguistic Isolation	Population	0.8
Unemployment	Population	0.8

5.2.2 Water Risk Calculation

Methodology for calculating environmental, population, and final scores beginning from the raw collection data is sourced directly from CalEnviroScreen 4.0. The stepwise calculations are included below. Raw collection of data for each indicator can be found in the CalEnviroScreen 4.0. Report (CalEnviroScreen 4.0, 2021). Because CalEnviroScreen incorporates 21 indicators and only 10 are used for the water risk calculation, the calculations account for such discrepancies.

1. Direct & Indirect Environmental Indicators Calculation

   $X_D = Direct\ Environmental\ Indicators$

   $X_I = Indirect\ Environmental\ Indicators$

   a. Average direct environmental indicators per census tract

   $$X_D + X_D + X_D / 3 = \overline{X_D}$$

   b. Average indirect environmental indicators per census tract

   $$(X_I + X_I / 2) * 0.5 = \overline{X_I}$$

   c. Average of all environmental indicators per census tract

   $$\overline{X_D} + \overline{X_I} / 1.5 = \overline{X}$$

   d. Max average of environmental indicators across all census tracts

   $$Max(\overline{X}) = \overline{X}_{max}$$

   e. Scaled component environmental score

   $$\overline{X} / \overline{X}_{max} * 10 = X_{final}$$

2. Population Indicators Calculation

   $Y = Population\ Indicators$

a. Average population indicators per census tract

$$((Y + Y + Y + Y + Y) / 5) * 0.8 = \overline{Y}$$

b. Maximum average of population indicators across all census tracts

$$Max(\overline{Y}) = \overline{Y}_{max}$$

c. Scaled component population score

$$\overline{Y} / \overline{Y}_{max} * 10 = Y_{final}$$

3. Water Risk Score & percentile calculation

$$Water\ Risk\ Score = X_{final} * Y_{final}$$

The empirical cumulative distribution function in R/RStudio was used to calculate the percentile ranking of water risk scores per census tract and is shown below where *Fn* is a step function with jumps *i/n* at observation values, *i* is the number of tied observations at that value, and missing values are ignored.

$$Fn(t) = \#\{xi <= t\}/n = 1/n\ sum(i = 1,\ n)\ Indicator(xi <= t)$$

5.3 Advanced Water Treatment Model (AWTM)

5.3.1 About the Application

To assist in the technology selection for each site, we developed an application written in R script to evaluate and compare energy and economic requirements for indirect potable reuse, direct potable reuse, groundwater desalination, and ocean desalination. The application, named the Advanced Water Treatment Model (AWTM), calculates the Specific Energy Consumption (SEC) in kWh/m^3, the unit capital cost in one million USD per million gallons per day ($MM/MGD), as well as the unit operations and maintenance costs also in $MM/MGD. An

Excel sheet contains all the data relating to the process name, fitted constants for the numerical models, and the SEC values which are used as inputs.

5.3.2 Inputs

The AWTM has a variety of input parameters needed to calculate energy and economic requirements. The first input section is “Select a Technology.” This is a checkbox group that allows for the selection of which technologies to include in the analysis. The default selection includes all four technologies (Direct Potable Reuse, Indirect Potable Reuse, Groundwater Desalination, and Seawater Desalination). Following this, the section Select Unit Processes” allows for the choice of which unit processes will be included in each technology. There are eleven advanced water treatment unit processes encoded into the application. Each technology has default unit processes encoded as seen in Table 5-2.

***Table 5-2**: Default unit processes for each technology in the SHINY Application.*

Direct Potable Reuse	Indirect Potable Reuse	Groundwater Desalination	Seawater Desalination
Ultrafiltration	Microfiltration	Groundwater pumping	Seawater Desalination
Reverse osmosis	Reverse osmosis	Brackish water desalination	—
Ozonation	UV / H_2O_2 Oxidation	—	—
Biological Activated Carbon	—	—	—

The first group of advanced treatment processes is membrane processes, which are microfiltration, ultrafiltration, nanofiltration, wastewater reverse osmosis, brackish water reverse osmosis, and seawater reverse osmosis. Microfiltration removes bacteria and suspended solids from water. Ultrafiltration filters remove viruses and very large molecules. Nanofiltration filters remove multivalent ions and 50-90% of monovalent ions such as chloride and sodium from wastewater. Reverse osmosis membranes remove almost everything from water including all ions, except for a few small, neutral organic molecules (Keller et al., 2022; MRWA, 2001). A summary of the membrane process pore size and operating pressures is available in Table 5-3. The various reverse osmosis processes in the application consider different operating pressures, where brackish water is the lowest, followed by wastewater, then by seawater reverse osmosis. As the pore size decreases, a higher operating pressure is needed, which creates a higher specific energy consumption and higher capital and operating costs. A higher operating pressure also removes more of the suspended particles in the water undergoing treatment. The model assumes the energy requirements and expenditures found in the literature studying economics and energy requirements for these processes (see Appendix 11.2 and 11.3).

Table 5-3: *Summary of membrane processes.*

Process	Membrane Pore Size (microns)	Operating Pressure (psi)	References
Microfiltration	0.03 - 10	15-60	MRWA, 2001
Ultrafiltration	0.002 - 0.1	30-100	MRWA, 2001
Nanofiltration	0.0005 - 0.001	90-150	MRWA, 2001
Wastewater Reverse Osmosis (RO)	0.0001 - 0.001	100-800	MRWA, 2001 Backer, 2019
Brackish Water Desalination RO	0.0001 - 0.001	250-400	MRWA, 2001 UNEP, 1997
Seawater Desalination RO	0.0001 - 0.001	800-1000	MRWA, 2001 UNEP, 1997

The next group of advanced treatment processes are the chemical and physical processes, which includes ozonation, granular activated carbon, and coagulation. The ozonation process also includes UV light oxidation and has an assumed ozone dosage of 3 mg/L of water (Plappally et al., 2014). The combination of ozone and UV light promotes the formation of hydroxyl radicals which are highly reactive and are efficient at removing remaining organic matter remaining in the water (Plappally et al., 2014). Granular activated carbon (GAC) is a filtration technology that removes organic chemicals and chemicals that give odor such as hydrogen sulfide and chlorine. This technology is made from raw organic materials high in carbon that are heated in the absence of oxygen to vastly increase its surface area (Gumerman et al., 1979). Biological Activated Carbon (BAC) is a modified version of GAC that establishes bacterial communities on the filter. These microbial communities metabolize the remaining complex organic compounds left in the wastewater (Suez, n.d.). Generally, BAC is placed directly after ozonation in order to remove oxidation byproducts, and is planned to be an integral part of direct potable reuse systems. Coagulation is mainly used in primary treatment, but serves a function in tertiary advanced treatment as well. Ions such as aluminum sulfate or ferric chloride are added to the water where the chemicals adsorb to suspended particles and remove their negative charge (Plappally et al., 2014). The particles then coagulate and form flocs that settle rapidly to the bottom of the coagulation chamber. This technology is a very effective pretreatment to filtration and membrane processes.

The final unit process we included in the application is groundwater pumping, which has its own set of parameters. Inputs for the pumping rate in cubic meters per second (cms), extraction depth in meters, pump efficiency, friction losses, and pipe fitting losses are found under the "Groundwater Pumping Parameters" tab, which we used to calculate the energy requirements for this technology (Fournier et al. 2016).

The next input needed for the analysis is the operational flow rate of the technologies in MGD. In Section 6 we provide examples of how to calculate the flow rate for these communities. Finally, if the biological activated carbon unit process is being utilized in any of the technologies, there is an input that allows for the selection of the empty bed contact time (EBCT) of default 20 minutes or 10 minutes.

5.3.3 Energy

For each unit process's energy requirements, we used an averaged value expressed in kWh/m^3. We found energy requirements from various studies performed on advanced wastewater treatment (see Table 11-1 in the Appendix for more information). The total energy requirement is expressed as a sum of the selected process energy requirements.

$$E_{total} = \sum_i E_i$$

We used separate equations for groundwater pumping energy requirements, as the value is a function of depth and pumping rate. The application utilizes physical equations with variables that include pumping rate, depth, pipe diameter, pump efficiency, and losses from friction and pipe fittings (Fournier et al., 2016). For the groundwater pumping calculations, we assumed a pipe diameter of 6 inches. We used a series of three equations to calculate the groundwater pumping energy requirements. The first equation calculates the friction factor of the pipe as a function of the Reynold's number (*Re*), the pipe roughness factor (*k*), and the pipe diameter (*D*) in meters (Fournier et al., 2016). Once the friction factor of the pipe was calculated, we obtained the system losses from the friction factor (*f*), the pumping depth (*z*) in meters, the pipe diameter (*D*), and the assumed losses from pipe fittings (k_f) (Fournier et al., 2016). After calculating the total pumping losses, we could estimate the total pumping energy requirement based on the total systems losses (K_t), pumping rate (x_{pump}) in cubic meters per second, the water velocity (v^2) in m/s as well as the pump efficiency (ρ). The energy requirements are given in kWh (Fournier et al., 2016). The groundwater pumping equations are found in Appendix 11.1. The function *energy_req* utilizes these equations as well as the input parameters to calculate an energy requirement and then normalizes the energy required to calculate a value in kWh/m^3.

Since the SEC data were tabulated from a variety of sources, we calculated both the mean and the variance. For the error assumption, we squared, summed, and then took the square root of the variance of each selected process to calculate the total standard deviation, following the equation below:

$$\sigma = \sqrt{\sum_i S_i^2}$$

We then used the resulting standard deviation as the error assumption for the energy graphs. The final output is the mean ± standard deviation.

5.3.4 Economics

We modeled the capital cost expenditures (CAPEX) and the operations and management expenditures (OPEX) in our AWTM using various empirical equations found from various economic studies of water treatment processes. Each unit process has its own CAPEX and OPEX equation. The error assumption for the economic models is that there is a +50%/-30% relative error. The time period associated with OPEX calculations is always per year.

The first economic model is the Williams Power Log Rule, which models both CAPEX and OPEX in US dollars ($USD) as a function of the flow rate in cubic meters per day (m^3/d). The unit processes that utilize this equation are reverse osmosis, ultrafiltration, granular activated carbon, and coagulation (Guo et al., 2014; Keller et al., 2022). The Williams Power Log Rule is given as:

$$y = a[log(x)^b] + c$$

Each unit process has unique values for a, b, and c.

The second economic model uses the power rule, which models CAPEX and OPEX in $MM/MG as a function of flow rate in MGD (Plumlee et al., 2014). The unit process cost models developed by Plumlee et al. are ozonation, UV oxidation, microfiltration, and nanofiltration. The power rule is also used to model seawater desalination, where the CAPEX and OPEX are modeled in millions of dollars ($MM) as a function of flow rate in MGD, and to model the CAPEX for brackish water reverse osmosis (Bhojwani et al. 2019; McGivney et al., 2008). The power rule is given as:

$$y = ax^b$$

We modeled the operations and maintenance costs for brackish water reverse osmosis as a linear equation based on a 2021 Florida study by Pearson et al. The OPEX per day ($/day) is modeled as a function of plant capacity in cubic meters per day (m^3/day). The OPEX model has an R^2 of 0.8254.

$$y = 0.3678x + 330.13$$

Groundwater pumping OPEX costs utilize unit cost per energy data for California groundwater pumping (U.S. EIA, 2022). The unit cost in the application is 19.74 cents per kWh. In our AWTM, the function *economics_plot* takes all the constants from the data.xlsx sheet and outputs a CAPEX and OPEX estimate based on the selected flow rate and other parameters selected. Then based on the output of *economics_plot*, the function *economics_techplot* calculates the costs based on the selected technology. We performed a linear combination of the models to obtain the total CAPEX and OPEX costs.

$$y_{total} = \sum_i y_i$$

AWTM visualizes the relative contributions to both CAPEX and OPEX as a bar plot with the error bars shown representing a +50%/-30% error on the total costs. The app converts all the various equations to the same units before being summed, which are then normalized to unit costs expressed in $MM/MGD.

5.3.4 Model Comparison

To evaluate model results, the outputs were compared to currently operating advanced wastewater treatment plants and processes. The comparisons are tabulated in Table 5-4 below.

Table 5-4: *Real data compared to model outputs for each advanced wastewater treatment plant.*

Site	Technology	Metric	Real Value ($MM/MGD)	Model Output ($MM/MGD)	Model % Difference
Orange County GRS 70 MGD Fountain Valley, CA (GRS, 2007)	IPR	CAPEX	4.1	3.7 (2.2 - 4.8)	-9.7
		OPEX	0.4	0.5 (0.4 - 0.8)	30
Kranji NEWater 11 MGD Singapore (Law et al. 2007)	IPR	CAPEX	3.3	4.5 (3.2 - 6.8)	28
Charles E. Meyer Desalination Plant 3 MGD Santa Barbara, CA (Quon et al. 2022)	Seawater Desalination	CAPEX	35	9.5 (6.6 - 14)	-274
		OPEX	1.4	2.7 (1.9 - 6.1)	50
Tampa Bay Desalination Plant 25 MGD Tampa Bay, FL (Quon et al. 2022)	Seawater Desalination	CAPEX	7.9	5.2 (3.6 - 7.8)	-52
		OPEX	0.6	1.3 (0.9 - 2.0)	-52
Claude Lewis Desalination Plant 50 MGD Carlsbad, CA (Quon et al. 2022)	Seawater Desalination	CAPEX	20	4.3 (3.0 - 6.4)	-368
		OPEX	1.0	1.0 (0.7 - 1.5)	-1.0
Roscoe Groundwater Desalination Plant 0.3 MGD Roscoe, TX (Pearson et al., 2021)	Groundwater Desalination	CAPEX	2.7	5.8 (4.1 - 8.8)	54
North Cameron Regional Desalination Plant 1 MGD Harlingen, TX (Pearson et al., 2021)	Groundwater Desalination	CAPEX	7.0	4.4 (3.1 - 6.6)	-60
Cape Coral North Desalination Plant 12 MGD Cape Coral, FL (Pearson et al. 2021)	Groundwater Desalination	CAPEX	11	2.2 (1.5 - 3.3)	-395

Indirect Potable Reuse comparisons validated the model for these processes as for both the Orange County GRS and the Kranji NEWater Plant, the values are within the range of AWTM outputs. Desalination processes showed significant variation in costs compared to flow rate. The CAPEX costs were significantly underestimated and out of range for the Charles E. Meyer Desalination Plant, the Claude Lewis Desalination Plant, and the Cape Coral North Desalination Plant. For Charles E. Meyer, land remediation costs and other expenses not considered in the model are incorporated into the capital costs (Quon et al. 2022). Furthermore, Claude Lewis incorporates a multistage and multipass system while Charles E. Meyer operates with a single pass, which contributes significantly to the CAPEX differences (Quon et al. 2022). Overall, desalination processes showed large variance that simple economic models in the application cannot capture. We did not consider OPEX costs for groundwater desalination, as all sources did not incorporate the same components into the OPEX calculations as the model, leading to a significant difference in the model output to the real value.

5.4 Calculating Flow Rates

To use our AWTM, a water agency must first determine the desired flow rate to input into the model. This flow rate represents how much of an agency's water demand will be met by one of, or a combination of, the technologies analyzed by the model. Various factors such as an agency's current water supplies, projected future water supplies, projected future demand, and climate change modeling can influence their flow rate calculations. Given the uncertainties of such projections, any user of the model will ultimately have to use their own discretion to determine how much of the water demand should be met by these technologies.

In the analysis of the water supply and demand of each city, we calculate flow rates to use as model inputs for each of the three sites. To address a variety of future outcomes we delineate an upper, normal, and lower scenario flow rate for each site. The upper scenario corresponds to the highest unmet future demand and thus the largest amount of water supplied by the technologies we analyzed. These calculations aim to serve as examples of how an agency might approach developing flow rates to use with AWTM; however, we stress that communities best understand their own needs, and recognize that our calculations provide a different outlook on the future of California water than observed in many UWMPs. The logic behind each flow rate is outlined for each city in the following section.

6 Site Analysis

6.1 The City of Oxnard

Oxnard is the most populous city residing in Ventura County, with a population of approximately 206,000 residents as of 2020 (City of Oxnard, 2021). This seaside city in southern California is located roughly halfway between Los Angeles and Santa Barbara. It is a major transportation hub, it has significant connections to nearby oil rigs, and it is recognized for its fruitful agricultural industry. Given its proximity to the coast, nearly all the city and nearby region is almost at sea level (Figure 6-1). The high density of oil, industry, and agricultural activities in the area, coupled with the projected increase of its population and the overdrafted state of its groundwater basin, poses a significant threat to the future clean water supply of the city's inhabitants (City of Oxnard, 2021).

6.1.1 Service Area

Oxnard's water service area differs from its city limits (Figure 6-2). Most of the incorporated area of Oxnard is included in the water service area, as well as some portions of unincorporated Ventura County. In total, Oxnard's service area covers approximately 27 square miles (City of Oxnard, 2021). Regions that are not covered by the service area but are within Oxnard city boundaries, receive water allocations from other mutual water companies through an agreement with the city (Figure 6-2). This agreement requires Oxnard to make extra capacity available within its Calleguas pipeline for water transfer to Port Hueneme Water Agency (PHWA) in exchange for an annual transfer of 700 AFY of Fox Canyon Groundwater Management Agency allocations to the city.

Figure 6-1. *Digital elevation model for the region showing a consistent topography throughout (California Department of Technology, 2022; City of Oxnard, 2023; United States Geological Survey, 2008).*

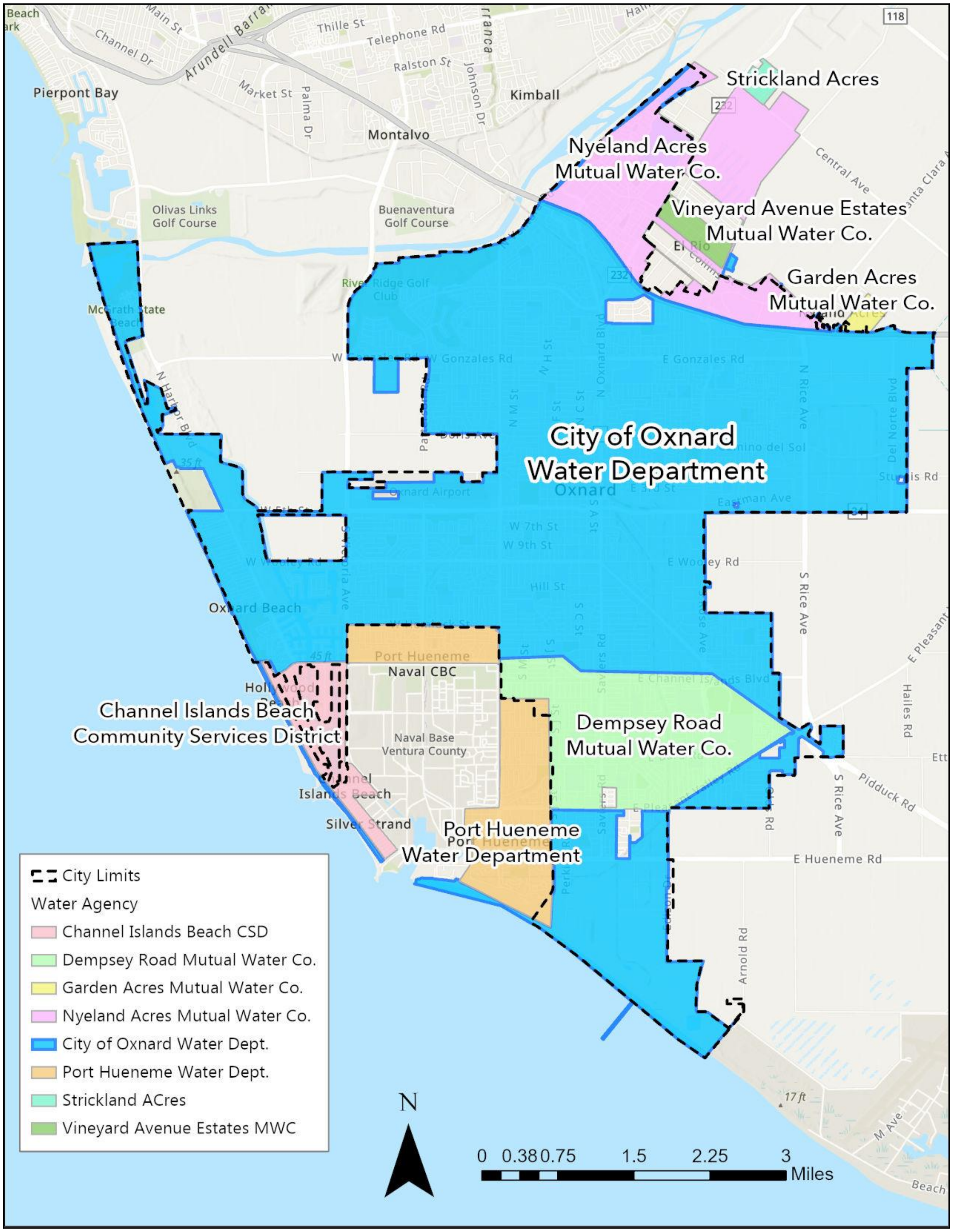

Figure 6-2. *City of Oxnard's water service area, including its spheres of influence (California Department of Technology, 2022; City of Oxnard, 2023).*

6.1.2 Climate

Positioned next to the Pacific Ocean, Oxnard's climate is subtropical and dry. Its climate follows typical Southern California patterns with the wettest and coldest months historically being December through March and the hottest and driest months being August (Figure 6-3; Figure 6-4). Precipitation has historically peaked in February with 30-year averages of just under 4 inches for the month. In contrast, precipitation is uncommon in the hottest months (July-September) where 30-year temperature averages peak around 60-65 F with highs around 65-75 F (Prism, 2022).

According to a climate change report drafted by Watersheds Coalition of Ventura County in 2019, coastal areas such as Oxnard should expect to see an average increase in temperature of 2-3 °F and 5-10% in evapotranspiration for 2021-2040, compared to baselines recorded from 1950 to 2005. The average annual precipitation is not predicted to change much, however, the number of dry days is expected to increase, resulting in more rainfall over shorter periods of time. These changes in precipitation patterns can affect surface water conveyance and groundwater recharge.

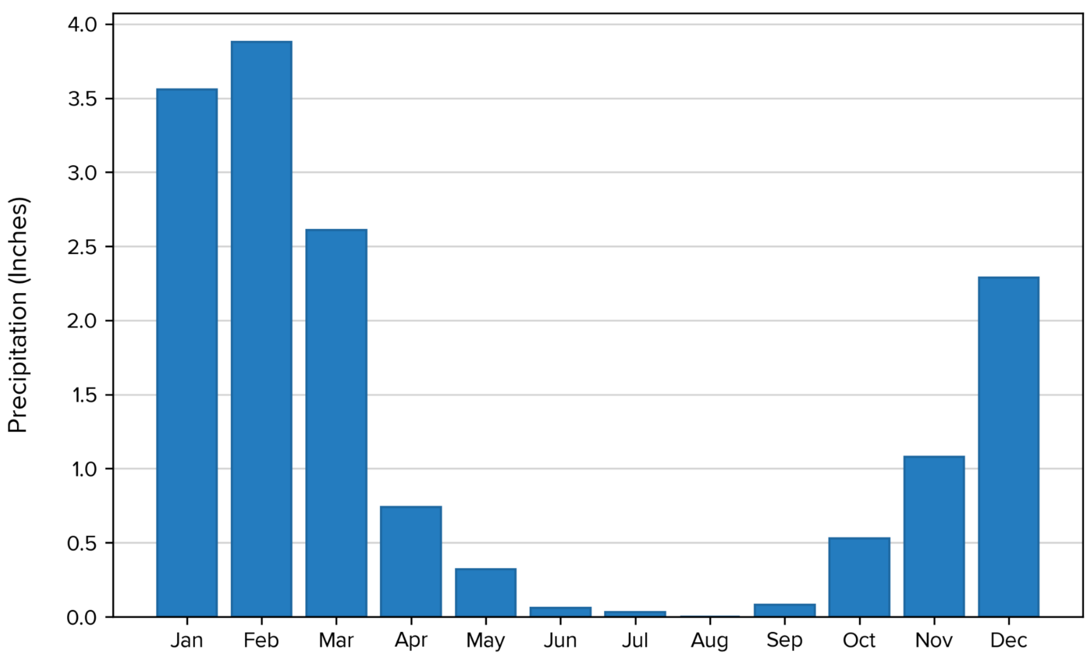

Figure 6-3. *Monthly precipitation averages over a 30-year period in Oxnard (Oregon State University (OSU), n.d.).*

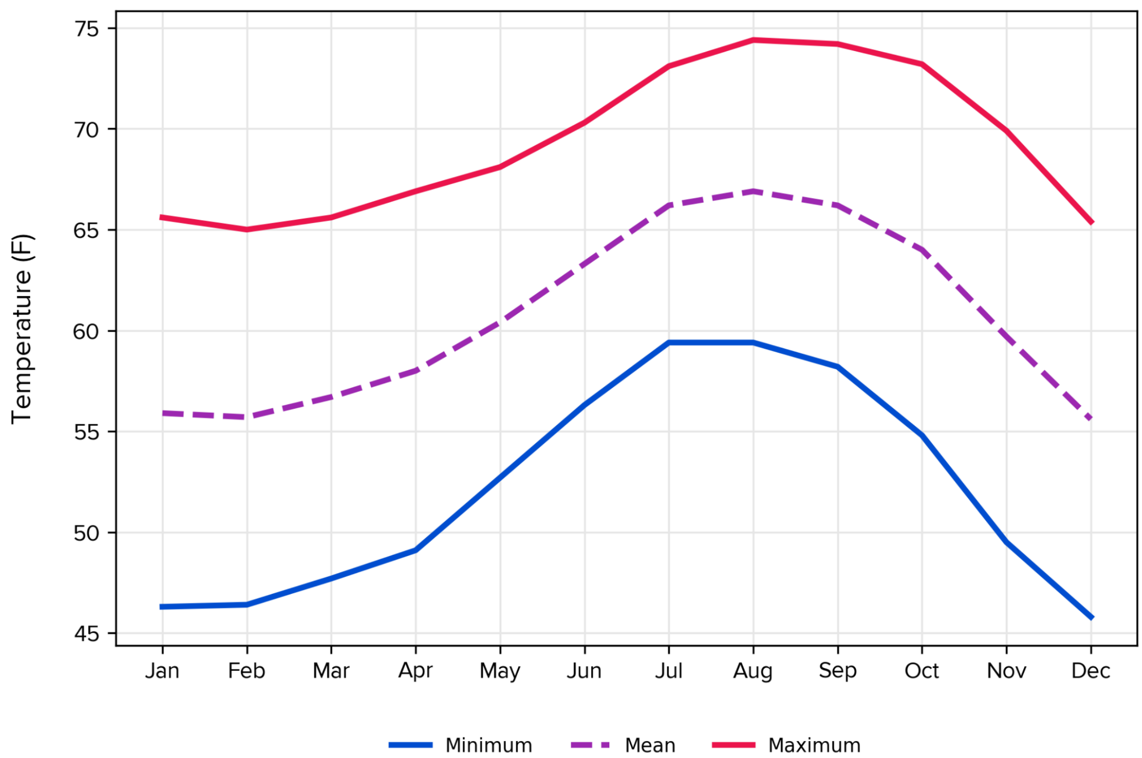

Figure 6-4. *Monthly temperature averages over a 30-year period in Oxnard (OSU, n.d.).*

6.1.3 Population

As of 2020, the population served by the Oxnard water district was 199,852, which is in contrast to the total city population of 206,352. Over a 30-year period beginning in 2015, the service area population is expected to grow by approximately 14% (Table 6-1). Although the population is projected to increase, the household size is expected to decline. For this reason, the city is required by state law to prepare its 2021-2029 housing element to include the potential addition of 8,549 housing units. Although these additional units don't necessarily correlate to excessive or rapid increases in population, the city does expect an increase in impervious surface coverage and thus increased polluted runoff to the city's water resources, if stormwater management practices are not implemented (City of Oxnard, 2021).

Table 6-1. *Past and projected population for the City of Oxnard (City of Oxnard, 2021).*

Year	Total City Population	Population Served by Mutual Water Companies	Population Served by the City
2015	205,512	6,500	199,012
2016	206,085	6,500	199,585
2017	205,974	6,500	199,474
2018	206,222	6,500	199,722
2019	206,221	6,500	199,721
2020	206,352	6,500	199,852
2025	216,845	6,500	210,345
2030	225,720	6,500	219,220
2035	230,105	6,500	223,605
2040	234,115	6,500	227,615
2045	238,126	6,500	231,626

6.1.4 Historical and Projected Water Use

The city services a variety of users via 43,000 service connections, however, single-family residences are the largest customer class (~34% of total deliveries). In combination with multi-family residences, the two customer classes consumed nearly 48% of the total available water supply for the year 2020, with the remaining 52% of the supply being consumed by a variety of sectors ranging from commercial to agricultural (Table 6-2). Over the last five years, Oxnard delivered an average of 26,000 AFY of potable and non-potable water to its customers. The average consumption over that period was 23,000 AFY. The extra ~3,000 AFY was allocated to non-potable uses such as groundwater recharge, used for transfers and exchanges, or lost (City of Oxnard, 2021).

Table 6-2. *Actual water demand in 2020 for the City of Oxnard (City of Oxnard, 2021).*

Use Type	Additional Description	Water Quality	2020 Volume (AFY)	Percentage of Total Demand
Single Family		Drinking Water	8,830	34
Multi-Family		Drinking Water	3,613	14
Commercial		Drinking Water	3,744	14
Industrial		Drinking Water	2,227	9
Landscape		Drinking Water	2,915	11
Other	Fire Hydrants	Drinking Water	31	0.1
Agricultural Irrigation		Drinking Water	1,084	4
Losses		Drinking Water	2,434	9
Sales/Transfers/Exchanges to Other Agencies	Transfer to PHWA	Drinking Water	1,007	4
Recycled Water		Drinking Water	154	1
Total:			**26,039**	**~100%**

Using population projections and per capita water use estimates, future potable water demand was derived (Figure 6-5; Table 6-3). Although the projected demand for 2025-2045 is higher than current and historical demand, it is approximately 15% lower than pre-drought levels due to conservation mandates and improvements in infrastructure efficiencies during the 2002-2020 period. Additional state conservation standards are forthcoming from the DWR and are assumed in the demand projections (City of Oxnard, 2021).

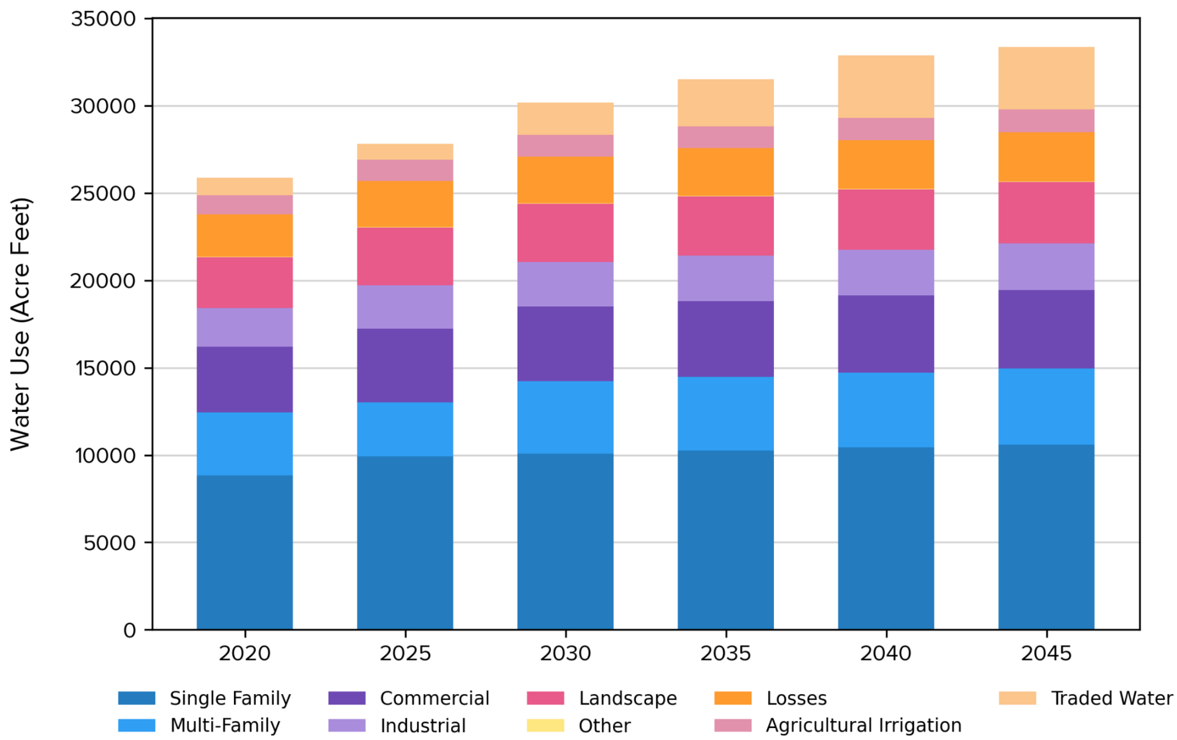

Figure 6-5. *Projected water use from 2020 to 2045 (City of Oxnard, 2021).*

Table 6-3. *Projected water use for the City of Oxnard from 2025 to 2045 (City of Oxnard, 2021).*

Use Type	Additional Description	Projected Water Use (AFY)				
		2025	2030	2035	2040	2045
Single Family		9,939	10,091	10,266	10,436	10,604
Multi-Family		4,067	4,128	4,200	4,269	4,339
Commercial		4,215	4,279	4,354	4,425	4,497
Industrial		2,507	2,545	2,590	2,632	2,675
Landscape		3,282	3,331	3,390	3,445	3,501
Agricultural Irrigation		1,221	1,239	1,261	1,281	1,302
Other	Fire Hydrant	35	35	36	37	37
Losses		2,636	2,676	2,723	2,768	2,813
Sales/Transfers/Exchanges to Other Agencies	Transfer to PHWA	917	1,857	2,704	3,581	3,581
Total:		**28,819**	**30,181**	**31,524**	**32,874**	**33,349**

We also evaluated climate projections; however, they were not included in our demand projections. An analysis based on a 1950-2022 baseline period was conducted for Ventura County, and it projected an average increase in temperature of 2-3°F for coastal communities during the 2021-2040 period (VCWC, 2019). Among other changes, it also predicts shifts in precipitation patterns, extensive fire seasons, and an increase in debris flows. These climate change considerations currently remain within a separate report and have yet to be integrated into Oxnard's water consumption projections (City of Oxnard, 2021).

6.1.5 Land Use and Socioeconomic Factors

Of the various users served by the Oxnard Water Agency, single-family residences comprise the largest portion. The region is mostly composed of younger to middle-aged residents with the median age being 32 years old. The median household income as of 2020 is $68,000, while the average home value is $462,000 (City of Oxnard, 2021). The City of Oxnard's 2030 General Plan summarizes predicted land use designations within its formal planning and jurisdictional boundaries, which includes unincorporated areas surrounding the city. The unincorporated land "which in the planning agency's judgment bears relation to its planning", comprises the majority of the ~39,700 acres included in the 2030 General Plan. The land designated for agriculture is unincorporated, yet it accounts for 51.8% (20,576 acres) of the total acreage considered for city land use planning (Figures 6-6 and 6-7; City of Oxnard, 2022). In order of most to least acreage, residential, industrial, and commercial land comprises the majority of the remaining 48% of city-bounded acreage (City of Oxnard, 2021).

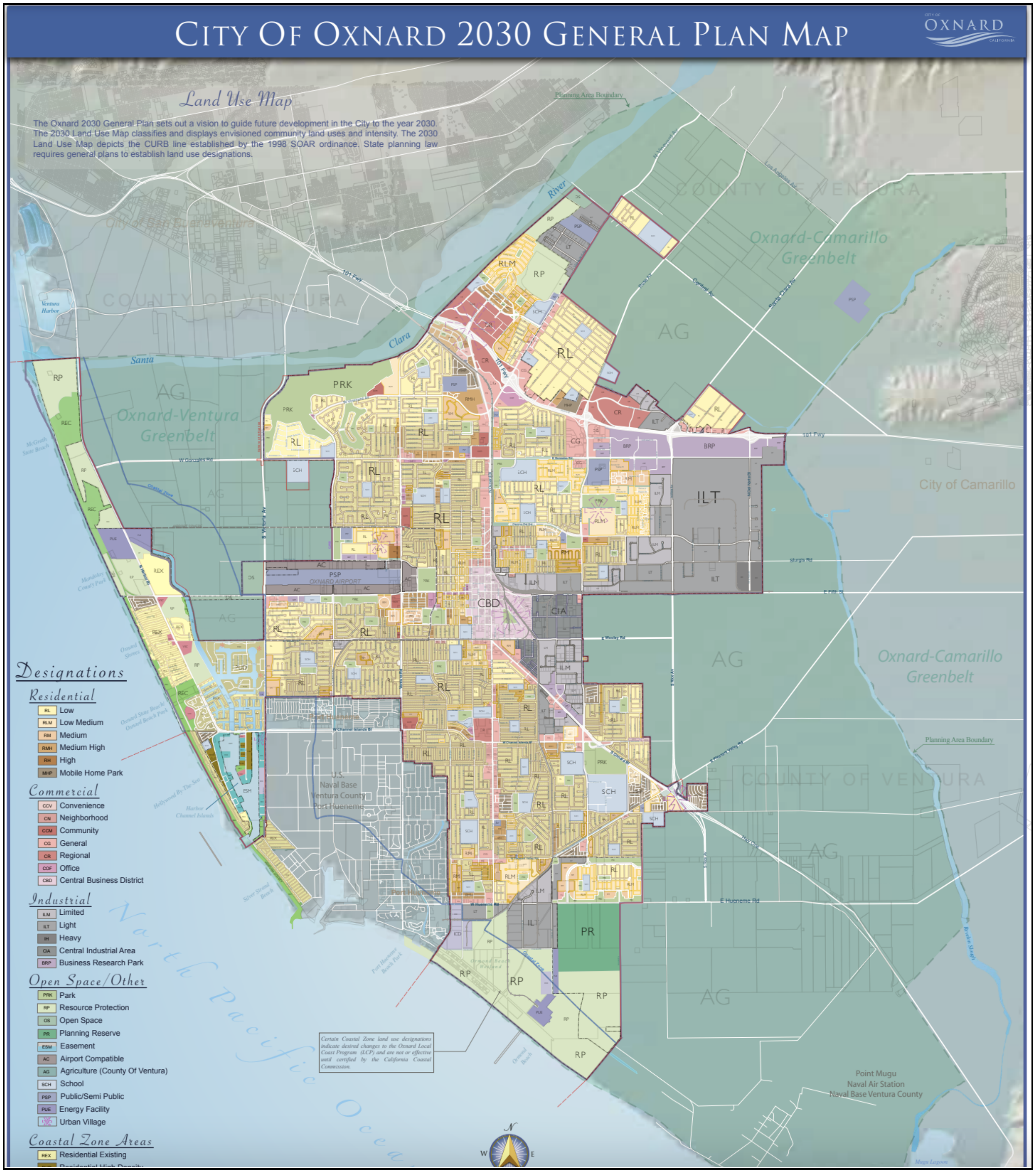

Figure 6-6. *General plan map of the City of Oxnard and its surrounding unincorporated areas.(City of Oxnard, 2022).*

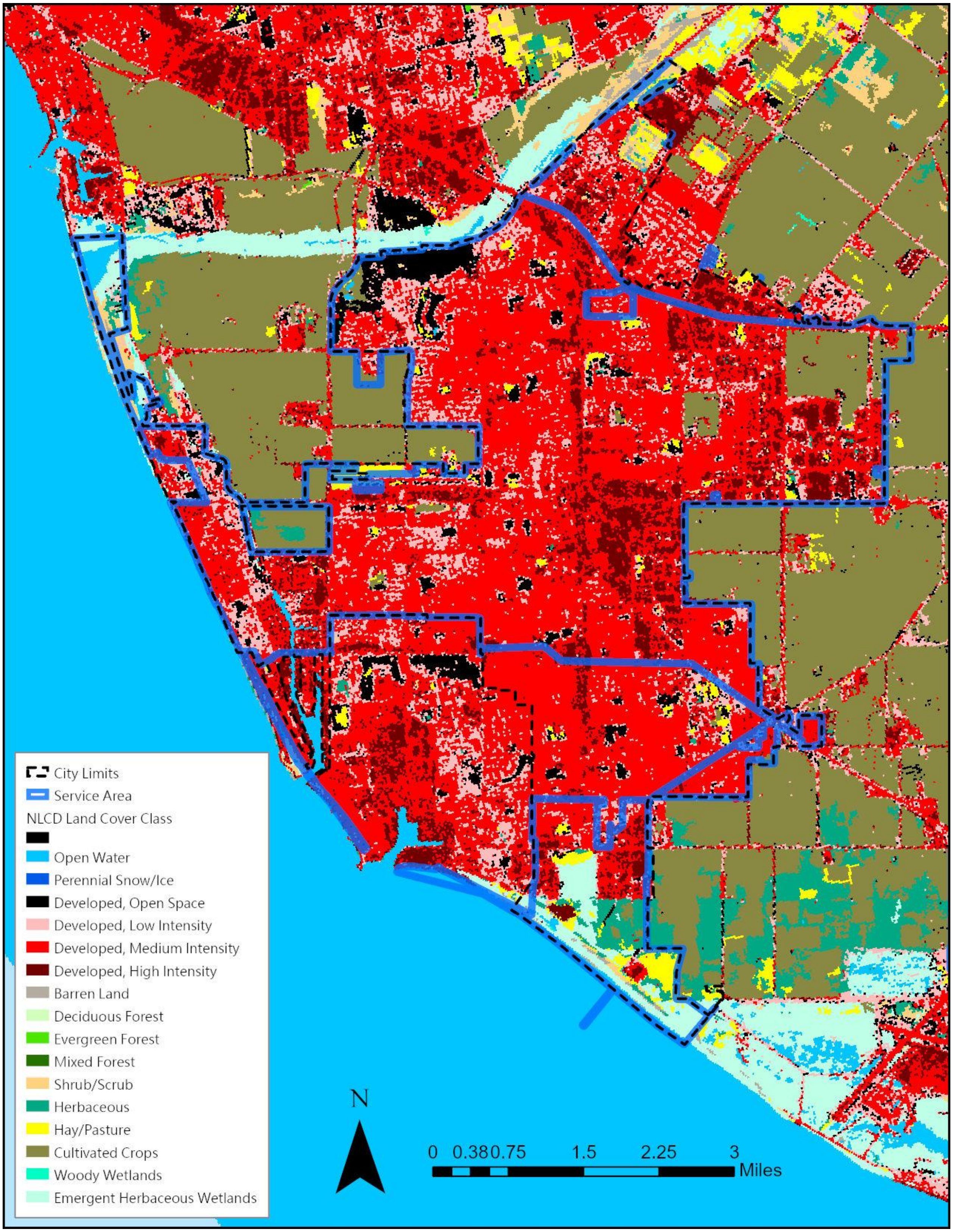

Figure 6-7. *Land use overview for the City of Oxnard (California Department of Technology, 2022; City of Oxnard, 2023; United States Geological Survey, 2021)***.**

6.1.6 Water Supply Overview

In 2020, Oxnard supplied 26,039 AFY of water to its users from various sources (Table 6-4). Much of that water was drinking water quality, and 154 AFY was recycled water quality for agriculture. Groundwater serves as Oxnard's primary water source. It is accessed in two ways: via city well pumping, and via extraction by the United Water District on behalf of the city. Oxnard also imports water from a wholesale provider, Calleguas, and is gradually increasing its recycled water production. The current recycled water system is designed for a maximum capacity of 25 MGD, but is only operating at 6.25 MGD. Currently, the city does not utilize any surface water or stormwater sources (City of Oxnard, 2021).

Table 6-4. *Sources for water supply in 2020 by the City of Oxnard (City of Oxnard, 2021).*

Water Supply	Additional Description	2020 Volume (AFY)	Water Quality
Groundwater (not desalinated)	City	7,744	Drinking Water
Groundwater (not desalinated)	United	10,074	Drinking Water
Purchased or Imported Water	Calleguas	7,060	Drinking Water
Purchased or Imported Water	PHWA	1,007	Drinking Water
Recycled Water		154	Recycled Water
Total:		**26,039**	

6.1.7 Groundwater

The Oxnard basin underlies the entirety of the city of Oxnard and extends beneath the Point Mugu Naval Air Station located southeast of Oxnard within the city's planning boundaries (Figure 6-6). It is divided into the forebay (unconfined), the upper aquifer system (confined; connected to the Pacific Ocean), and the lower aquifer system (confined; separated by 80 ft thick clay layer; Figure 6-9). The forebay is currently the primary means of Oxnard basin groundwater recharge via the Santa Clara riverbed infiltration and constructed spreading basins. The upper aquifer system is hydraulically connected to the Pacific Ocean via the Oxnard and Mugu aquifers and is therefore the main pathway for seawater intrusion when it is overdrafted, and is used for the city water supply. The lower aquifer system constitutes the

Fox Canyon and Grimes Canyon Aquifers (Figure 6-9) and is therefore only distributed to the city via groundwater allocations (City of Oxnard, 2021).

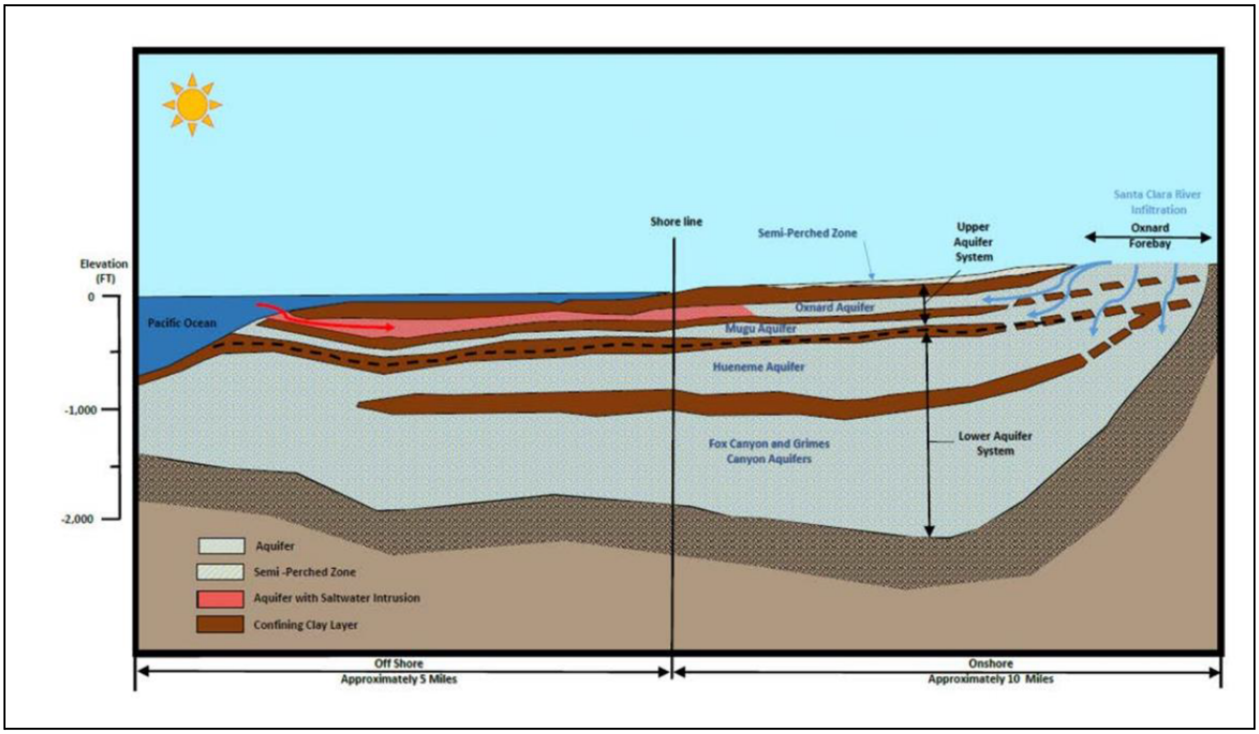

Figure 6-9. *Geologic cross-section of the Oxnard Basin and associated aquifers. From shallowest to deepest are the Oxnard Aquifer, the Mugu Aquifer, the Hueneme Aquifer, and the Fox Canyon and Grimes Canyon Aquifers (City of Oxnard 2021).*

Oxnard owns and operates 10 city wells that pump directly from the Oxnard basin and account for about 30% of the annual water supply and 50% of the total drinking water supply. In addition to the city, the Port Hueneme and Port Mugu naval bases draw water from the Oxnard basin, but most of the basin's remaining water is pumped by agriculture in the unincorporated areas within Ventura County (Fox Canyon Groundwater Management Agency, 2019). The basin is critically overdrafted, yet it is anticipated to serve as the primary source of Oxnard's water supply for the next 30 years. Therefore, an independent district called Fox Canyon Groundwater Management Agency (FCGMA) took control of the basin's management. FCGMA adopted a Groundwater Sustainability Plan which includes a resolution that calls for a 45% reduction in groundwater withdrawal by 2040. To attain this goal, the City of Oxnard plans to linearly reduce groundwater pumping by 2.2% each year through 2040. It is also important to acknowledge that the Oxnard and Pleasant Valley Basins are hydraulically connected and thus are jointly managed (Figure 6-10). For reference, Oxnard's current extraction is approximately 17,000 AFY and Pleasant Valley's is approximately 11,600 AFY (City of Oxnard, 2021). As multiple users pump water from the basin, it is important that all users collaborate to better manage the basin's water supplies.

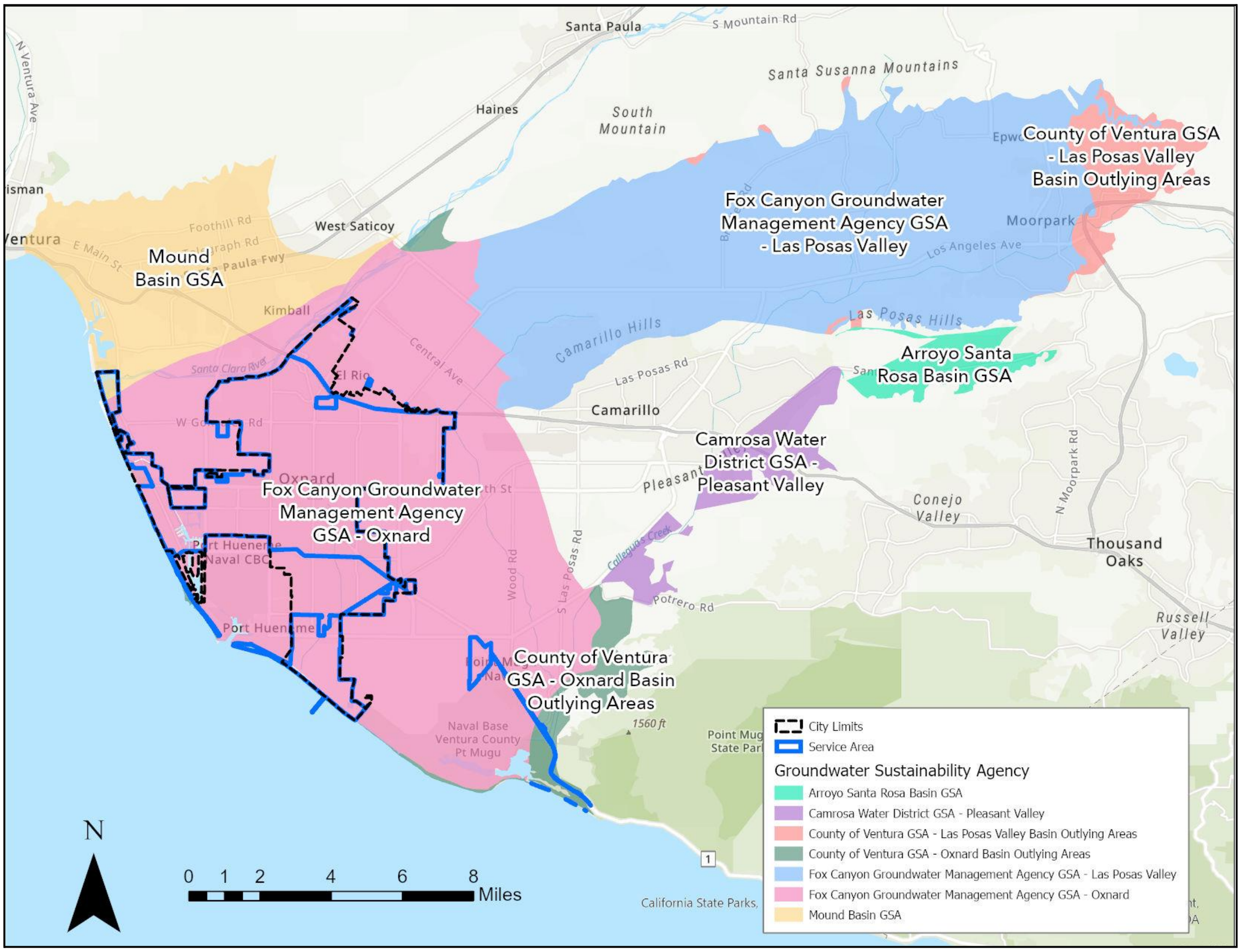

Figure 6-10. *Overview of the relevant management agencies and basins in the region (California Department of Water Resources, 2023b; Fox Canyon Groundwater Management Agency, 2019.*

The groundwater in the basin is brackish, and it is susceptible to water quality issues; however, Oxnard operates a groundwater desalter and six blending stations that mix the local groundwater with imported water to keep the total dissolved solids as low as possible. The desalter, completed in 2008, is located at the city's Water Campus and has an operating flow rate of 7.5 MGD. The brine created from this process is commingled with the plant's secondary-treated effluent and discharged into the Pacific Ocean (California Regional Water Quality Control Board, 2013).

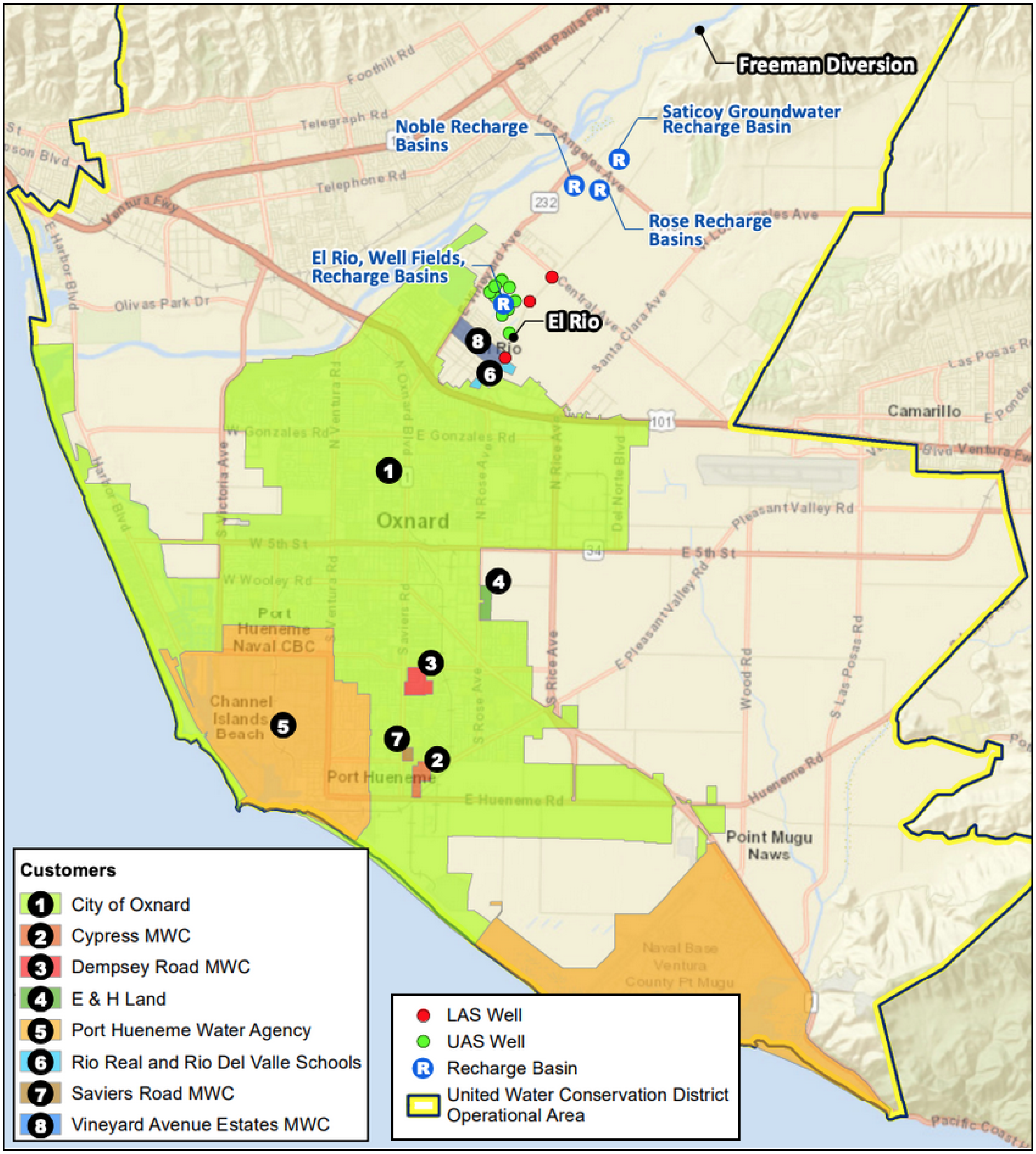

Figure 6-11. *Map of customers served by the United Water Conservation District (City of Oxnard, 2021)*

In addition to the city well extraction, Oxnard maintains an agreement with a wholesale water supplier that provides additional groundwater allocations. United Water Conservation District diverts water from the Santa Clara River first to recharge the Oxnard forebay groundwater aquifers which extend across the entire Oxnard Basin and then pumps from any of the 12 groundwater wells included in the Oxnard-Hueneme (OH) Pipeline (Figure 6-11; UWCD, 2021).

The agreement protects the Oxnard basin and other water agencies against seawater intrusion because of the inland location of United's pumping wells. Although the water is physically imported into the city via pipeline, the allocation is accounted for by the city's groundwater allocations rather than considered an imported source (City of Oxnard, 2021).

6.1.8 Imported Water

Calleguas Municipal Water District (CMWD) is a regional wholesale agency that obtains water from the Metropolitan Water District (MWD) and State Water Project (SWP) and sells it to the City of Oxnard. Calleguas' water rates are determined by a tiering system, thus, to minimize costs, Oxnard operates within the first tier. For example, Tier 1 is based on 90% of the city's historical base demand or a 10-year average. Metropolitan and Calleguas both expect to meet all normal and dry year demands. However, Oxnard recognizes that other regional customers rely on imported water from CMWD as its primary water supply. Therefore, in anticipation of future water shortages, dry hydrological conditions, and exorbitant demands from all water agencies, Oxnard is adamantly seeking additional supplies as to not rely on imports (City of Oxnard, 2021).

MWD also faces water quality challenges which can directly impact Oxnard's supply if not properly identified and treated by both parties. MWD operates blending stations and water treatment plants to mitigate salinity levels. There are several other regional contaminants of concern such as uranium, perchlorate, total organic carbon, arsenic, and bromide, that MWD must minimize before distributing the water to Oxnard and its other customers. This is another reason Oxnard blends the water from all its sources before distribution (City of Oxnard, 2021).

In 2002, Port Hueneme Water Agency (PHWA), Calleguas, and Oxnard entered into a Three-Party Agreement. Calleguas delivers both Oxnard and PHWA's supply to Oxnard's pipeline and Oxnard transfers PHWA's allocation via the city pipeline. In exchange, PHWA transfers 700 AFY of its FCGMA allocation to Oxnard. This is an annual transfer agreement that is reflected in Oxnard's water supply portfolio (City of Oxnard, 2021).

6.1.9 Recycled Water

The Oxnard Advanced Water Purification Facility (AWPF) is currently equipped to produce approximately 6.25 million gallons of non-potable water per day. It is currently distributed for landscape irrigation, agriculture, and industrial process water, but the city has goals to expand its production capacity and utilize the AWPF as an additional water supply. Oxnard has received the wastewater and water recycling requirements from the SWRCB to expand the AWPF to create a reliable recycled water supply for Indirect Potable Reuse (IPR). Furthermore, the city views the facility expansion as an opportunity to recharge its basin (City of Oxnard, 2021).

The city has devised a Groundwater Recharge Enhancement and Treatment (GREAT) program to restore and protect the health of the basin. It also aims to increase the dependability of meeting present and future demands while simultaneously decreasing reliance on imported sources. The short-term plan is to inject around 1,600 AFY (1.42 MGD) of recycled water into the groundwater basin via the aquifer storage and recovery (ASR) well located at Campus Park. There are benefits to utilizing ASR wells; however, injection also comes with challenges, such as the potential for others to pump out this water without exchanging credits to the city. By 2045, Oxnard expects to recharge approximately 7,680 AFY (6.86 MGD) of recycled water into the basin. Furthermore, GREAT has already created opportunities for interagency water recycling. In 2015, the city entered an agreement with several surrounding water districts and entities, outside the service area, that are interested in tapping into Oxnard's AWPF. As the agreement stands, these user groups receive allocations of recycled water for agriculture and irrigation in exchange for groundwater allocations on a one-to-one basis. The city may accrue these "pump back allocations" and redeem them during "favorable" Oxnard Basin conditions (City of Oxnard, 2021).

6.1.10 Desalination

In addition to Oxnard's groundwater desalter, which the city plans to expand to 16,800 AFY soon, city officials have evaluated seawater desalination opportunities. The city's proximity to the Pacific Ocean grants opportunities for desalination as a means of water security. The city evaluated desalination operations in 2012, as an alternative to the planned AWPF expansion. It was not found to be cost-effective, especially in comparison to the AWPF. After revisiting desalination opportunities once again in 2015, officials maintained that the infrastructure requirements and permitting hurdles were significantly difficult at the present time. In the future, if AWFP expansions become limited by a second effluent or the costs of desalination operations can be reduced by technological advancements, the opportunity will be revisited (City of Oxnard, 2021).

6.1.11 Flow Rate Calculations

The City of Oxnard anticipates a significant decline in groundwater supplies in the coming decades as pumping will be reduced to obtain sustainable levels in the basin as required by SGMA. To replace this supply, the city outlines two new sources in its UWMP: ASR wells, and Recycled Water Pumping Allocation (RWPA) credits.

Oxnard expects its ASR wells to be constructed and operational by 2026. In conjunction, the city plans to expand the production capacity of its AWPF by 6,000 AFY to provide Title 22 non-potable recycled water for injection into the wells. In addition to ASR wells, Oxnard receives RWPA credits from the Fox Canyon Groundwater Management Agency (FCGMA) in exchange for recycled water the city exports to agricultural users in the basin. For every acre-foot of pumping reduced in the basin due to recycled water exported from the city, Oxnard is allowed to pump an acre-foot of groundwater at a later date. While these credits can theoretically be exchanged for water at any time, the FCGMA stipulates that the water cannot be provided if the conditions in the basin are not “favorable.” The FCGMA’s Groundwater Sustainability Plan (GSP) defines “favorable” as any time that groundwater levels are greater than 19 feet above mean sea level or any time that less than 80,000 AF of groundwater have been evacuated from the basin.

Upper Bound Scenario

For the upper flow rate, we assumed a worst-case scenario where the City of Oxnard would not receive any water from its ASR wells or its RWPA credits, but would continue to receive its surface water imports. As the ASR wells have not yet been constructed, it is reasonable to assume that construction could be delayed. Water may not be available to recharge the aquifer during prolonged drought, even if the ASR wells are built. Further, with worsening drought conditions and increasing temperatures in California, it is likely that the city will need additional supplies as it may not be able to redeem its RWPA credits from the FCGMA if the basin continues to face critical water shortages. Finally, we used the projected demand from the city’s UWMP to find the difference from the projected supplies to calculate the demand to be met via the modeled technology (Table 6-5). This results in a demand of 14,000 AFY, which corresponds to a flow rate of approximately 12.6 MGD.

Normal Scenario

Our assumptions for the normal scenario remain the same as our upper bound scenario; however, we assumed the city would receive 50% of its projected supply from a combination of ASR wells and RWPA credits (encompassed in the groundwater supply in Table 6-4). This results in a demand of 7,050 AFY, which corresponds to a flow rate of approximately 6.3 MGD.

Lower Bound Scenario

As above, our assumptions for the lower bound scenario remain the same as our upper bound and normal scenarios. For this flow rate, we assumed the city would receive 75% of its projected supply from a combination of ASR wells and RWPA credits. This results in a demand of 3,525 AFY, which corresponds to a flow rate of approximately 3.1 MGD (Table 6-5).

Table 6-5. *City of Oxnard 2045 projected water supply and demand estimates, AFY (City of Oxnard 2021).*

Scenario	Projected Demand	Projected Surface Water Supply	Projected Groundwater Supply	Total Projected Supplies	Demand to be met via modeled technology	Calculated Flow Rate (MGD)
Upper	33,349	9,750	9,499	19,249	14,100	**~13**
Normal	33,349	9,750	16,549	26,299	7,050	**~6.3**
Lower	33,349	9,750	20,074	29,824	3,525	**~3.1**

6.2 The City of Bakersfield

The metropolitan City of Bakersfield, located at the southern end of the San Joaquin Valley, is surrounded by the Sierra Nevada mountains to the northeast and the Tehachapi mountains to the south (Figure 6-12). As a result of residing within the valley, Bakersfield's climate can be best described as hot and arid, as it experiences high temperatures in the summer months and mild winters with minimal precipitation. It is the largest city within Kern County with an estimated population of approximately 395,000 residents. Bakersfield is known for its agricultural and energy production. However, the combination of its climate patterns and growing population places pressure on the city's water supply portfolio and puts industries such as these at risk (City of Bakersfield, 2021).

6.2.1 Service Area

The City of Bakersfield is served by several water agencies (Figure 6-13). The remaining analysis will specifically focus on the western portion of the city, which is served by both the City Wholesale Water System (WWS) and the City Domestic Water System (DWS). The WWS service area includes all land within the city boundaries. The agency's rights to Kern River water and canals provide the source for its water supply that is then delivered citywide (including to DWS via treatment plants). The DWS service area boundaries encompass approximately 58 square miles of the western portion of the city (Figure 6-13)**.** This agency primarily services residential, commercial, industrial, and institutional/governmental uses such as city-owned land with groundwater, stormwater, wastewater, recycled water, and the surface water it receives from WWS.

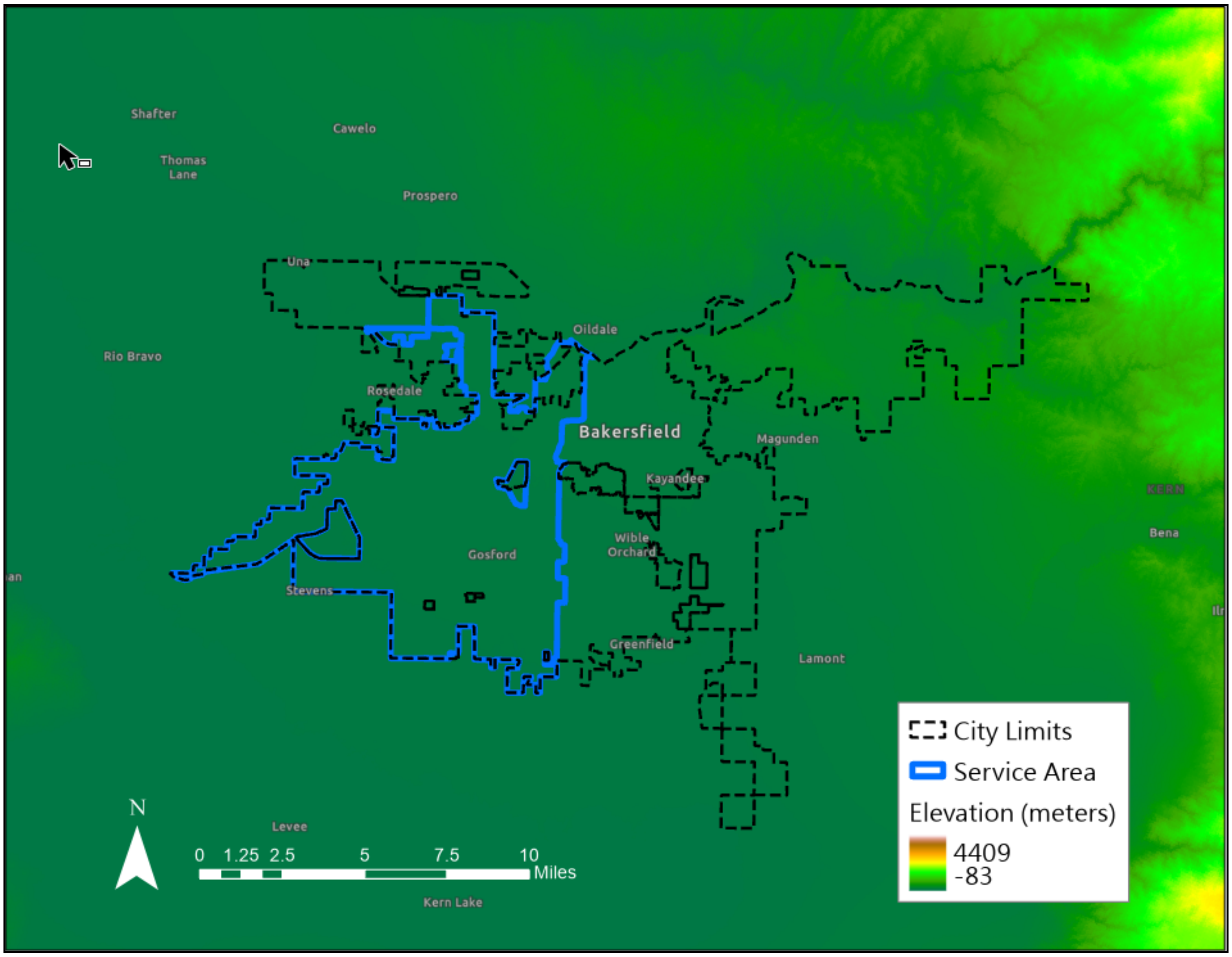

Figure 6-12. *Digital elevation model for the region showing a consistent topography throughout (California Department of Technology, 2022; City of Bakersfield, 2023; United States Geological Survey, 2008).*

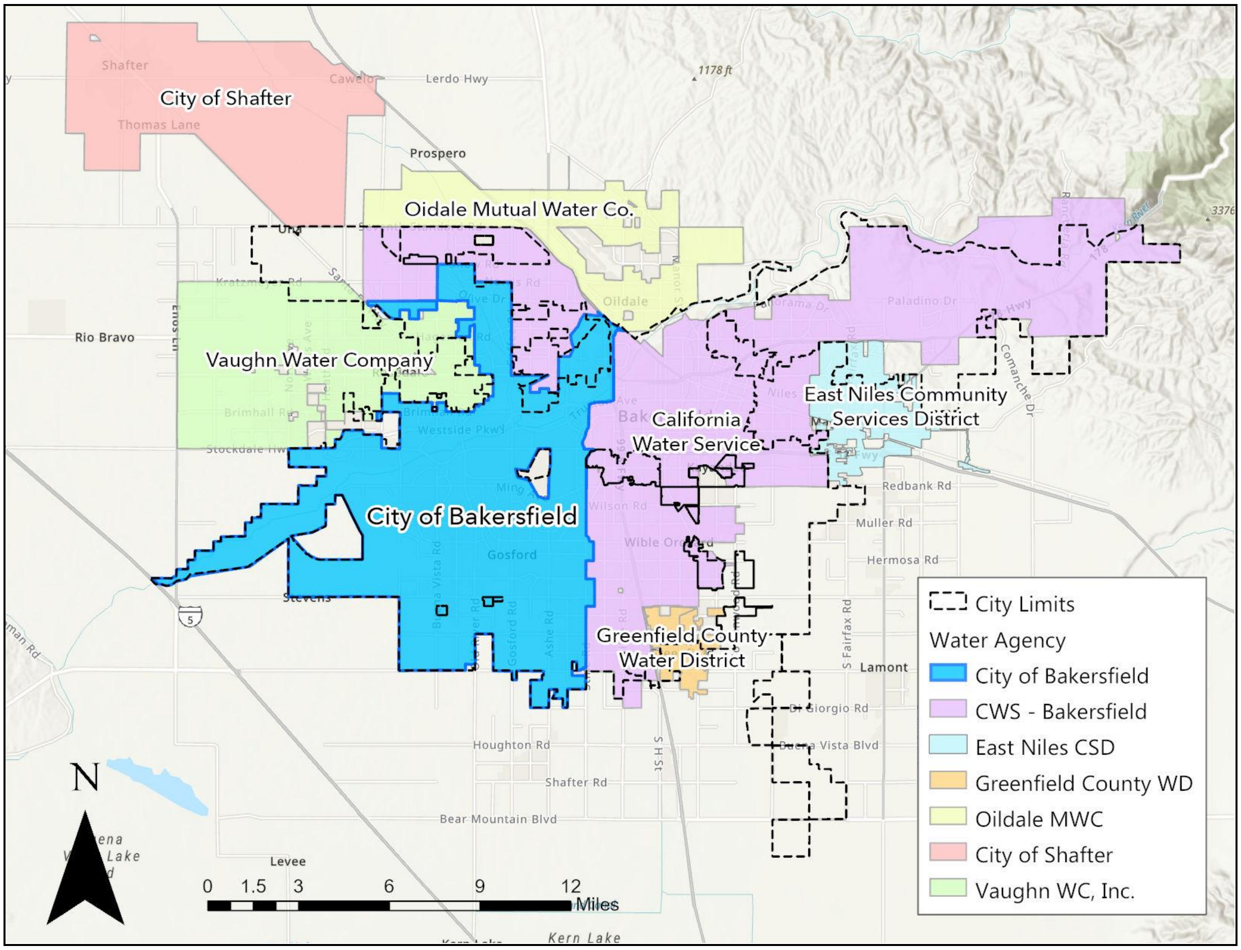

Figure 6-13. *City of Bakersfield's water service area (California Department of Technology 2022; City of Bakersfield, 2023).*

6.2.2 Climate

Positioned away from the coast and within a valley, the city's hot and arid climate produces little precipitation and creates a dry and hot atmosphere during the warmer months (Figure 6-14; Figure 6-15). Throughout an average year, city residents experience temperatures as low as 30°F and high as ~95°F, with June through September typically being the hottest months. On average, December through April are the wettest months of the year for the city, amounting to about 6.5 inches of precipitation (City of Bakersfield, 2021). Throughout the rainy season and leading into early spring (March/April), cities residing within the valley experience a climate phenomenon called tule fog. This typically occurs after heavy rain when there is a high relative humidity and rapid cooling throughout the night. The extended period of ground cooling during these winter months creates a pronounced temperature inversion at low altitudes which creates the climate for tule fog to condense (National Weather Service, 2023). This fog is very dense and leads to several traffic accidents each year (NASA, 2005).

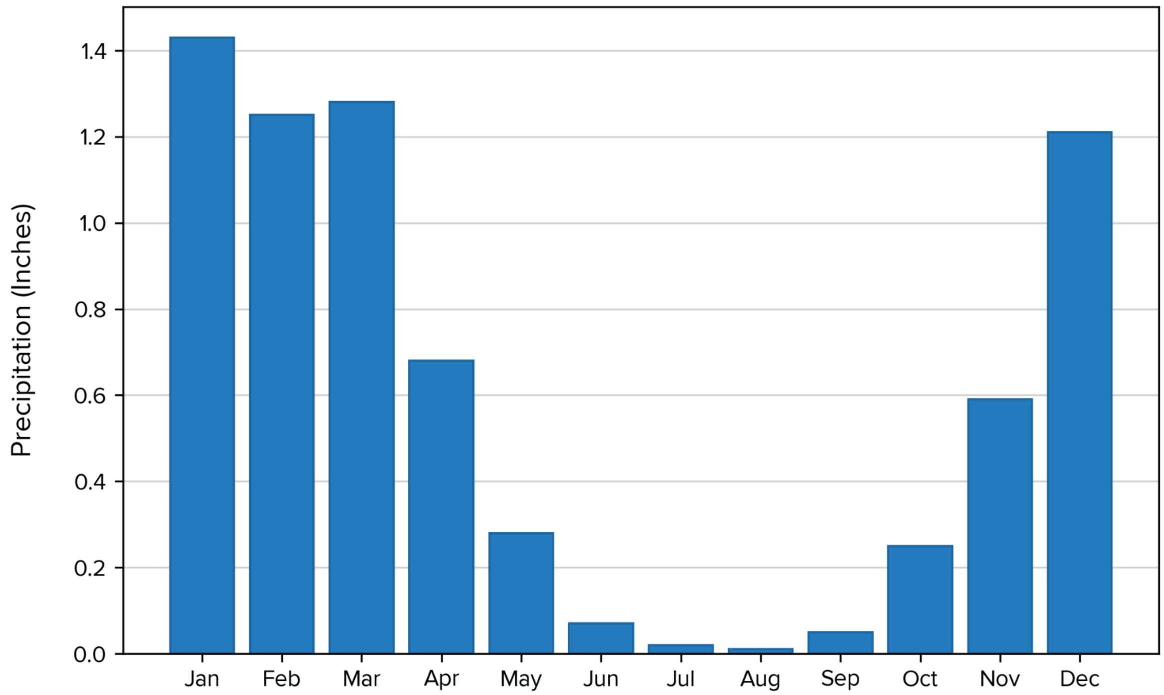

Figure 6-14. *Monthly precipitation averages over a 30-year period in Bakersfield (OSU, n.d.).*

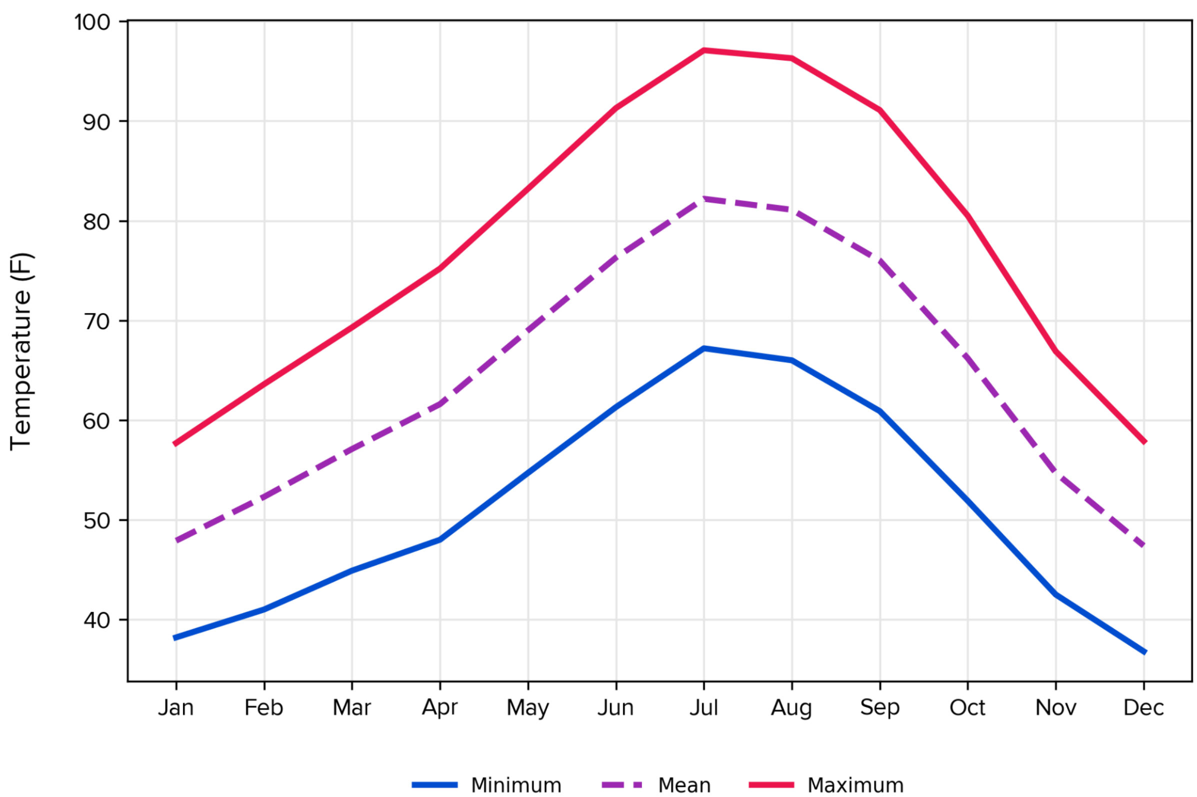

Figure 6-15. *Monthly temperature averages over a 30-year period in Bakersfield (OSU, n.d.).*

6.2.3 Population

The approximate 2020 city population is 395,000 residents. The actual population served by the DWS is around 40% of the total city population. The rest of the population is serviced by the WWS. Table 6-6 lists the projected population growth for both the Wholesale Water System and the Domestic Water System (retail). The retail population served in 2020 is based on a persons per residential connection trend, which is estimated to be 3.59 persons per connection in 2020. In the same year, there were 45,120 residential service connections within the DWS service area. Therefore, the estimated serviced population in 2020 is 161,980. The 2018 Regional Transportation Plan prepared by the Kern Council of Governments provided a 1.8% population growth rate for the Metro Bakersfield Area, which is used by both the Retail and Wholesale agencies in projections for the 2025-2040 service populations (City of Bakersfield, 2021).

Table 6-6. *Past and projected population for the City of Bakersfield (City of Bakersfield, 2021).*

Year	Retail Population Served	Wholesale Population Served
2020	161,980	394,328
2025	177,090	431,112
2030	193,610	471,328
2035	211,670	515,295
2040	231,420	563,363

6.2.4 Historical and Projected Water Use

Retail

In 2020, the DWS delivered 45,649 AF of water to residents, which is 13% higher than the average annual delivery between 2016-2019. At delivery, the level of treatment each user receives is drinking water quality. Sixty-six percent (~30,000 AF) of the actual water consumed was by the single-family residence sector in 2020. Each year single-family residences are the city’s largest consumer. The second-largest consumer is the commercial industry which used ~6,900 AF in 2020, followed by public facilities and losses which used ~3,500 and ~3,100 AF, respectively (Table 6-7). The city also provides water for multi-family residences, industrial users, and miscellaneous uses such as construction (Figure 6-16). Together, these remaining customers demanded less than 5% of the total water deliveries in 2020.

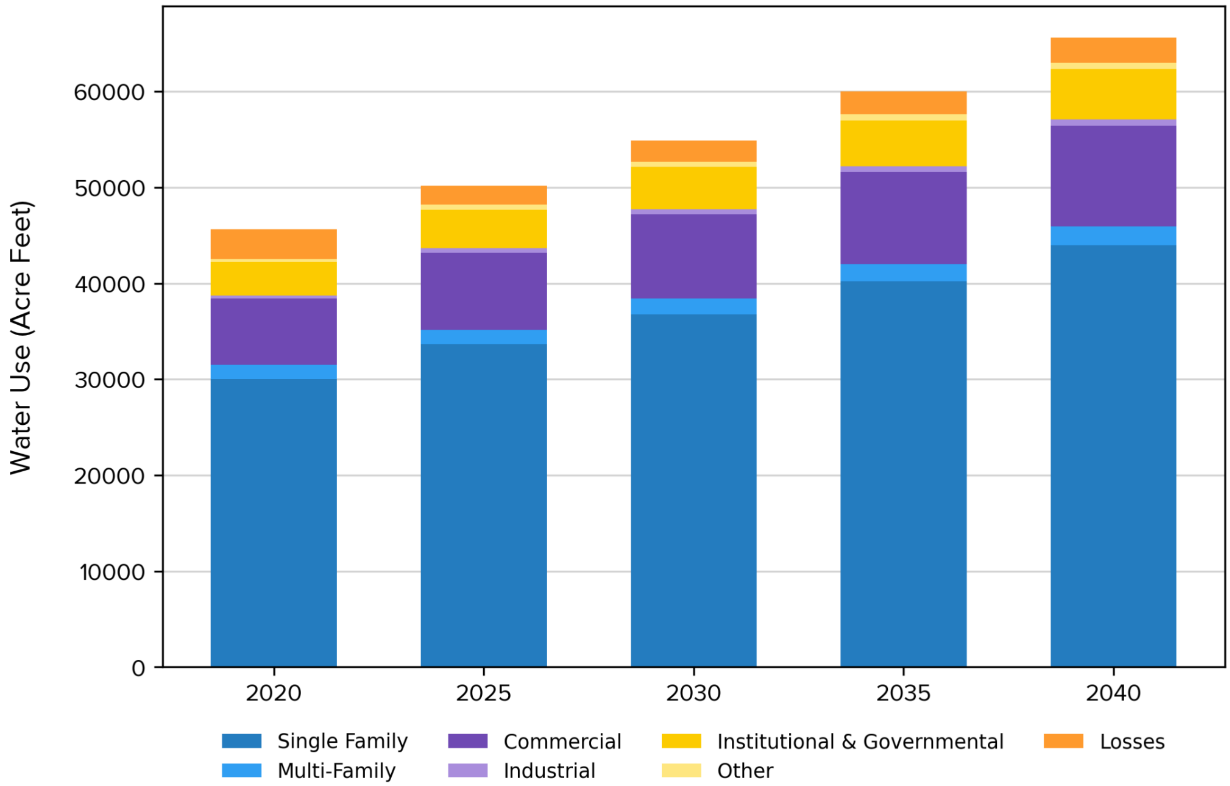

Figure 6-16. *Projected water use from 2020 to 2040 (City of Bakersfield, 2021).*

Table 6-7. *Actual retail water demand in 2020 for the City of Bakersfield (City of Bakersfield, 2021).*

Use Type	Additional Description	Water Quality	2020 Volume (AFY)	Percentage of Total Demand
Single Family		Drinking Water	29,986	66
Multi-Family		Drinking Water	1,534	3
Commercial		Drinking Water	6,904	15
Industrial		Drinking Water	314	1
Institutional/Governmental	Public Facilities	Drinking Water	3,527	8
Other	Construction Water	Drinking Water	250	1
Losses		Drinking Water	3,134	7
Total:			**45,649**	**~100%**

The projections of potable and raw water demand for 2025-2040 are based on sector percentages like those experienced in 2020. Single family residential is expected to consume 67% of the total water delivered each year, while commercial is projected to be 16%, public use is estimated to be 8%, and losses are expected to account for 4% of total consumption (Table 6-8). These estimates include population projections and a daily per capita use target of 263 GPCD in the calculations (City of Bakersfield, 2021).

Table 6-8. *Projected retail water use for the City of Bakersfield from 2025 to 2040 (City of Bakersfield, 2021).*

Use Type	Additional Description	Projected Water Use (AFY)			
		2025	2030	2035	2040
Single Family		33,627	36,764	40,194	43,944
Multi-Family		1,506	1,646	1,800	1,968
Commercial		8,030	8,780	9,598	10,494
Industrial		502	549	600	656
Institutional/ Governmental	Public Facilities	4,015	4,390	4,799	5,247
Other	Construction Water	502	549	600	656
Losses		2,008	2,195	2,400	2,624
Total:		**50,190**	**54,873**	**59,991**	**65,589**

Bakersfield expanded its water supply portfolio to recycled water in 2020 and plans to increase this supply in the next couple of decades. The city's recycled water delivery in 2020 was 664 AF for landscape irrigation on city-owned property. By 2040, the city expects to provide 8,961 AF each year for landscape irrigation and potential indirect potable reuse (City of Bakersfield, 2021). These actual and projected recycled water use estimates are not included in the tables below, as those highlight the potable and raw water uses only.

Wholesaler

The Wholesale Water System delivered a total of 77,528 AF of raw water, in 2020, to Cal Water Northeast Treatment Plant (NETP), Cal Water Northwest Treatment Plant (NWTP), Kern County Water Agency Improvement District No. 4's Henry C. Garnett Water Purification Plant

(KCWA WPP), and Kern River and Carrier Canal for groundwater recharge. The DWS receives allocations of the water treated at these plants to distribute to its service population. The remaining supplies are distributed to the city population outside the DWS service area. In 2020, groundwater recharge was the largest customer class, receiving ~68% of the total annual delivery. NETP consumed ~14%, KCWA WPP received ~9.5%, and NWTP used 8% (Table 6-9; City of Bakersfield, 2021).

Table 6-9. *2020 actual wholesale water demand for the City of Bakersfield (City of Bakersfield, 2021).*

Use Type	Additional Description	Water Quality	2020 Volume (AFY)	Percentage of Total Demand
Sales to other agencies	Cal Water Northeast Treatment Plant	Raw Water	11,124	14
Sales to other agencies	Cal Water Northwest Treatment Plant	Raw Water	5,918	8
Other Potable	KCWA ID4 Henry C. Garnett Water Purification Plant	Raw Water	7,380	10
Groundwater recharge	River and Carrier Canal Recharge	Raw Water	53,106	68
Total:			**77,528**	**~100%**

Cal Water and City Water Resources staff provided individual projections for 2025-2040 potable and raw water demand for the Cal Water treatment plants and the KCWA WPP, respectively. By 2040, it is projected that 44.8% of water resources will be delivered to NETP, 9% to NWTP, 6.5% to KCWA WPP, and 39.7% to river and carrier canal recharge and acre banking (Table 6-10). There are no projections for recycled water demands as the WWS does not distribute recycled water (City of Bakersfield, 2021).

Table 6-10. *City of Bakersfield projected wholesale water use, 2025 to 2040 (City of Bakersfield, 2021).*

Use Type	Additional Description	Projected Water Use (AFY)			
		2025	2030	2035	2040
Sales to other agencies	Cal Water Northeast Treatment Plant	22,400	44,800	44,800	44,800
Sales to other agencies	Cal Water Northwest Treatment Plant	9,000	9,000	9,000	9,000
Other Potable	KCWA ID4 Henry C. Garnett Water Purification Plant	6,500	6,500	6,500	6,500
Groundwater recharge	River and Carrier Canal Recharge, 2800 Acre Banking, and other City Facilities	62,100	39,700	39,700	39,700
Total:		**100,000**	**100,000**	**100,000**	**100,000**

6.2.5 Land Use and Socioeconomic Factors

The city's UWMP describes land uses within the city primarily consisting of residential, commercial, industrial, parks, and some agriculture (Figure 6-17). In 2020, the city population had a median age of 31, a median property value of $258,700, and a median household income of about $65,687 (Data Source USA, 2020). The three largest ethnic groups reported in the city in 2020 are White (Non-Hispanic; 31.4%), White (Hispanic; 29.7%), and Other (Hispanic; 14%). Furthermore, it is estimated that 89.8% of Bakersfield residents are citizens (Data USA, 2020). The city's General Plan indicates that approximately 43% of the population identifies as low-income or very low-income. Few Census Block Groups qualify as low-moderate income, which is approximately 3% of the DWS service area. This may be explained by the relatively high number of persons per low-income household (City of Bakersfield, 2021).

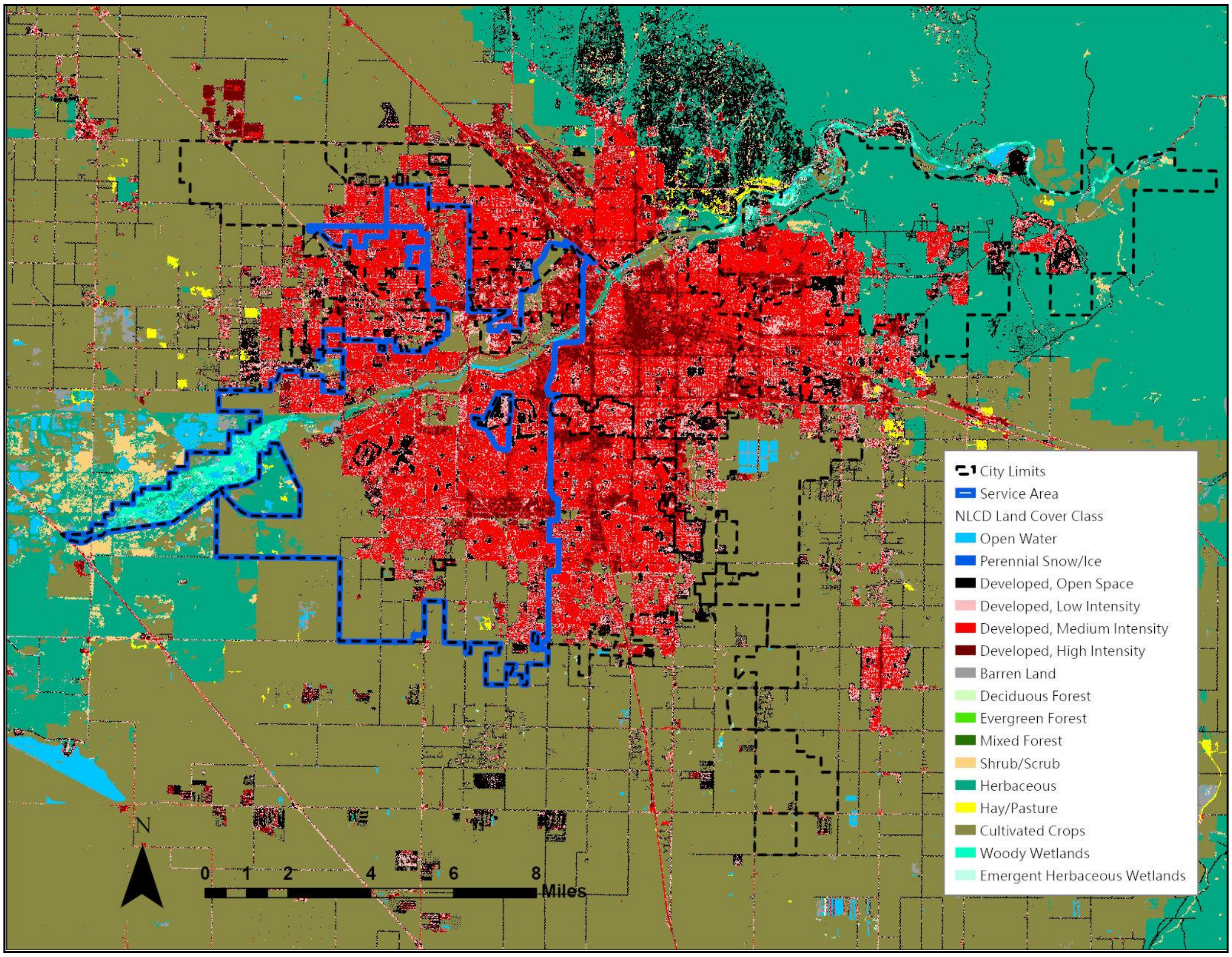

Figure 6-17. *Land use overview for the City of Bakersfield (California Department of Technology, 2022; City of Bakersfield, 2023; United States Geological Survey, 2021).*

6.2.7 Water Supply Overview

Retail

The City of Bakersfield sourced 45,649 AF of drinking water in 2020. In addition, the city sourced 664 AF of recycled water. The DWS relies heavily on treated surface water distributed by the Cal Water Treatment Plants, and groundwater resources (Table 6-11). Further, the city operates stormwater basins to recharge the groundwater basin. It does not purchase, transfer, exchange, or import water, nor does the system currently have desalination. As mentioned, current recycled water supplies are minimal; however, the city is planning to expand wastewater and recycled water resources over the next decade. To adjust for growing demand, Bakersfield plans to expand groundwater production in the next 25 year (Table 6-12).

Table 6-11. *Actual retail water supplies in 2020 for the City of Bakersfield (City of Bakersfield, 2021).*

Water Supply	Additional Description	Water Quality	2020 Volume (AFY)
Groundwater (not desalinated)	City Wells	Drinking Water	34,107
Surface Water (not desalinated)	Cal Water Northwest Treatment Plant	Drinking Water	2,872
Surface Water (not desalinated)	Henry C. Garnett Water Purification Plant	Drinking Water	8,670
Recycled Water	WWTP No.3 Tertiary	Recycled Water	664
Total:			**46,313**

Table 6-12. *Current and projected retail water supplies in 2020 for the City of Bakersfield (City of Bakersfield, 2021).*

Water Supply	Additional Description	Water Quality	Current and Projected Water Supplies (AFY)				
			2020	2025	2030	2035	2040
Groundwater (not desalinated)	City Wells	Drinking Water	34,107	39,190	43,873	48,991	54,589
Surface Water (not desalinated)	Cal Water Northwest Treatment Plant	Drinking Water	2,872	4,500	4,500	4,500	4,500
Surface Water (not desalinated)	Henry C. Garnett Water Purification Plant	Drinking Water	8,670	6,500	6,500	6,500	6,500
Recycled Water	WWTP No.3 Tertiary	Recycled Water	664	2,240	8,961	8,961	8,961
Total:			**46,313**	**52,430**	**63,834**	**68,952**	**74,550**

Wholesale

In addition to retail supplies, Bakersfield sourced 77,528 AF of water in 2020 from its Kern River allocation for wholesale to other users (Table 6-13). The city projects this will increase to a flat rate of 100,000 AFY from 2025 onward (Table 6-14).

Table 6-13. *Actual wholesale water supplies in 2020 for the City of Bakersfield (City of Bakersfield, 2021).*

Water Supply	Additional Description	Water Quality	2020 Volume (AFY)
Surface Water (not desalinated)	Kern River Supply	Other Non-Potable Water	77,528
Total:			**77,528**

Table 6-14. *Current and projected wholesale water supplies in 2020 for the City of Bakersfield (City of Bakersfield, 2021).*

Water Supply	Additional Description	Water Quality	Current and Projected Water Supplies (AFY)				
			2020	2025	2030	2035	2040
Surface Water (not desalinated)	Kern River Supply	Other Non-Potable Water	77,528	100,000	100,000	100,000	100,000
Total:			**77,528**	**100,000**	**100,000**	**100,000**	**100,000**

6.2.8 Groundwater

The City of Bakersfield sources groundwater (34,107 AF in 2020) from the Kern County Subbasin—part of the greater San Joaquin Valley Groundwater Basin. At present, the Kern County Subbasin is designated as critically overdrafted by the DWR. To address the basin's high-priority status, the city is a member of the Kern River Groundwater Sustainability Agency (KRGSA), which was formed in response to the passing of SGMA (Figure 6-18). The KCGSA's jurisdiction covers approximately 361 square miles of the Kern County Subbasin and, in addition to the city, includes Kern Delta Water District, KCWA's ID4, North of the River Municipal Water District/Oildale Mutual Water Company, and East Niles Community Services District as other member agencies.

Through collaboration with four other GSAs, the KGCSA works to bring the 2,834 square mile subbasin into compliance with the regulations outlined by SGMA. To this end, a collaborative GSP among the five agencies was submitted to the DWR in 2020. Per the GSP, The city does not plan to decrease groundwater pumping as it anticipates it will have access to additional

Kern River water that it will use for groundwater recharge (Kern River GSA, 2022). Further information on water sourcing can be found in **Section 6.2.9**.

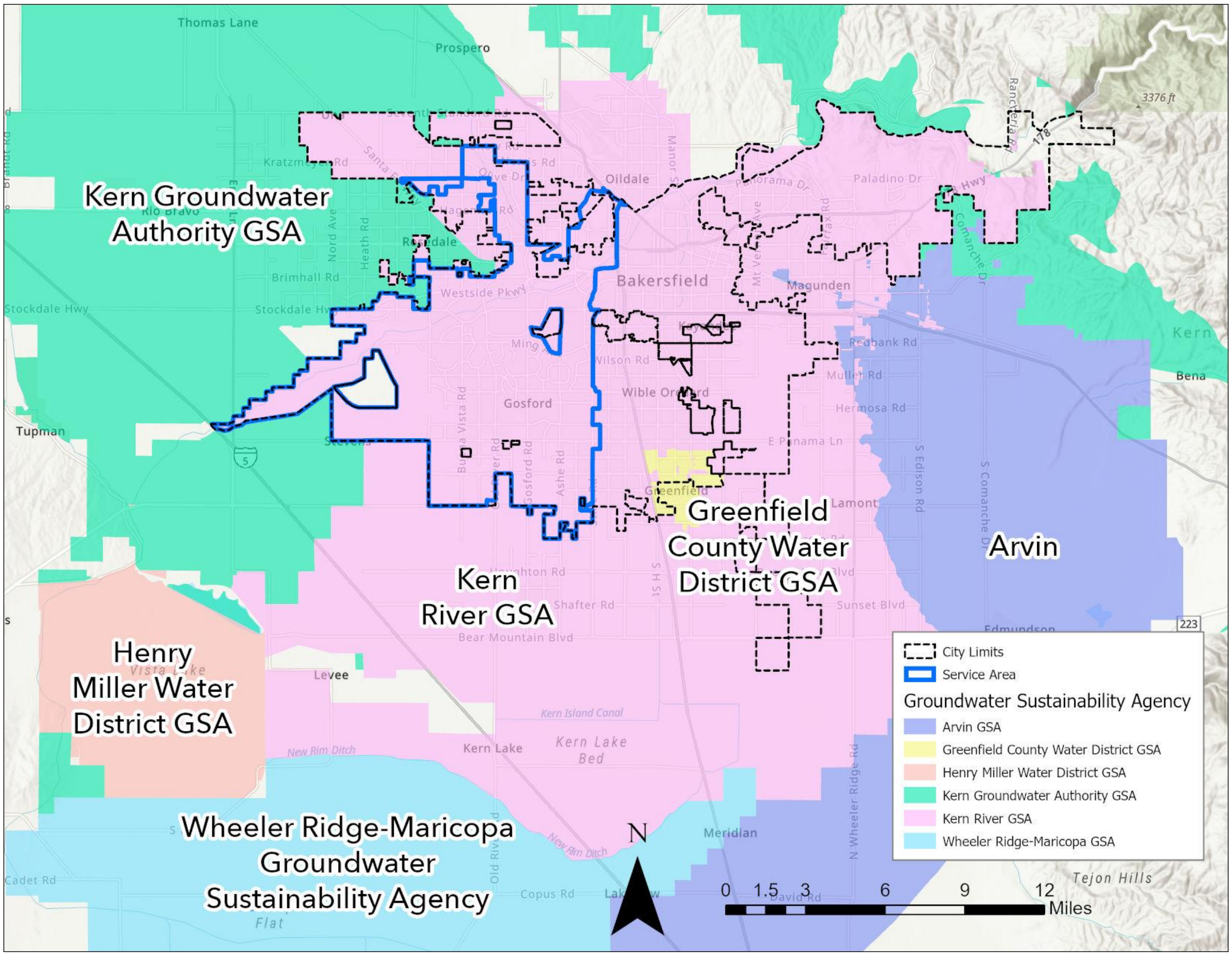

Figure 6-18. *Overview of the relevant management agencies and basins in the region (California Department of Technology, 2022; California Department of Water Resources, 2023b; City of Bakersfield, 2023; Kern River Groundwater Sustainability Agency, 2022).*

6.2.9 Surface Water

Kern River surface water is the main water supply for the City Wholesale Water System. This supply is provided to the Cal Water Treatment Plants for purification and delivery to the City's Domestic Water System. Kern County Water Agency's ID4 Henry Garnett Water Purification Plant receives its main supply from the State Water Project (SWP), however when SWP supplies are unavailable the city provides untreated Kern River water supplies.

The average annual use of Kern River water supplies is estimated to be 135,000 acre-feet for both urban and agriculture combined. Of that total, 100,000 AFY is designated for urban use

(~50-55% for DWS). Historically, Bakersfield has contracted out Kern River supplies to outside agencies and cities; however, the city recently terminated three long-term contracts allowing for the city to optimize its full entitlement of Kern River water. The city now expects to have an additional 70,000 AFY, increasing the reliability of its surface water source (Kern River Groundwater Sustainability Agency, 2022). The city also holds storage rights in Lake Isabella, which allows for flexibility in the management of annual supplies (City of Bakersfield, 2021).

6.2.10 Stormwater

Stormwater supplies captured by the estimated 400 stormwater basins across the city become part of Bakersfield's groundwater and recharged water supply. On average, 16,000 AFY are captured and recharged stormwater runoff, and 4,272 AFY of the annual average is diverted into the Kern River and unlined canals (City of Bakersfield, 2021).

6.2.11 Wastewater & Recycled Water

The city's WWTP No. 3 treats all wastewater generated within the Domestic Water System service area, providing non-disinfected secondary and tertiary treated water. The non-disinfected secondary effluent is stored in percolation ponds for agriculture, while the tertiary treated effluent is utilized for landscape irrigation at the Sports Village Complex, a city-owned property. In 2020, the wastewater collected was estimated to be 30% of the total demand (approximately 14,000 AFY). Currently, the city is required by contract to sell and deliver additional non-disinfected secondary effluent to the City of Los Angeles for farm irrigation, however, that contract will not be renewed after 2026. Bakersfield intends to use the additional effluent supply for other regions in the DWS service area that require landscape irrigation. This will serve as a supply buffer as the city population continues to rise and demand increases. Likewise, the city plans for an expansion of the tertiary treatment capacity from 2 MGD to 8 MGD at WWTP No. 3 to be used for irrigation and potentially indirect potable recharge by 2030 (City of Bakersfield, 2021).

6.2.12 Flow Rate Calculations

The City of Bakersfield's UWMP contains projections of future water demand and supply up to 2040 (City of Bakersfield, 2021). Bakersfield is dependent primarily on groundwater pumped from city wells, and on treated surface water from two plants, the Cal Water Northwest Treatment plant and the Henry C Garnett Water Purification Plant, whose supplies were assumed to be constant through 2040. To meet future demand, Bakersfield expects to expand its groundwater pumping considerably, despite the fact that the Kern County Subbasin—from which the city sources its groundwater—is characterized as critically overdrafted by the DWR. In light of this fact, we decided that in our estimates of future unmet demand, we would use more conservative groundwater pumping projections (Table 6-15).

Upper Bound Scenario

We estimated Bakersfield's upper flow rate by taking projected 2040 surface water and current actual groundwater supplies and subtracting them from projected 2040 demand. We justified this assumption by pointing to the current state of the Kern County Subbasin, along with a lack of evidence that groundwater pumping could be reliably increased year on year to meet demand as would be required of the Bakersfield projections.

Normal Scenario

Our assumptions for the normal scenario remain the same as in the upper scenario, with the only change being a 50% decrease in unmet demand (10,241 AFY) that we then added to projected groundwater supplies. This mid-range scenario comes closer to Bakersfield's projections of future groundwater pumping but is still roughly 10,000 AFY lower than the city's projected supply volume (City of Bakersfield, 2021).

Lower Bound Scenario

For the Lower scenario flow rate, we predicted half of the unmet demand in the normal scenario would be supplied by more groundwater pumping. Other values (2040 projected demand and surface water supply) are unchanged from the Normal and Upper scenarios.

Table 6-15. *City of Bakersfield 2040 projected water supply and demand estimates, AFY (City of Bakersfield, 2021).*

Scenario	Projected Demand	Projected Surface Water Supply	Projected Groundwater Supply	Total Projected Supplies	Demand to be met via modeled technology	Calculated Flow Rate (MGD)
Upper	65,589	11,000	34,107	45,107	20,482	**~18**
Normal	65,589	11,000	44,348	55,348	10,241	**~9.1**
Lower	65,589	11,000	49,469	60,469	5,121	**~4.6**

6.3 The City of Fresno

6.3.1 Service Area

While the City of Fresno's planning area covers approximately 106,000 acres, Fresno's water service area covers 70,400 acres (Figure 6-19). Roughly two-thirds of the city's water service area is within city limits, with the remainder consisting of unincorporated land (City of Fresno, 2021). Figure 6-20 overlays the Fresno city limits and the city's water district boundaries: the southwest portion of the city that lies outside service area boundaries is where the Fresno-Clovis Regional Wastewater Reclamation Facility, which treats sewer flows from the city and county, is located (City of Fresno, 2021). The service area excludes areas served by other agencies including the Bakman Water Company, Pinedale County Water District, Park Van Ness Mutual Water Company, California State University Fresno, as well as private groundwater users located within Fresno County (City of Fresno, 2021).

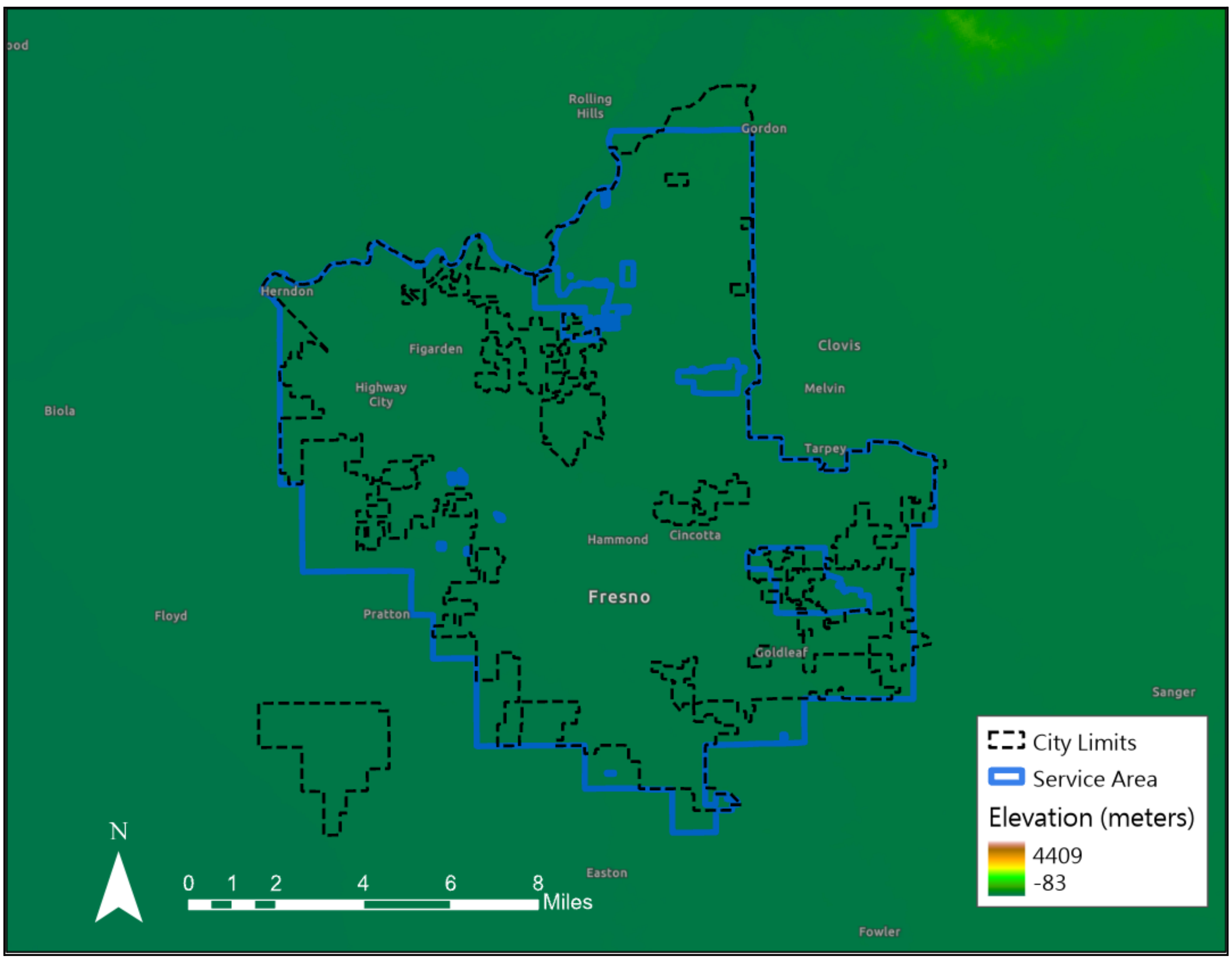

Figure 6-19. *Digital elevation model for the region showing a consistent topography throughout (California Department of Technology, 2022; City of Fresno, 2022; United States Geological Survey, 2008).*

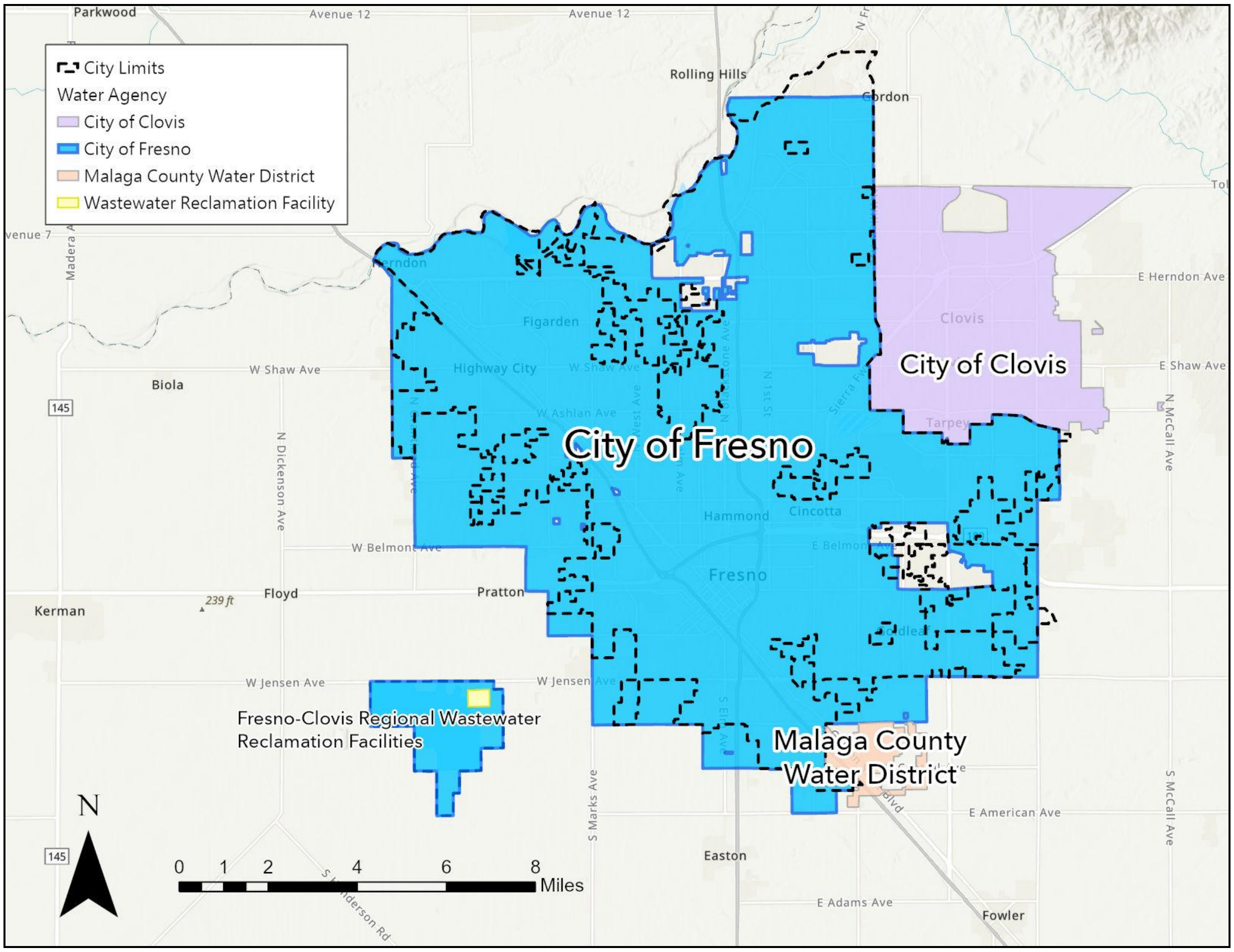

Figure 6-20. *City of Fresno's water service area (California Department of Technology, 2022; City of Fresno, 2022).*

6.3.2 Climate

Fresno's climate is best described as Mediterranean, with hot, dry summers and cool winters. Rainfall can vary significantly from year to year: although the annual average is 11 inches, Fresno received over 18 inches of precipitation in 2011 and less than 4 inches in 2014 (City of Fresno, 2021). Like other areas in the region, the wettest months are typically from December through March, peaking in January with an average rainfall of roughly 2.5 inches (Figure 6-21). The summer months see little precipitation, with June to August being particularly dry and recording the highest average evapotranspiration rates of the year (City of Fresno, 2021). Fresno's average temperatures also correspond to the trend, peaking during the drier summer months (65 - 95 °F) and decreasing to the lowest average values (40 - 55 °F) during the wetter winter months (Figure 6-22).

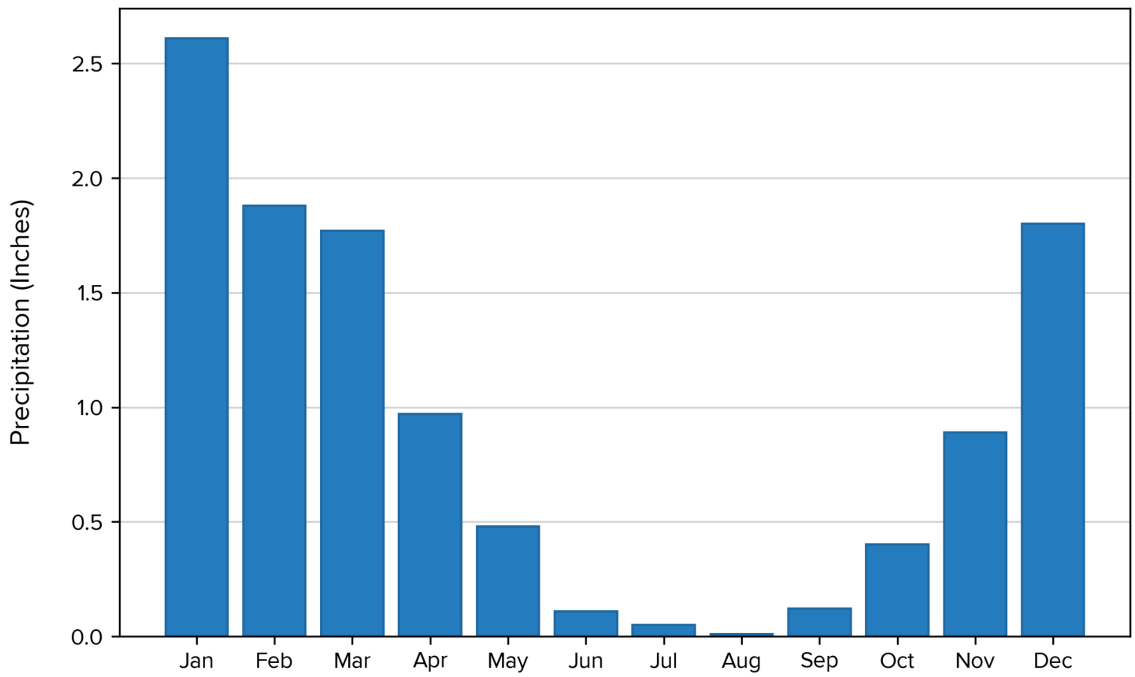

Figure 6-21. *Monthly precipitation averages over a 30-year period in Fresno (OSU, n.d.).*

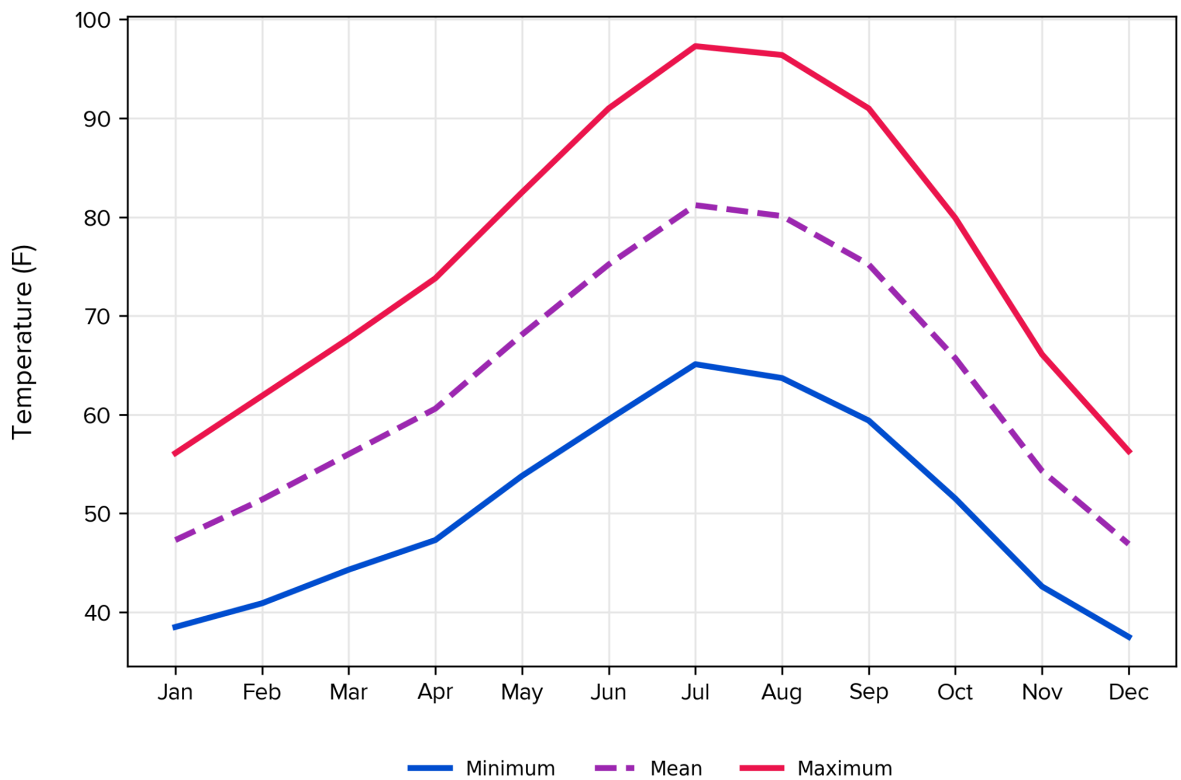

Figure 6-22. *Monthly temperature averages over a 30-year period in Fresno (OSU, n.d.).*

6.3.3 Population

Population estimates for the City of Fresno and Fresno's water service area closely correspond to one another: the city's most recent UWMP reported a population of 545,769 residents in the city and 546,502 residents in the water service area as of 2020 (City of Fresno, 2021). The city's annual growth rate has been declining since the 1990s, decreasing to an average of around 1% from over 2% before 1995 (City of Fresno, 2021). In its projections of future population growth, the city expects the water service area population to grow at a greater rate than the population of Fresno itself, as the city incorporates areas within the city's sphere of influence currently being served by other water agencies (Table 6-16; City of Fresno, 2021). For this reason, the city's projected population growth rate ranges between 1.1-2.1% between 2020 and 2045, averaging a 1.56% annual growth rate during that period (City of Fresno, 2021). These projections would mean Fresno's water service area population would number 812,529 residents by 2045 (DWR, 2018).

Table 6-16. *Past and projected population for the City of Fresno's service area (City of Fresno, 2021).*

Year	Population Served
2020	550,217
2025	609,433
2030	674,677
2035	719,327
2040	765,278
2045	812,529

6.3.4 Historical and Projected Water Use

The city provides water to over 139,500 residential, commercial, industrial, and institutional service connections, of which nearly 90% serve residential customers (City of Fresno, 2021). In 2013, the City of Fresno installed meters to measure single-family residential water use. Since these meters were installed, single-family residential water use decreased by more than 20,000 AFY; in 2020, consumption was still only at 79% of its 2013 value (City of Fresno, 2021). Demand for water in 2020 by customer type is shown in Table 6-17. Accounting for distribution losses, which were estimated to be 7.8% of all system production (9,568 AF), the total demand for potable water within the city's service area in 2020 was 121,993 AF (City of Fresno, 2021). Residential water use accounted for approximately 65% of all potable water uses in the city's service area, with commercial, institutional, and landscape water use accounting for most of the remaining demand (Figure 6-23).

Table 6-17. *Actual water demand in 2020 for the City of Fresno (City of Fresno, 2021).*

Use Type	Additional Description	Water Quality	2020 Volume (AFY)	Percentage of Total Demand
Single Family		Drinking Water	60,065	49.2
Multi-Family		Drinking Water	18,842	15.4
Commercial	Includes Institutional & Governmental use	Drinking Water	16,971	13.9
Industrial		Drinking Water	5,729	4.7
Landscape		Drinking Water	10,478	8.6
Other	Travel Meters	Drinking Water	340	0.3
Losses		Drinking Water	9,568	7.8
Total:			**121,993**	**~100%**

Despite an increasing population, the city's potable water demand has decreased in recent years due to Fresno's conservation efforts, which have lowered per capita daily water use beneath target levels (City of Fresno, 2021). Fresno's future potable water demand was derived using population projections and per capita water use estimates, as seen in Figure 6-23 and Table 6-18. The city expects that the ongoing update to its Metro Plan will include recommendations for programs and projects that will improve the city's water supply portfolio and meet future demand projections, including expanding the recycled water distribution system, surface water treatment capacity, and groundwater recharge program.

The City of Fresno is also evaluating its water transfer and exchange program with the Fresno Irrigation District (FID) and the U.S. Bureau of Reclamation, to sell or exchange water, such as the standing agreement with FID exchanging recycled water for the delivery of surface water to the east of the city (City of Fresno, 2021). Along with demand projections for potable water use, Fresno plans on increasing passive conservation water savings, such as the replacement of old water fixtures and appliances with more efficient alternatives, to 5,000 AFY by 2045 (City of Fresno, 2021). Projected non-potable water use, primarily for groundwater recharge, is shown in Table 6-19.

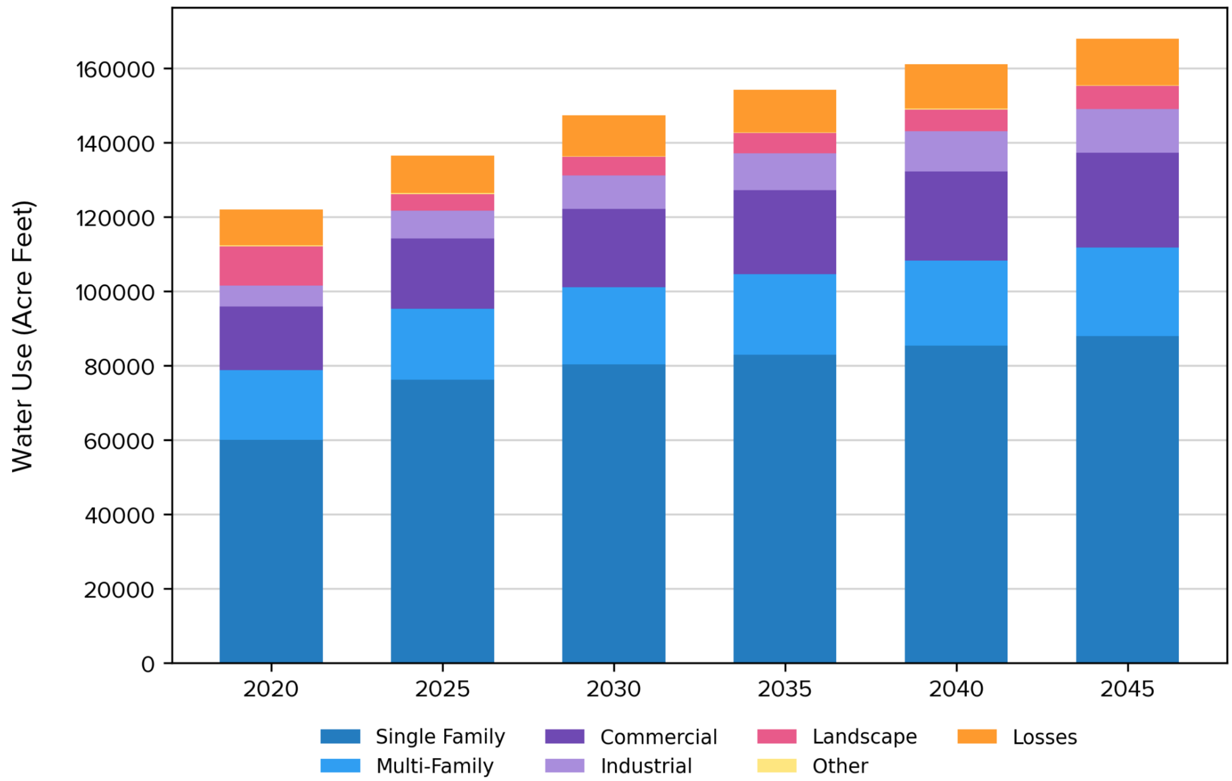

Figure 6-23. *Current and projected water demand by end use category (City of Fresno, 2021).*

Table 6-18. *Projected potable water use for the City of Fresno from 2025 to 2045 (City of Fresno, 2021).*

Use Type	Additional Description	Projected Water Use (AFY)				
		2025	2030	2035	2040	2045
Single Family		76,255	80,429	82,934	85,437	87,936
Multi-Family		19,000	20,654	21,737	22,831	23,935
Commercial	Includes Institutional & Governmental use	19,052	21,135	22,587	24,041	25,496
Industrial		7,410	9,003	9,922	10,841	11,758
Landscape		4,490	5,035	5,422	5,809	6,196
Other	Travel Meters	200	200	200	200	200
Losses		10,097	10,900	11,408	11,917	12,426
Total:		**136,504**	**147,356**	**154,210**	**161,076**	**167,947**

Table 6-19. *Projected non-potable water use for the City of Fresno from 2025 to 2045 (City of Fresno, 2021).*

Use Type	Additional Description	Projected Water Use (AFY)				
		2025	2030	2035	2040	2045
Groundwater Recharge	Raw Water	62,700	65,400	68,100	70,800	73,500
Total:		**62,700**	**65,400**	**68,100**	**70,800**	**73,500**

6.3.5 Land Use and Socioeconomic Factors

Single family residential households account for the largest proportion of land use across the City, with over 39% of the 70,400 acres within the service area belonging to that category. Open landscape irrigation (18.6%) and vacant/partially vacant land (15.9%) are the next two largest land use types, with the rest of the categories—multifamily residential, commercial, public, and industrial use—accounting for between 5-8% of the city's total land use (Figure 6-24; City of Fresno, 2021).

Compared to the rest of California, Fresno has a lower median family income—$57,211 compared to $84,097 across the state—and a significantly higher poverty rate, which at 22.9% is almost twice that of California (U.S. Census, 2022). The Fresno population is also majority Latino, making it one of the largest majority Latino cities in the U.S. (U.S. Census, 2022). Relatedly, over 43% of Fresno residents report speaking a language other than English at home. Taken together, these factors point to a population that is at disproportionate risk of an array of environmental, economic, and health problems. One of the primary goals of the City of Fresno's General Plan is to "respond to the city's relatively low household income and high rates of poverty, and the related importance of education and workforce development for raising income and quality of life in the long term" (City of Fresno, 2014). Such issues are important to consider when undertaking any long-term planning, especially concerning public water systems that provide a critical service to all city residents.

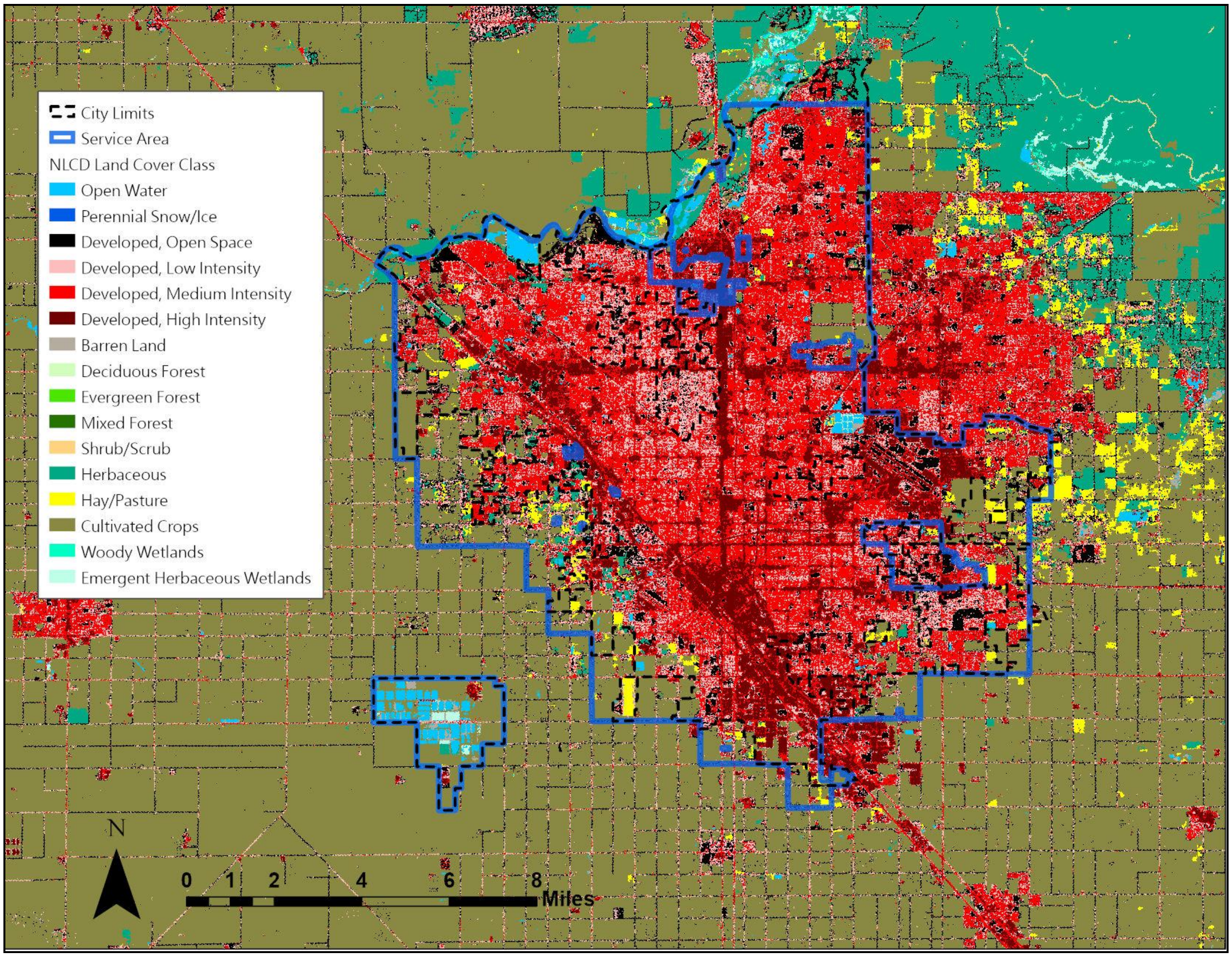

Figure 6-24. *City of Fresno Water District land use and primary vegetation (California Department of Technology, 2022; City of Fresno, 2022; United States Geological Survey, 2021).*

6.3.7 Water Supply Overview

In 2020, the City of Fresno used 121,993 AF of water, all of which was treated to drinking water quality (City of Fresno, 2021). Prior to 2004, Fresno relied entirely on groundwater pumped from municipal supply wells for its water supply (City of Fresno, 2021). The city now relies on groundwater from the North King's Valley Subbasin, surface water from the Central Valley Project, an allotment of the Fresno Irrigation District's allotment of water from the Kings River, and a marginal amount of recycled water.

Table 6-20 shows the actual water supplies for 2020, the majority of which are treated to drinking water standards, and the projected water supplies through 2040 (City of Fresno, 2021). Water is treated at the city's three surface water treatment facilities, and Fresno plans on expanding its water treatment capacities to meet more of its potable water demands. Note that projections are based on normal year yields (City of Fresno, 2021). In normal and wet years, the city relies on surface water supplies and imports to meet demand; during dry years, groundwater pumping is increased to fill in the gap between demand and supply.

Table 6-20. *Current and projected retail water supplies for the City of Fresno (City of Fresno, 2021).*

Water Supply	Additional Information	Water Quality	Current and Projected Water Supplies (AFY)					
			2020	2025	2030	2035	2040	2045
Groundwater		Drinking Water	55,028	138,090	143,630	149,100	154,490	159,820
USBR CVP	U.S. Bureau of Reclamation contract	Drinking Water	37,447	60,000	60,000	60,000	60,000	60,000
FID Kings River	Fresno Irrigation District contract	Drinking Water	71,292	125,030	131,600	131,600	131,600	131,600
Recycled Water, RWRF	Fresno-Clovis Regional Wastewater Reclamation Facility	Recycled Water	858	5,800	5,800	5,800	5,800	5,800
Recycled Water, NFWRF	North Fresno Wastewater Reclamation Facility	Recycled Water	54	110	110	110	110	110
Total			**164,679**	**329,030**	**341,140**	**346,610**	**352,000**	**357,330**

6.3.8 Groundwater

The City of Fresno overlies the Kings Subbasin—a critically overdrafted groundwater basin situated primarily in Fresno County with portions extending into the Tulare and Kings counties. Kings Subbasin is part of the greater San Joaquin Valley Groundwater Basin and is bounded to the north by the San Joaquin River, to the east by the Sierra Nevada Foothills, to the south by the Kings River, and to the west by the Delta-Mendota and Westside Subbasins (City of Fresno, 2021). Highly permeable, coarse-grained deposits comprise the upper several hundred feet of the Kings Subbasin allowing for significant groundwater recharge due to the aquifer's high hydraulic conductivity. Below this, at depths around 600-1,200 feet, lie fine-grained sediments that have historically produced substantial groundwater for the city (Figure 6-25).

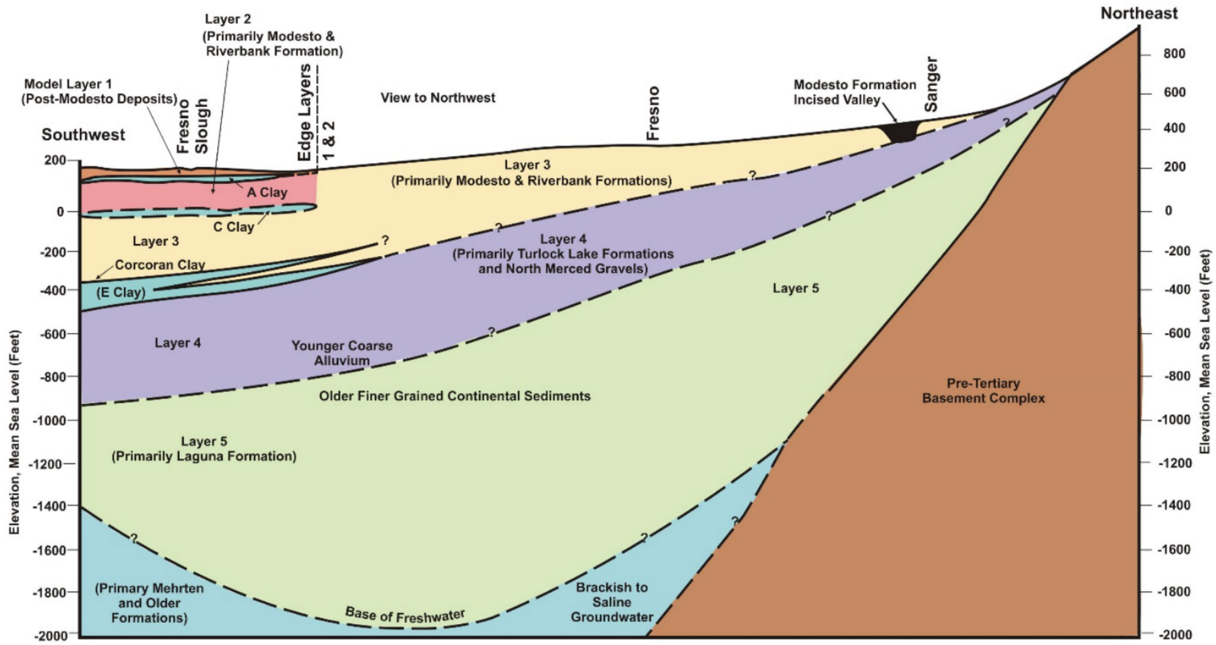

Figure 6-25. *Geologic cross-section of the Kings Subbasin and associated aquifers (City of Fresno, 2021).*

The city owns and operates 270 municipal wells, with approximately 202 currently operating within the Kings Subbasin. As the Kings Subbasin is designated as critically overdrafted under SGMA, the basin is managed by a conglomerate of seven GSAs: North Kings, South Kings, Central Kings, Kings River East, North Fork Kings, McMullin Area, and the James GSA (Figure 6-26). The City of Fresno was a founding member of the North Kings GSA, which works with the other GSAs via a coordination agreement that helps standardize approaches to basin management (City of Fresno, 2021).

Groundwater levels in the Kings Subbasin have faced a significant decline from 1975 to 2020; however, the rate decreased in 1990, and then again in 2004 due to a focused effort by the city to increase recharge within the basin. In 2019 and 2020, more than half of all water supplied by the city was sourced from surface water, which has led to an increase in groundwater in certain parts of the basin. To further help groundwater levels recover, the city expects to continue operating its three surface water treatment facilities into the future, while decreasing rates of groundwater pumping (City of Fresno, 2021).

Water quality in the Kings Subbasin often meets the primary and secondary levels needed to produce municipal water; however, there are localized plumes of contaminated groundwater throughout. The primary contaminant found in the basin is nitrate due to heavy agricultural use, but other contaminants such as DBCP (1,2-Dibromo-3-chloropropane) and TCP (1,2,3-Trichloropropane) are present as well. These contaminants require the city to use wellhead treatment and water blending in certain areas to reach potable standards (City of Fresno, 2021).

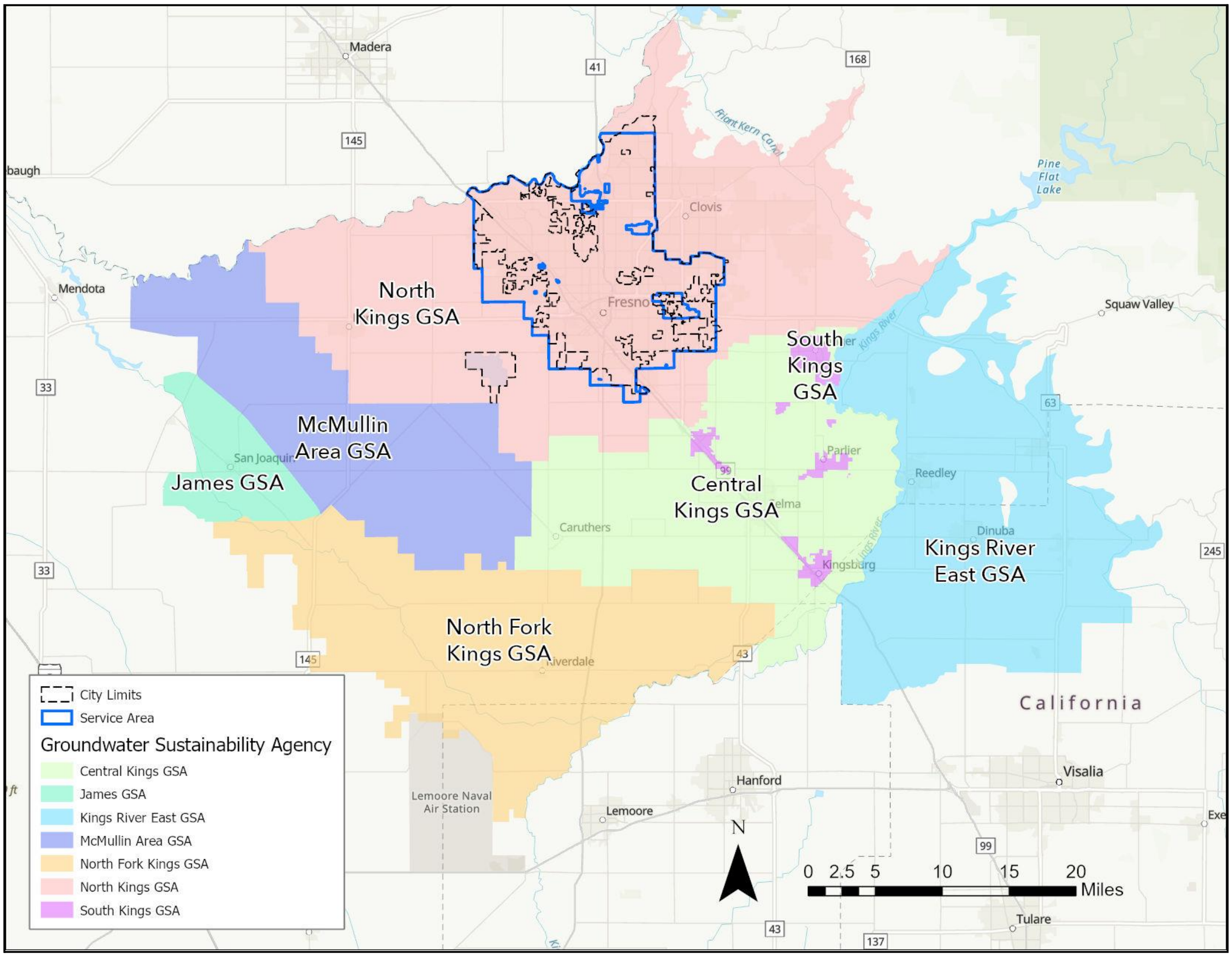

Figure 6-26. *Overview of the relevant management agencies in the region (California Department of Technology, 2022; California Department of Water Resources, 2023b; City of Fresno, 2022).*

6.3.9 Imported Surface Water

The city receives allocations of surface water from both the United States Bureau of Reclamation (USBR) and the Fresno Irrigation District (FID) (City of Fresno, 2021). These contracts supply raw surface water which is then treated by Fresno's Southeast Surface Water Treatment Facility, which is now the primary source for meeting potable demand within the city's operational area. Surface water not distributed to city customers is routed to groundwater recharge basins (City of Fresno, 2021). The city has two primary contracts through which it imports water: the USBR's Friant Division contract (wholesale supply) and the contract with FID.

Last renewed in 2010, the USBR Friant Division Contract secures 60,000 AF of Class 1 Central Valley Project (CVP) water for the city in perpetuity (City of Fresno, 2021). The average simulated delivery is 53,680 AFY, brought down from the median value of 60,000 AF due to drought years factored into the projections. The city receives an entitlement from the Kings River supply through the Fresno Irrigation District. Fresno's exact entitlement is a percentage of Kings River water based on the percentage of FID land area that also falls within the city's water service area (City of Fresno, 2021). This means that if the city increases its land area by incorporating adjacent plots, its percentage of FID water would increase as well, so long as that land also falls within the FID's jurisdiction and the new area was receiving water deliveries through the Fresno district. However, there is a cap on the maximum percentage the city can receive, which in the most recent FID agreement was set at 29% (City of Fresno, 2021). Currently, Fresno receives 25.79% of Kings River water, and is not projected to hit the 29% cap until 2030; it is also important to note that historically the city has not used all of its annual allocation in a given year, with FID reallocating excess water to other customers (City of Fresno, 2021).

Fresno also falls within the boundaries of the Fresno Metropolitan Flood Control District (FMFCD), which has the responsibility of managing stormwater flows throughout its service area (City of Fresno, 2021). During the rainy season (November-April) the city's stormwater runoff mostly flows into urban stormwater basins, where FMFCD either retains the water for groundwater recharge or pumps it to local irrigation canals. Estimates of stormwater recharge are difficult due to a lack of data on actual stormwater flows into recharge basins, but FMFCD estimates that recharge during the rainy season ranges from 7,000 AFY to 22,200 AFY (City of Fresno, 2021).

6.3.11 Recycled Water

In 2013, Fresno adopted a Recycled Water Master Plan to increase the city's recycled water use, with a focus on replacing the use of potable water for landscape irrigation. Two main water reclamation facilities currently exist to accomplish this goal: the Fresno-Clovis Regional Wastewater Reclamation Facility (RWRF) and the North Fresno Wastewater Reclamation Facility (NFWRF).

The RWRF treats sewage flows from the City of Fresno and select areas throughout the county that are connected via the city's sewage system. These areas include the City of Clovis, Pinedale County Water District, and the Pinedale Public Utility District (City of Fresno, 2021). The facility takes in around 63,000 AF per year, which is then put through primary, secondary, and tertiary treatment. The city has three options for effluent disposal: secondary effluent that has not been disinfected can be used for limited irrigation of farmland or deposited in percolation ponds, or wastewater can be treated to a level where the city can use it in its recycled water distribution system. Disinfected tertiary effluent must be put through all three treatment units, of which tertiary treatment is the facility's rate-limiting step (City of Fresno, 2021). This system, called the Tertiary Treatment and Disinfection Facility (TTDF), began operation in 2017 and currently has a capacity of 5 MGD of effluent deemed Title 22 tertiary treated water by the State Water Resources Control Board (City of Fresno, 2021). The city states that the TTDF can be expanded to 30 MGD in the future (City of Fresno, 2021).

The NFWRF is located in the northern part of the city and was constructed as part of a planned community. Like RWRF, the NFWRF produces tertiary-level effluent that the city can use as recycled water. The facility is smaller than the RWRF: it has a rated average monthly flow of 0.71 MGD and is expandable to 1.25 MGD (City of Fresno, 2021). The NFWRF produced 325 AF of treated wastewater in 2020, most of which was used to irrigate the Copper River Ranch golf course, and for irrigation of turf (City of Fresno, 2021). The remaining unused, treated effluent is diverted to the RWRF.

The city used 4,757 AFY of recycled water in 2020, which fell significantly short of the 21,200 AFY of recycled water the city projected in its 2010 water management plan (City of Fresno, 2021). Over 3,800 AFY of total recycled water use underwent secondary treatment, meaning the water was not disinfected but still fit for irrigating non-food crops (City of Fresno, 2021). The remaining was tertiary treated water, which was used for food crops and landscape irrigation. Fresno predicts that by 2025, recycled water production will reach 14,220 AFY (City of Fresno, 2021). The city has laid out various steps in its UWMP to accomplish this goal, which include expanding its tertiary treatment capacity at its RWRF and NFWRF wastewater treatment sites, overhauling development ordinances to require new developments to install better-recycled water transmission and distribution infrastructure, establishing approved uses of recycled water, and encouraging the use of voluntary retrofits so its customers can use recycled water (City of Fresno, 2021).

6.3.12 Flow Rate Calculations

The City of Fresno conducted a Drought Risk Assessment (DRA) as part of the UWMP, as is required of suppliers under a new DWR Water Code provision. In the DRA, the city provides supply and demand projections by water use type for a five-year drought. To create our flow rate estimates, we added projected supplies for the city's three main types of water—groundwater, surface water, and recycled water—using Fresno's DRA projections and sustainable yield estimates for groundwater pumping. Flow rate estimates and information on the assumptions we made in creating them are grouped by scenario below (Table 6-21).

Upper Bound Scenario

Fresno provides demand projections through 2045, so we used the city's values for our own estimate of future water demand. We used the city's projected values for "Single Dry Year Supply" in 2045 as our flow rate estimate for surface water supplies in our upper, normal, and low-supply scenarios, which were outlined in **Section 6.3.4**. Recycled water supplies are projected to remain the same regardless of precipitation.

The city's groundwater supply projections include the quantity of water allocated to intentional recharge each year; however, the city also states that the quantity of water it can put toward groundwater recharge varies based on factors such as annual precipitation, i.e., whether the city is experiencing a drought (City of Fresno, 2021). If current climatic trends continue, the city's intentional recharge allocations will fall short of its aspirational projections outlined in the 2021 UWMP (City of Fresno, 2021). For this reason, we used the city's projections of the maximum sustainable yield Fresno predicts will be feasible in 2045 for our Upper scenario's estimate of available groundwater supply. We then added these estimates to obtain our estimate of future supply.

Normal Scenario

As in the Upper scenario, we used the city's recycled water projections and maximum sustainable yield for the projected groundwater supply. For our estimate of future surface water supplies, we took the city's lower limit for the average allocation during drought years, labeled "critical" in the UWMP. Despite a nonzero value for the maximum allotment during "critical" years, the city's USBR allotment is set to zero to keep consistent with the city's DRA estimates, also provided in the UWMP (City of Fresno, 2021).

Lower Bound Scenario

Our estimates of recycled and groundwater supply remained constant with the values in our normal scenario. We estimated the city's future surface water supplies from the average "dry" year allotment values, with the same exclusion of USBR allotments as in the Normal scenario. We subtracted half of the Normal scenario's calculated unmet demand (7,313 AFY) from the city's average projected surface water supply, as the city made assumptions that by 2045, their water service area would increase by 40% and their allocation of Kings River water would increase to its maximum (29% of total flows) as stipulated in the contract (City of Fresno, 2021).

Table 6-21. *City of Fresno 2045 projected water supply and demand estimates, AFY (City of Fresno, 2021).*

Scenario	Projected Demand	Projected Surface Water Supply	Projected Recycled Water Supply	Projected Groundwater Supply	Total Projected Supplies	Demand to be met via modeled technology	Calculated Flow Rate (MGD)
Upper	167,947	45,852	5,910	86,320	138,082	29,865	**~26.6**
Normal	167,947	61,000	5,910	86,320	153,320	14,627	**~13.1**
Lower	167,947	83,687	5,910	86,320	183,320	7,313	**~6.5**

7 Results

7.1 Model Results

Below we present the model outputs—energy requirements, capital costs, and O&M costs—for each technology. All results presented will focus on the normal flow rate for each site, unless otherwise noted. Due to a limitation of the model, the energy requirements for indirect potable reuse, direct potable reuse, and ocean desalination remain constant across all sites and flow rates (Figure 7-1). The energy requirements are reflective of cost per unit of water (kWh/m^3), resulting in a mean energy requirement of ocean desalination (4.03 ± 2.09 kWh/m^3) that is nearly double that of DPR (2.22 ± 0.56 kWh/m^3) and IPR (2 ± 0.56 kWh/m^3) across sites.

The energy requirement for groundwater desalination changes for each city as it is primarily a function of well depth, which varies from region to region (Table 7-1; California Department of Water Resources, 2023a). At depths to groundwater of approximately 180 ft and 130 ft, Oxnard and Fresno have similar energy requirements for groundwater desalination at 2.89 ± 0.6 kWh/m^3 and 2.58 ± 0.6 kWh/m^3 respectively. In contrast, the energy requirement for

Bakersfield is slightly higher at 3.31 ± 0.6 kWh/m^3 due to a depth to groundwater of approximately 250 ft (California Department of Water Resources, 2023a).

Table 7-1. *Depth to groundwater and the associated energy requirements (kWh/m^3) for groundwater desalination are presented for each site (California Department of Water Resources, 2023a).*

Site	Depth to Groundwater (ft)	Energy Requirement (kWh/m^3) for Groundwater Desalination
City of Oxnard	~180	2.9 ± 0.6
City of Bakersfield	~250	3.31 ± 0.6
City of Fresno	~130	2.6 ± 0.6

Across all sites, capital, and O&M costs decrease as flow rates increase for each technology. For example, as the flow rate increases from 3.1 MGD to 12.6 MGD for the City of Oxnard, the relative capital costs for IPR decrease from 5.8 + 2.9/-1.7 to 4.4 +2.2/-1.3 $MM/MGD. The O&M costs reflect this same trend and this relationship is explained by larger facilities' capacities to process more water at lower per-unit costs. However, the change is non-linear, since the costs for different unit processes have different responses to increases in flow.

Ocean desalination, applicable only for the City of Oxnard, and DPR incur the highest capital cost of all technologies for all sites (Figure 7-2). In contrast, groundwater desalination incurs the lowest costs across all cities. At 6.5 MGD, the City of Oxnard can expect capital costs of 7.6 +3.9/-2.3 $MM/MGD for DPR, and 7.6 +3.8/-2.3 $MM/MGD for ocean desalination—more than double the cost of groundwater desalination at 2.6 +1.3/-0.8 $MM/MGD. Finally, IPR incurs a cost of 5.02 +2.5/-1.5 $MM/MGD. For both DPR and IPR, membrane filtration processes are the primary driver of cost (ultrafiltration and microfiltration respectively).

While ocean desalination incurs the highest O&M cost among technologies, DPR, IPR, and groundwater desalination are expected to have similar O&M costs (Figure 7-3). For example, at the normal flow rate of 9.1 MGD, and a depth to groundwater of ~250 ft for the City of Bakersfield, O&M costs for DPR, IPR, and groundwater desalination would cost 0.8 +0.4/-0.2, 0.6 +0.3/-0.2, and 0.5 +0.3/-0.2 $MM/MGD (Figure 7-3). When factoring in the uncertainty in the cost estimates, these cost differences become small. The primary driver of O&M costs for DPR and IPR are reverse osmosis and filtration processes. For a complete aggregation of model results, please refer to **Section 11.4** where we provide tables for each site and flow rate.

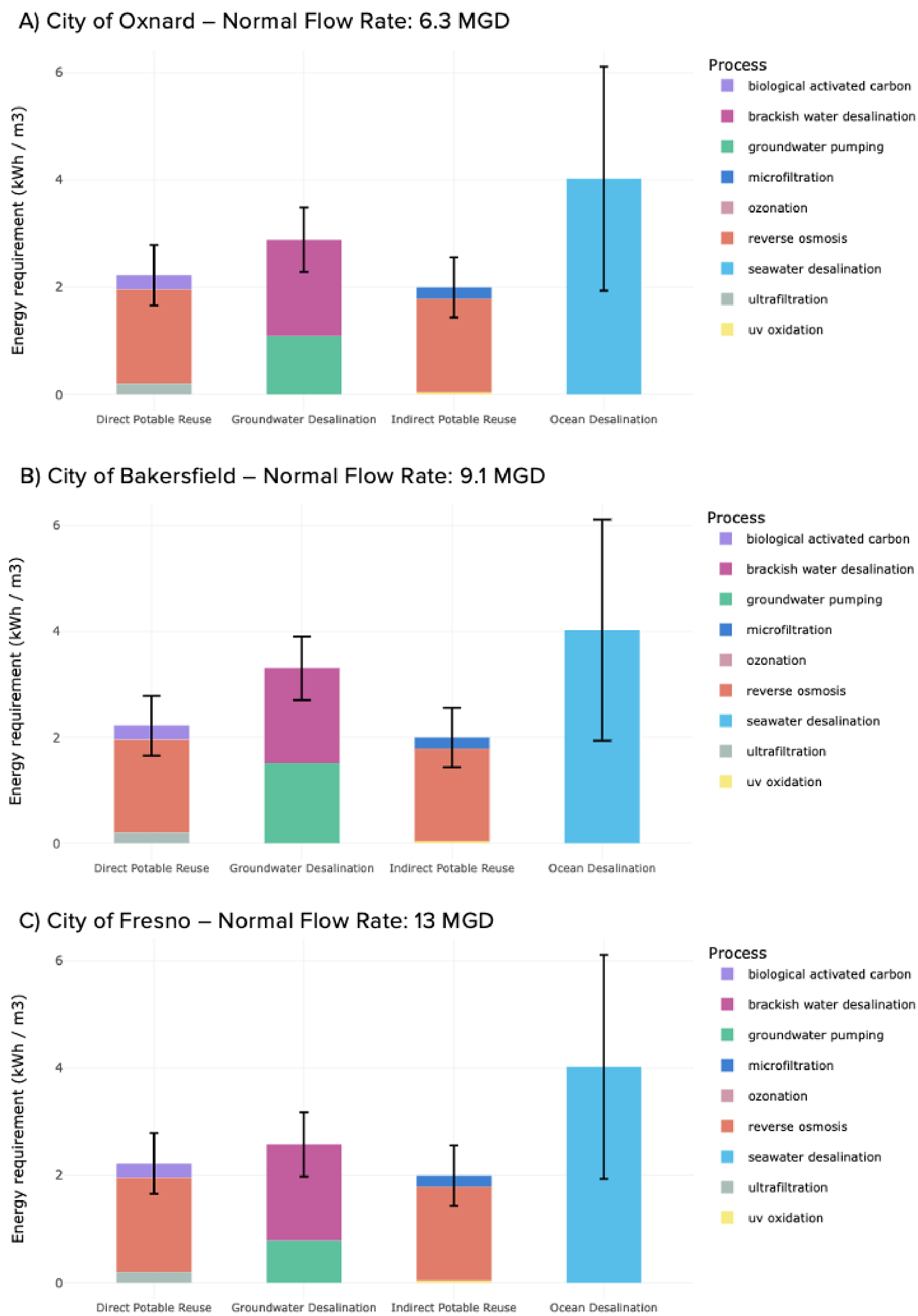

Figure 7-1. *Energy requirements (kWh/m^3) for each technology across all sites using normal flow rate calculations. Energy requirements remain constant across sites for all technologies except groundwater desalination. A) City of Oxnard, B) City of Bakersfield, C) City of Fresno.*

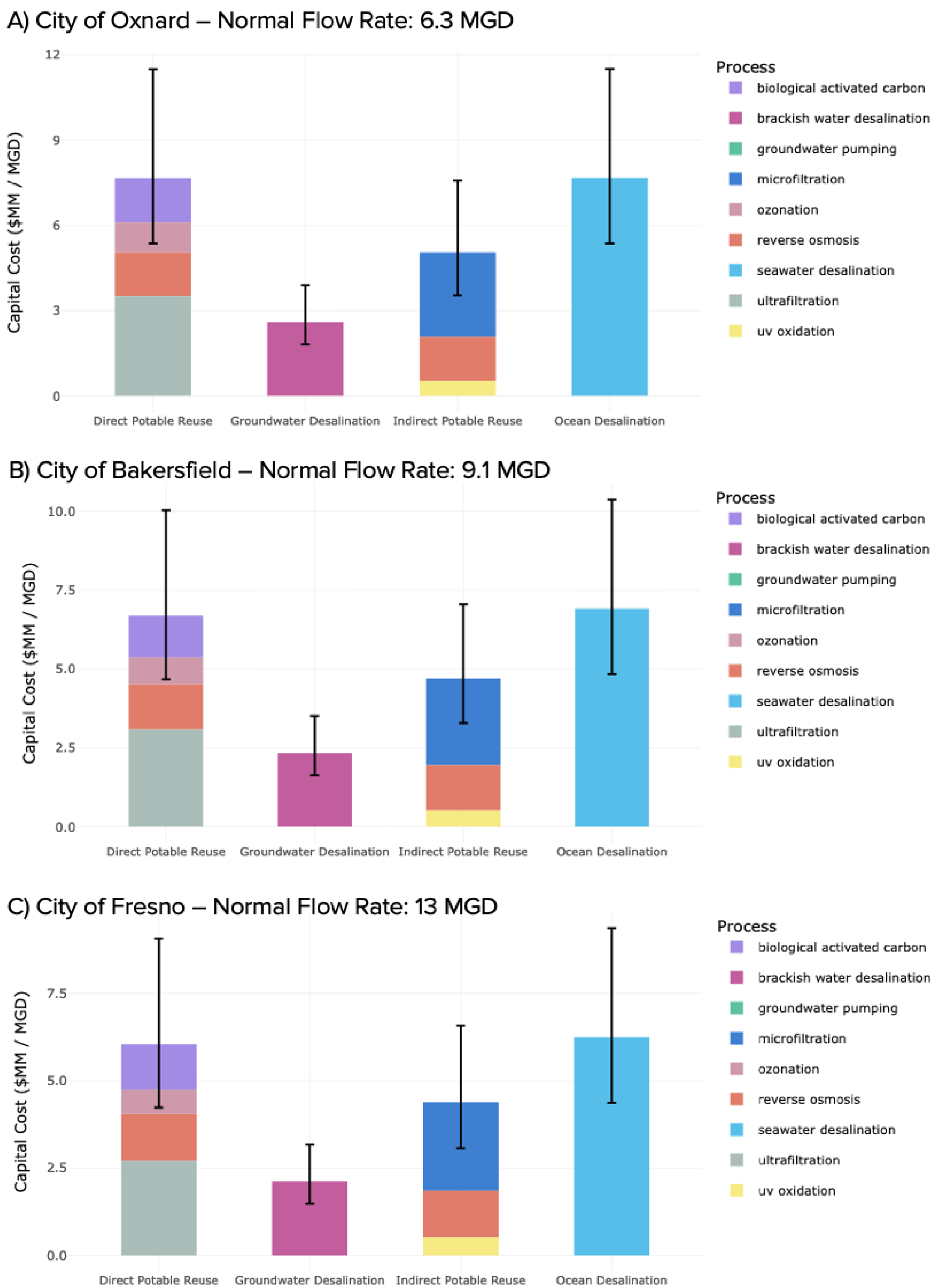

Figure 7-2. *Capital costs ($MM/MGD) for each technology across all sites using normal flow rate calculations. A) City of Oxnard, B) City of Bakersfield, C) City of Fresno.*

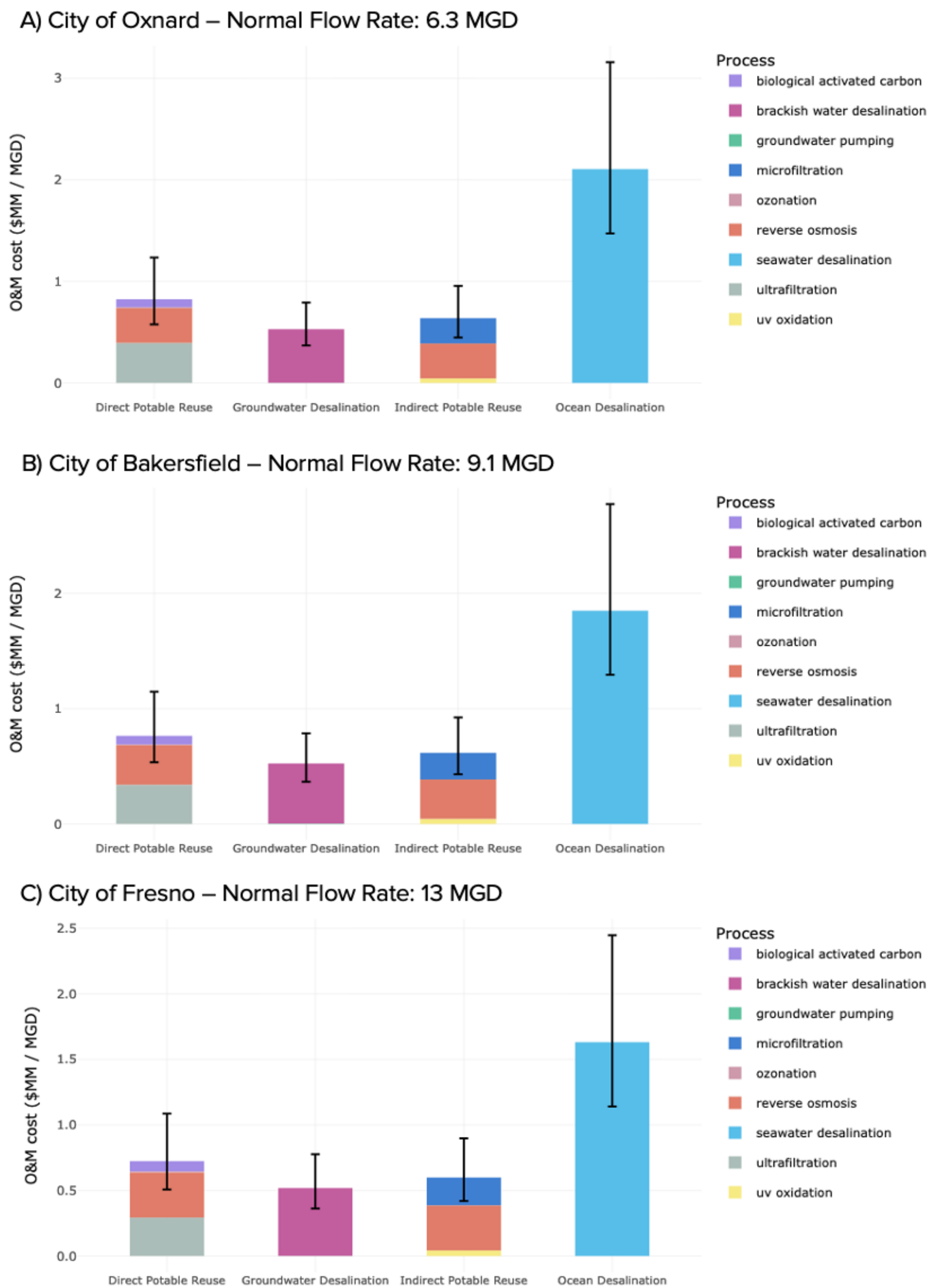

Figure 7-3. *Capital costs ($MM/MGD) for each technology across all sites using normal flow rate calculations. A) City of Oxnard, B) City of Bakersfield, C) City of Fresno.*

7.2 Water Risk Analysis

7.2.1 City of Oxnard

Water risk percentiles for the Oxnard Water District are shown in Figure 7-4, allowing for the identification of severely burdened tracts (top 20th percentiles). This figure demonstrates that severely burdened tracts are centrally located through the middle of district boundaries in addition to Oxnard's southernmost coast. Figure 7-5 shows percentile ranges, the associated population total, and the percentage of the total population within each percentile range. About 55,000 people, or 20% of the population served by Oxnard's water district, fall into the top 20th percentile for water risk.

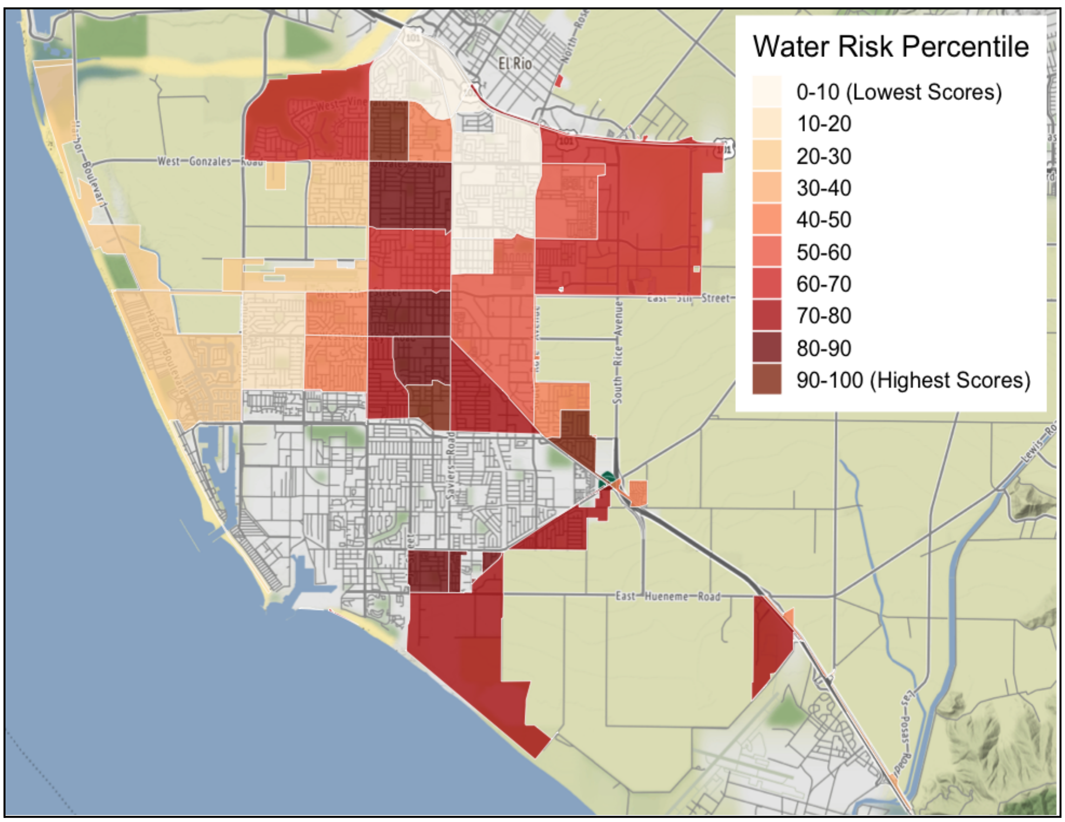

Figure 7-4. *Water risk score including socioeconomic and pollution burden indicators with the outermost boundary outlines the Oxnard Water Agency. Inner boundaries are representative of census tracts (CalEnviroScreen 4.0, 2021).*

The correlation matrix in Figure 7-6 shows strong positive correlations amongst some population indicators. Linguistic isolation demonstrates a strong positive correlation with both educational attainment and poverty. The correlations amongst environmental indicators show primarily weak or moderate positive correlations. Lastly, the correlations between population and environmental indicators are largely weak or moderately negative.

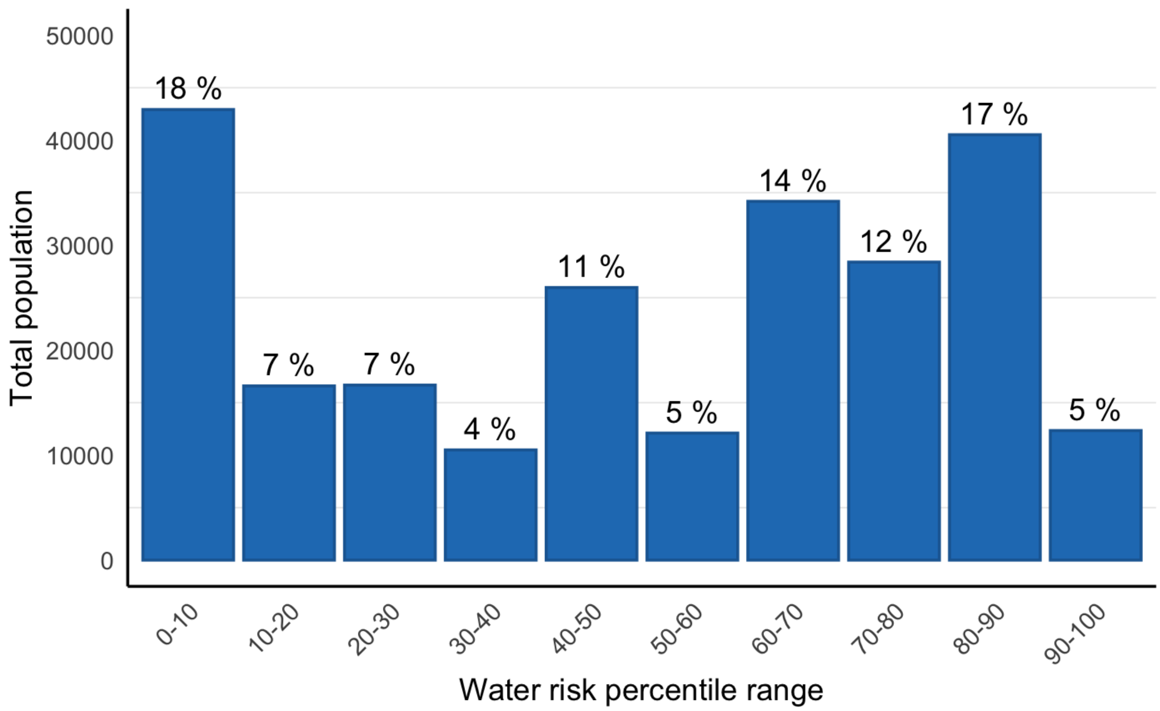

Figure 7-5. *City of Oxnard population totals in each water risk score percentiles. Percents represent the percent of the total population within the boundaries that are within the given percentile (CalEnviroScreen 4.0, 2021).*

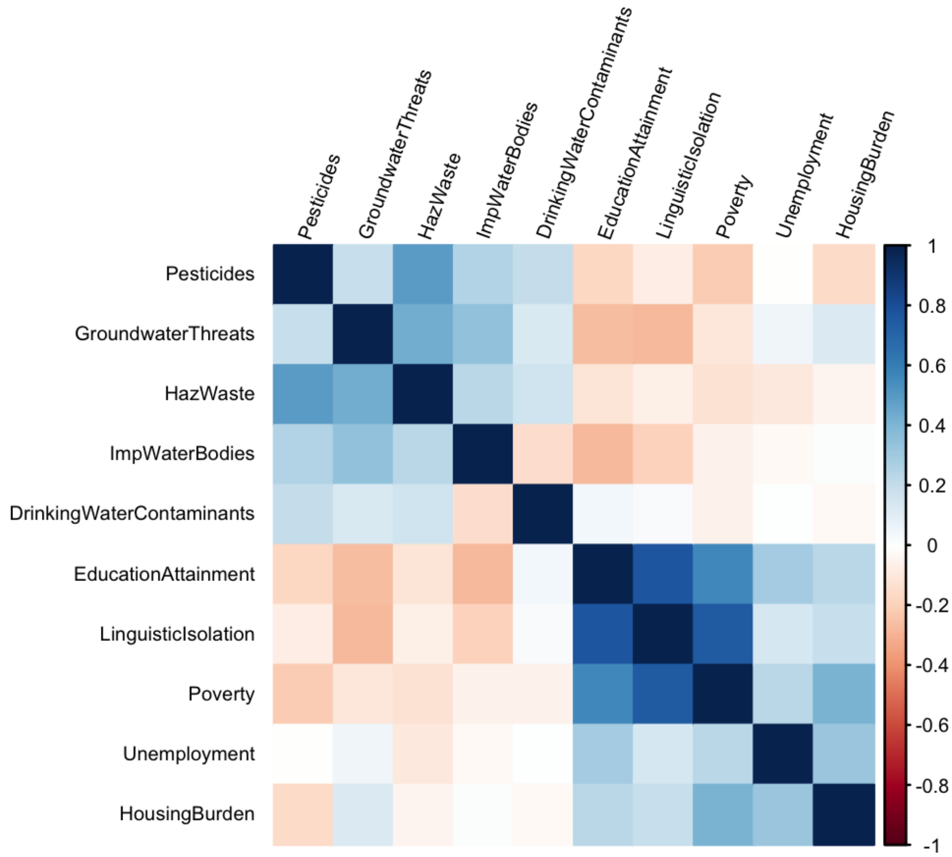

Figure 7-6. *Correlation matrix of both environmental and social indicator scores used to calculate water risk in Oxnard's Water District. Shades of blue indicate a positive correlation between indicators, while shades of red indicate a negative correlation. Darker colors on either end of the spectrum represent stronger correlations (closer to 1 or -1), while lighter colors represent weaker correlations (closer to 0)*

7.2.2 City of Bakersfield

The geographic distribution of water risk percentiles within Bakersfield water district is shown in Figure 7-7. Figure 7-7 demonstrates that tracts with the highest water risk score are concentrated on the southern and easternmost boundaries of the water district. Figure 7-8 shows population totals and the percentage of the total population within each percentile range. With severely burdened tracks being defined as the top 20th percentiles, approximately 54,000 people, or 21% are considered to be severely burdened. The correlation matrix in Figure 7-9 shows many strong positive correlations among population variables, while correlations between population and environmental indicators mostly demonstrate a weak positive correlation, except for some weak negative correlations. Drinking water contaminants and pesticides are an exception, however, as they show a strong positive correlation between one another.

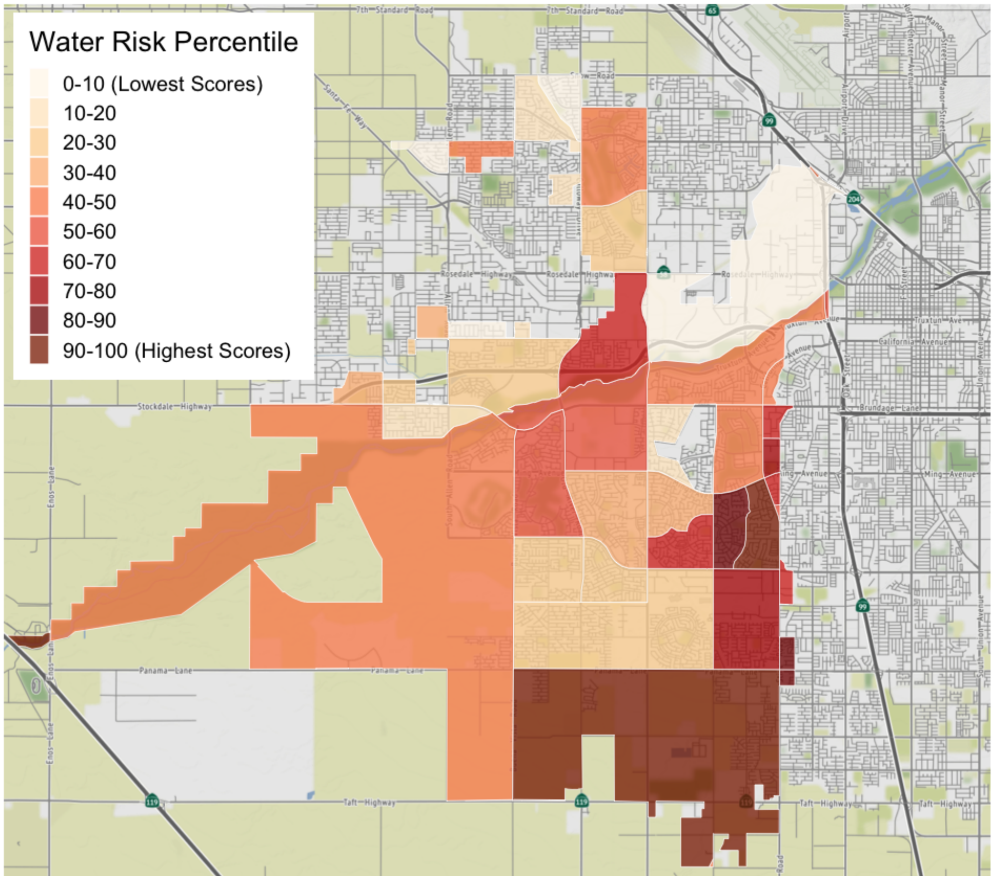

Figure 7-7. *Water risk percentiles including socioeconomic and pollution burden indicators with the outermost boundary outlining the Bakersfield Water Agency. Inner boundaries are representative of census tracts (CalEnviroScreen 4.0, 2021).*

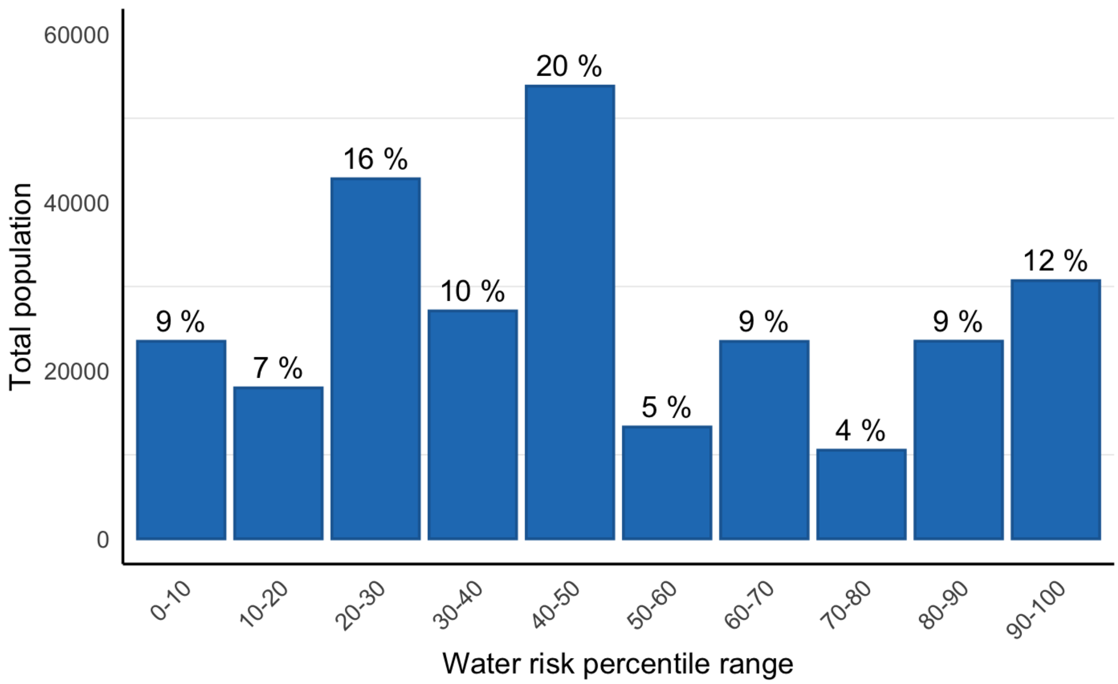

Figure 7-8. *City of Bakersfield population totals in each water risk score percentiles. Percents represent the percent of the total population within the boundaries that is within the given percentile (CalEnviroScreen 4.0, 2021).*

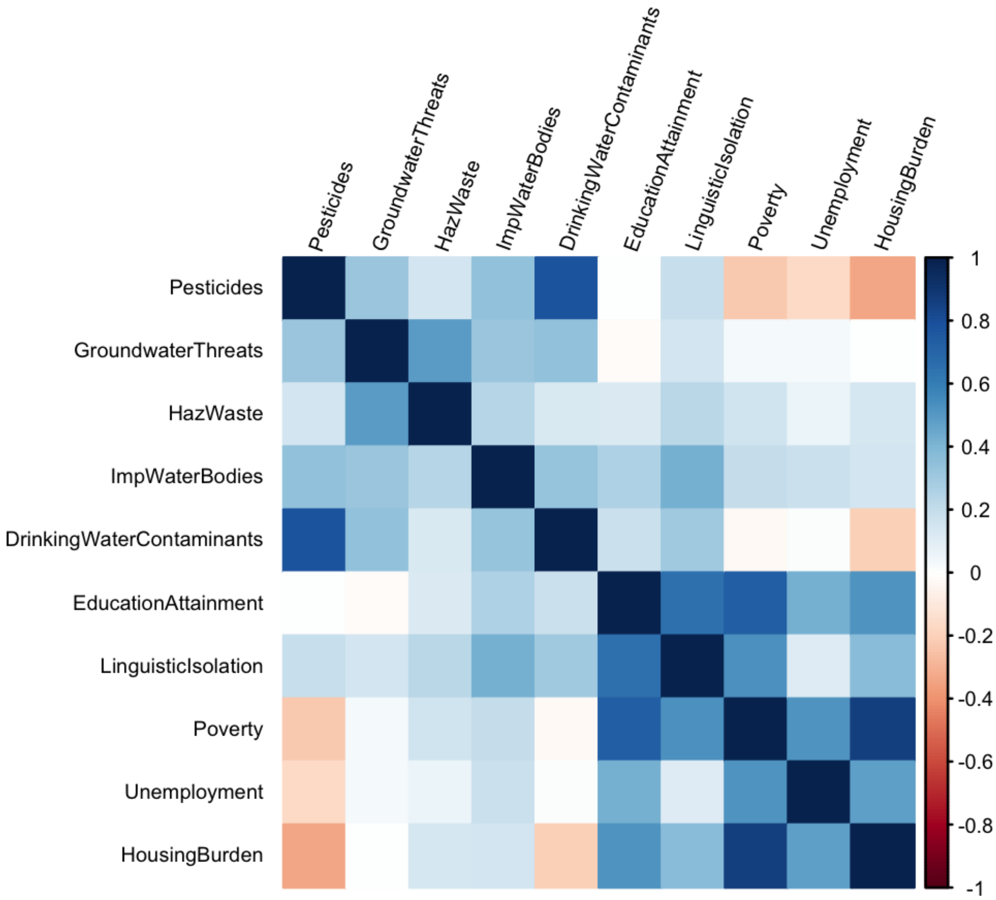

Figure 7-9. *Correlation matrix of both environmental and social indicator scores used to calculate water risk in Bakersfield's Water District. Shades of blue indicate a positive correlation between indicators, while shades of red indicate a negative correlation. Darker colors on either end of the spectrum represent stronger correlations (closer to 1 or -1), while lighter colors represent weaker correlations (closer to 0).*

7.2.3 City of Fresno

Water risk percentiles for the City of Fresno's water district are shown in Figure 7-10. Severely burdened tracts within the top 20th percentiles are widely distributed throughout the district except for the northernmost region. Figure 7-11 shows the total population and percentage of the total population that is served by Oxnard's Water District within each percentile range. These results indicate that roughly one-quarter of the census tracts within the city's jurisdiction fall within the 90th percentile for water risk. The correlation matrix in Figure 7-12 shows strong positive correlations among population variables, while correlations between population and environmental indicators mostly demonstrate a weak positive correlation, with the exception of the impaired water bodies indicator, which exhibits weak negative correlations across population variables.

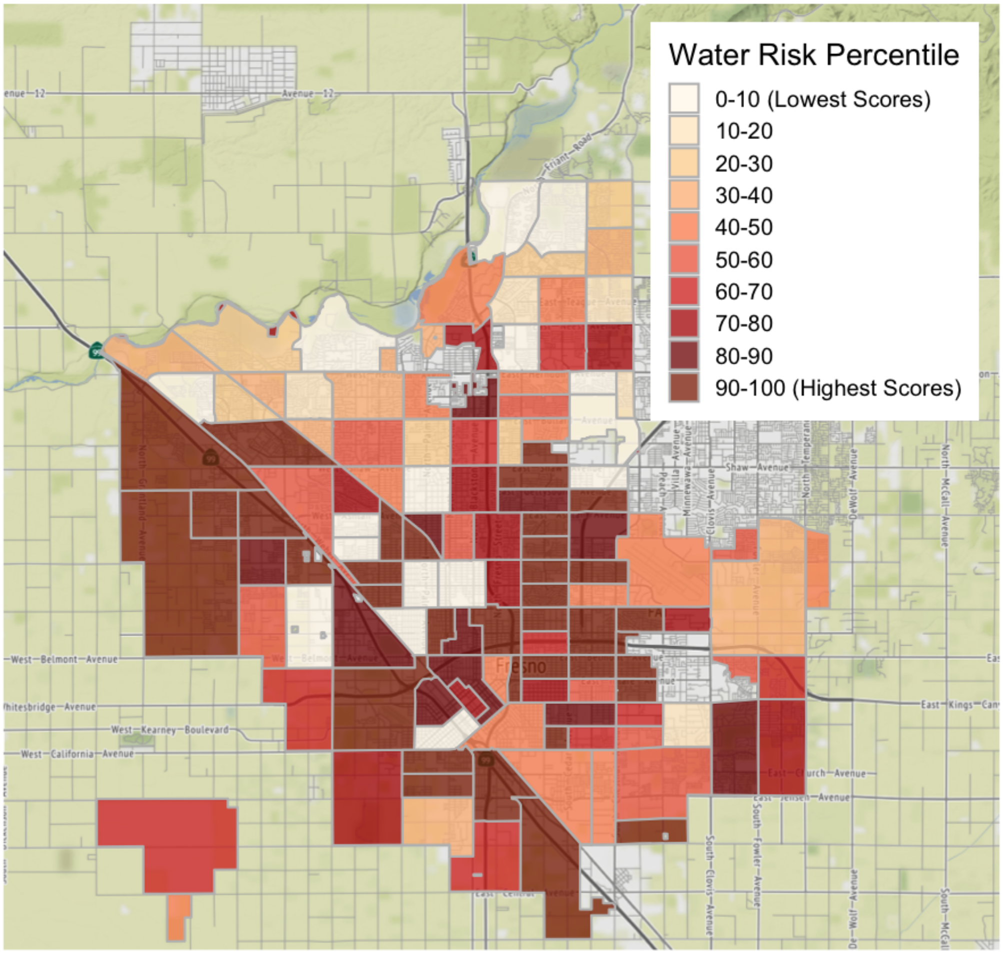

Figure 7-10. *Water risk percentiles including socioeconomic and pollution burden indicators with the outermost boundary outlining the City of Fresno. Inner boundaries are representative of census tracts (CalEnviroScreen 4.0, 2021).*

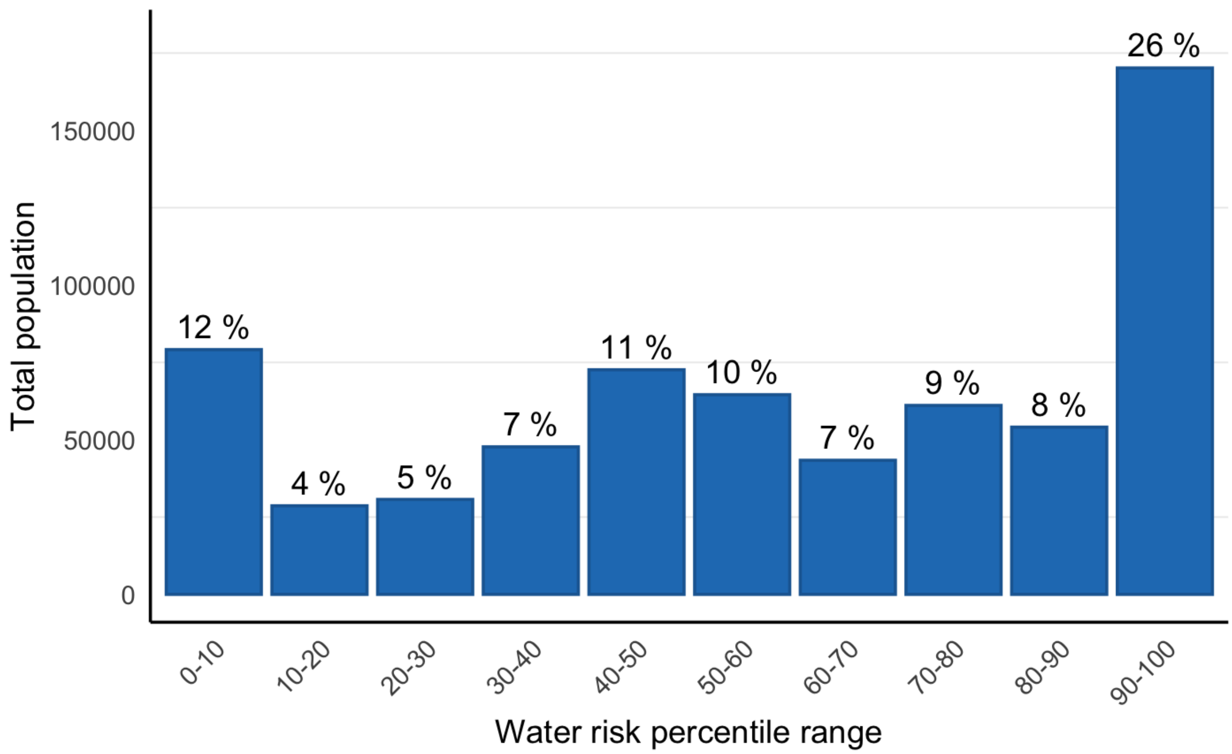

Figure 7-11. *City of Fresno population totals in each water risk score percentiles. Percents represent the percent of the total population within the boundaries that are within the given percentile (CalEnviroScreen 4.0, 2021).*

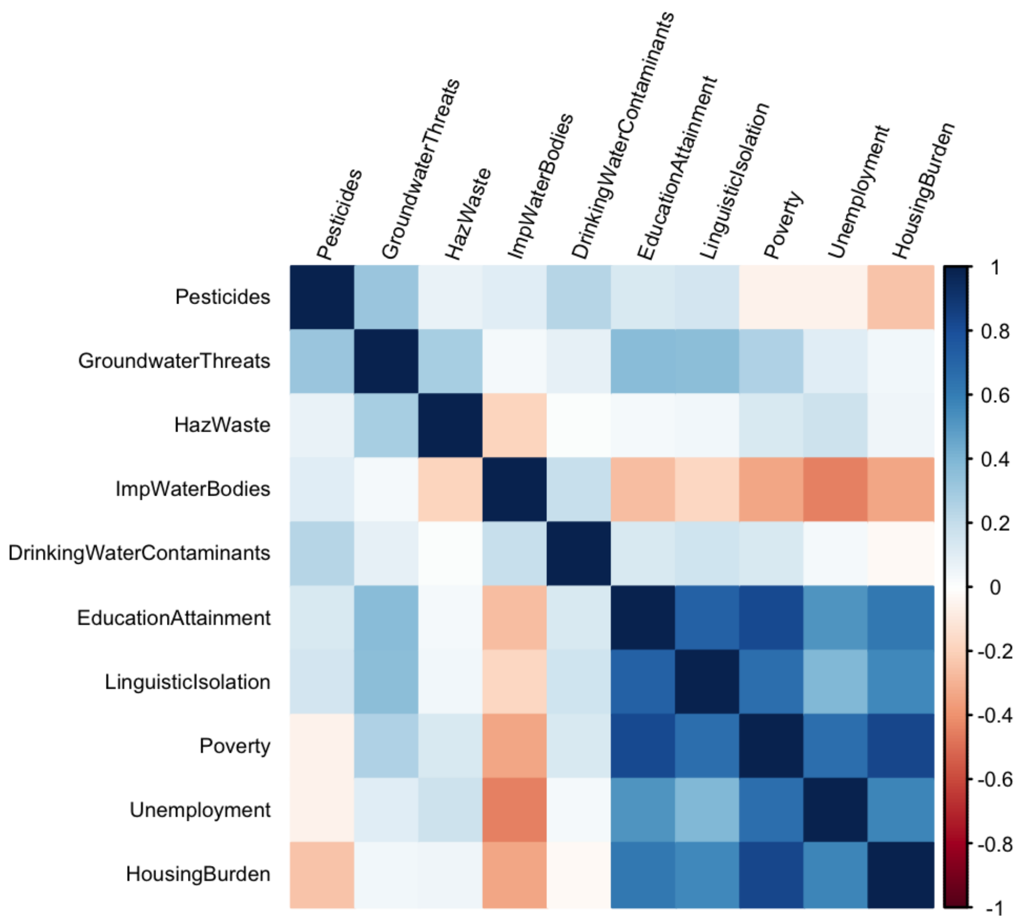

Figure 7-12. *Correlation matrix of both environmental and social indicator scores used to calculate water risk in the City of Fresno. Shades of blue indicate a positive correlation between indicators, while shades of red indicate a negative correlation. Darker colors on either end of the spectrum represent stronger correlations (closer to 1 or -1), while lighter colors represent weaker correlations (closer to 0).*

8 Recommendations

8.1 Model Analysis

The technology that best meets the water security of all three study sites is Indirect Potable Reuse. This technology has lower energy requirements and the lowest costs (both capital and O&M) compared to the other three technologies. IPR plants already exist in the United States, which provides the necessary legal framework and makes new IPR facilities a more feasible option than DPR. Furthermore, IPR is climate resilient and is recommended over groundwater desalination, as it does not require the existence of abundant groundwater resources for potable water production. In fact, IPR can be used to maintain a sustainable groundwater yield, by storing the treated water in the aquifer, if a surface water reservoir is not available. The Indirect Potable Reuse system is modeled after the already existing Groundwater Replenishment System (GWRS) in Orange County, California which has a treatment train that includes microfiltration, followed by reverse osmosis, then by UV oxidation. The biggest energy requirement and OPEX costs come from reverse osmosis and the highest capital costs come from microfiltration.

We reviewed seawater desalination for the City of Oxnard as an alternative to future AWPF expansions during the 2012 study for the GREAT program, but ultimately found it was not cost-effective (City of Oxnard, 2021). Additionally, the city has plans to upgrade its facility to perform IPR with a capacity of 6.25 MGD, which closely matches the calculated 6.3 MGD for the normal scenario in the model. We did not consider seawater desalination for Fresno and Bakersfield, since these inland cities are too far from the ocean to make such projects feasible.

8.2 Water Risk Analysis

8.2.1 City of Oxnard

The City of Oxnard poses unique challenges from a water risk perspective because it is a coastal city, unlike the other two cities in our study. The city has a high density of oil, industry, and agricultural activities, which employ a diverse population but put the city's groundwater and surface water at risk from various types of water pollution. Oxnard's groundwater basins are overdrafted, leaving them vulnerable to seawater intrusion. The City of Oxnard has ~55,000 people that fall in the high water risk percentile. That number makes up 20% of the population served by Oxnard's water district and is considered severely burdened (80-100th percentiles) by a combination of water pollution risk and socioeconomic factors that may make the population more sensitive to pollution.

Due to Oxnard's proximity to the ocean, desalination was considered a potential advanced water treatment technology. However, A desalination plant for Oxnard has already been rejected due to prohibitive costs (City of Oxnard, 2021). Additionally, Oxnard's southern coastline tract is placed within the 70-80th percentile for water risk. Environmental impacts linked with desalination—such as brine release into the ocean—wouldn't contribute to water risk but would be an additional pollution burden to a community already facing high cumulative impacts. Our model corroborates Oxnard's findings that seawater desalination is not the most cost-effective technology for the region, and indicates that indirect potable reuse is the region's most cost-effective and least energy-intensive technology.

IPR is also associated with certain environmental risks. As we discussed in 5.1.1 of this report, IPR produces hypersaline brine, which introduces the risk of pollution depending on the disposal method. Additionally, IPR requires an environmental buffer for a period of time. California State Water Resources Control Board defines environmental buffers in two categories: "groundwater replenishment" (e.g., basins) and “surface water augmentation" (e.g., reservoirs). If a city has high water risk and the water risk is attributed to groundwater contaminants, groundwater may not be an effective environmental buffer to support IPR. In these cases, DPR should be considered as the water reuse technology of choice, as it eliminates the need for an environmental buffer.

8.2.2 City of Bakersfield

The City of Bakersfield resides in the San Joaquin Valley, an area with the highest concentration of disadvantaged communities in California. Disadvantaged community members in this region are predominantly Latino and about half of Bakersfield’s population identifies themselves as Latino in the 2020 U.S. Census (Flores-Landeros et al., 2022). Due to the high concentration of socioeconomically disadvantaged communities, costs may be a key consideration in adopting an advanced water technology such as IPR. While IPR is the most cost effective option compared to the other technologies, the adoption of any advanced water treatment technology will result in an increase in water utility bills for customers (Radcliffe & Page, 2020).

Furthermore, the San Joaquin Valley has been subject to intensive agriculture since the early 1900s, requiring an immense volume of water and introducing new sources of pollution to the region. According to our water risk analysis, about 20% of the population served by the Bakersfield Water Agency faces severe water quality risks. The Bakersfield correlation matrix showed a unique correlation that the two other case study sites did not. In Figure 7-7**,** there is a strong positive correlation between pesticide use and drinking water contaminants. The drinking water contaminants do incorporate chemicals typically released from pesticides and agriculture such as 1,2,3,-Trichloropropane (1,2,3 - TCP) and nitrates (NO3) (SWRCB, 2022 & CalEnviroScreen 4.0, 2021). Bakersfield is within the 70-80th percentile for drinking water contaminants. Whether this can be attributed to agriculture would require additional analysis of individual chemical contributions to the drinking water contaminant indicator.

8.2.3 City of Fresno

As of the 2020 U.S. Census, about 70% of Fresno's population identify as Hispanic (50%), Asian (14%), or Black (6%). Our water risk analysis indicates that 32% of the population in the City of Fresno faces severe water quality risks that may increase sensitivity to pollution. Additionally, 28% of the population, or about 170,000 people fall within the highest (90-100th) percentile ranges for water risk. Out of our three case study sites, Fresno has the highest percentage of its population within the highest percentile for water risk.

Indirect potable use presents the same risks described for the previous case study sites. However, Fresno's high proportion of population in the highest for water risk percentile suggests a greater urgency in the adoption of advanced water treatment technologies such as IPR. Furthermore, CalEnviroScreen places Fresno in the 80-90th percentile for drinking water contaminants further supporting the need for IPR. There is also a wide geographic distribution of communities that have high water risk as seen in figure xx and should be considered when determining brine disposal locations to avoid additional pollution burdens on vulnerable communities.

9 Discussion

9.1 Other Considerations for Site Recommendations

The project's main objective was to analyze the associated costs and energy requirements for advanced water treatment methods. For the three sites, our modeling results indicated that IPR is the better option, for the technologies assessed, for several reasons. First, IPR was more cost-effective and less energy-intensive than ocean desalination and DPR. Although groundwater desalination was the most cost-effective and least energy-intensive treatment process, it assumes there will be a sufficient amount of groundwater to pump in the future. Since the aquifers in these three regions are already quite impacted, the assumption that they would be the primary source is not supportable. Groundwater desalination could be used in areas in Southern California that still have sufficient groundwater supplies that follow the guidelines outlined by SGMA. However, Mediterranean climate regimes are particularly susceptible to rapid shifts between drought and flood, and reliance on groundwater alone could threaten the resilience and reliability of local water supplies, as they are depleted during drought events but may only recharge partially during short periods of heavy rainfall. California's rapid transition from a record multi-year drought between 2012 and 2016 to extreme rainfall during the winter of 2016–2017 provides a dramatic and recent example

(Swain et al., 2018). Given the variability in precipitation between wet and dry years, groundwater may not be a reliable source because recharge rates may vary significantly. Since IPR relies on recycling wastewater, it's less impacted by inconsistent precipitation patterns. Another factor that led to our recommendation of IPR was there is already an existing regulatory framework in California, unlike DPR, which is still in development.

9.2 Model Limitations

The model's primary limitation is the need for more cost and energy data to further evaluate and validate the cost equations used for the unit processes. Ideally, we would have liked more data about specific processes to compare the results with other advanced water treatment facilities, allowing us to more accurately project costs and reduce the model's margin of error. This is especially true for more novel processes, such as nanofiltration, that have yet to be widely implemented and studied. For the economic calculations, we only employed equations that model capital cost or O&M cost as a function of flow rate. These models do not capture the importance of other variables for modeling the costs associated with unit processes, such as operating pressure, inlet water quality, materials, electricity costs, and chemical costs. Limited data is available to model energy requirements as a function of the flow rate for each unit process. Currently, the model produces the same energy requirement (in terms of kWh/m^3) and uncertainty regardless of the input flow rate, as no empirical models are available for each unit process. Similar to the economics of the treatment plant, energy requirements are highly variable even within the unit process, and a variety of external factors are necessary to incorporate to generate a comprehensive energy requirement calculation. The membrane processes (micro, ultra, nanofiltration, reverse osmosis, brackish water desalination, and ocean desalination) have the most potential cost and energy requirements variation as they have the most external factors affecting their performance (Plumlee et al., 2014).

Furthermore, extraneous processes such as pumping, storage, recharge, ocean outfalls, or basin spreading are not included in the model, and present potentially high costs or energy requirements depending on the location and operation of the advanced water technology. Though the unit process cost studies we obtained from our literature review generally considered a +50%/-30% uncertainty for the economic models–values which are also used in our AWTM—there are limited operational DPR and IPR facilities where we can compare cost and energy requirements. The Orange County Groundwater Recharge System is the basis for all the IPR unit process assumptions and matches the model outputs. There are no operational DPR facilities, so our IPR process assumptions used a more rigorous membrane filtration standard (ultrafiltration rather than microfiltration) to ensure higher water quality. Seawater reverse osmosis and brackish water reverse osmosis also have high variations in their costs and energy requirements due to differing levels of pretreatment at different sites depending on the influent water quality.

For seawater desalination technology, CAPEX and OPEX are difficult to capture in the economic models we utilized and would require a more rigorous model to more accurately reflect all the costs associated with building and operating the facilities. The CAPEX models only consider the construction of the unit process itself and not the purchase and development of the entire site, which can be substantial additional costs since these facilities have to have coastal access. Some sites have much more significant capital expenditures than the model predicts due to unforeseen construction costs, site remediation, or non-process costs. For example, ocean desalination facilities have high CAPEX costs for the intake and outfall pipes and pumping needed. OPEX models also do not account for differences in electricity costs, labor costs, and other operations and maintenance expenditures that vary depending on the region.

9.2.1 Energy Implications

The advanced treatment processes examined in this project are energy intensive, and the primary energy used to power these treatment facilities will be critical. Investment into a clean energy grid will be imperative to power the energy-intensive processes explored in this project to reduce greenhouse gas emissions from building and operating these facilities. Desalination is an energy-intensive technology, and high carbon emissions ensue when powered by fossil fuels (Heihsel et al., 2019). The increased emissions are from building as well as operating these facilities. A study examining Australia's greenhouse gas emissions for seawater desalination facilities found that the contribution of the upstream value chain to total greenhouse gas emissions increases for CAPEX and decreases for OPEX (Heihsel et al., 2019). Although the Australian power grid differs from California's, there are still significant energy implications for the power generation of advanced water treatment facilities. About 12% of California's total energy use is related to water, which is used for the following water activities: pumping water from underground aquifers, moving water from one location to another (water conveyance), treating water to make it drinkable, and heating and cooling water (California DWR, 2020). The state of California is committed to achieving 100% renewable energy by 2045. However, much work and investment are needed to make this goal a reality. Implementing renewable energy into power grids where water treatment plants are built and operated is critical to reduce greenhouse gas emissions.

9.3 Benefits Not Captured by the Model

9.3.1 Climate Change Resilience

There are several benefits beyond the scope of this project. Water reuse and desalination are not sensitive to potential climate change impacts. By the end of this century, the Sierra Nevada's snowpack is projected to experience a 48-65% loss from its historical April 1 average (California DWR, 2020). This significant decrease in snowpack directly impacts the state's water supply. Water reuse can provide alternatives to existing water supplies and enhance water security, sustainability, and resilience (U.S. EPA, n.d). These technologies address some mounting water supply challenges climate change poses by building adaptive capacity. This aspect of such projects is difficult to quantify, but could have significant value during severe droughts or other water supply risks. The water reuse technologies we evaluated in our model can also limit saltwater intrusion in groundwater aquifers, which significantly impacts agriculture and leads to potential revenue losses, jeopardizing the industry, and the local communities, in affected areas.

9.3.2 Environmental and Social Justice Benefits

There are also added social and health benefits that these technologies could bring to communities that are not captured in either model. With any water treatment process comes some level of risk, including conventional drinking water treatment and traditional drinking water sources (Rodriguez et al., 2009). However, using the best available technologies, risk assessment, and risk management practices, water agencies, health regulators, and other stakeholders can evaluate and mitigate the potential public health risks from the biological or chemical contaminants likely to be found in recycled water (Rodriguez et al., 2009). These technologies can improve water treatment while increasing capacity for the water district, improving overall water quality, especially in disadvantaged communities. The advanced treatment of this water and the health monitoring required for water recycling facilities can benefit communities that are drinking this water. This can be especially beneficial in areas exposed to groundwater and surface water contaminants or regions primarily relying on private wells, some of which are not regulated under the Safe Drinking Water Act.

9.3.3 Future Model Improvements

Given the scope and time available for the project, several improvements could be made to the model. Incorporating the water risk analysis into the model so that the user could identify water risk in their area while determining the costs for these systems. This would aim to ensure that the social and environmental justice aspects of water security don't get overlooked. While considering social and ecological impacts, another improvement for the model would be to incorporate indirect costs from these projects like brine disposal. Brine can be challenging to treat or discharge because the composition of the brine can vary from highly concentrated to low concentrations of salts. Depending on the makeup, brine waste is recyclable, but it is usually discharged or disposed of. Some standard brine disposal methods include evaporation pools and injecting into spent oil reservoirs. Including costs of disposal based on potential flow rates for ocean and groundwater desalination could benefit water districts that explore desalination technologies as a water supply solution.

To improve the energy calculations, empirical models for modeling the SEC as a function of flow rate for each unit process. For the economics section, particularly for membrane processes, additional parameters for inlet water quality, membrane configuration, and electricity costs would be incorporated to produce more accurate results for both the CAPEX and OPEX values. Overall, our AWTM model compares IPR, DPR, ocean desalination, and groundwater desalination to inform users about the best technology choice for water security. We designed the application so it can be used regardless of the site of interest. In the future, specific models with a higher parameterization should be utilized for more accurate energy and cost requirements that depend on the location and conditions of the water being treated.

10 References

Asadollahi, Mahdieh, Dariush Bastani, and Seyyed Abbas Musavi. 2017. "Enhancement of Surface Properties and Performance of Reverse Osmosis Membranes after Surface Modification: A Review." *Desalination* 420 (April): 330–83. http://dx.doi.org/10.1016/j.desal.2017.05.027.

August, Laura et al. 2021. *CalEnviroScreen 4.0*.

Backer, Howard. 2019. *Water Disinfection for International Travelers*. 4th ed. Travel Medicine.

Bermúdez, Laura Antiñolo, Jaime Martín Pascual, María Del Mar Muñio Martínez, and Jose Manuel Poyatos Capilla. 2021. "Effectiveness of Advanced Oxidation Processes in Wastewater Treatment: State of the Art." *Water (Switzerland)* 13(15): 1–19.

Bhojwani, Sumay et al. 2019. "Technology Review and Data Analysis for Cost Assessment of Water Treatment Systems." *Science of the Total Environment* 651: 2749–61. https://doi.org/10.1016/j.scitotenv.2018.09.363.

Bullard, R. D., and G. S. Johnson. 2002. "Environmental Justice: Grassroots Activism and Its Impact on Public Policy Decision Making." *Journal of Social Issues* 56(3): 555–78.

California Coastal Commission. (2023). PUBLIC RESOURCES CODE DIVISION 20 CALIFORNIA COASTAL ACT. *California Coastal Commission.* https://www.coastal.ca.gov/coastact.pdf

California Department of Technology. (2022). i03 Water Districts. *California State Geoportal.* https://gis.data.ca.gov/datasets/45d26a15b96346f1816d8fe187f8570d_0/about

California Department of Water Resources. (2018). Guidance for Climate Change Data Use during Groundwater Sustainability Plan. *California Department of Water Resources.*

California Department of Water Resources. (2020). Overview of Submittal and Evaluation of Groundwater Sustainability Plans in Critically Overdrafted Basins. *California Water Boards Sustainable Groundwater Management Office.*

California Department of Water Resources. (2023a). i08 GroundwaterDepthSeasonalPoints. *California Open Data Portal.* https://data.ca.gov/dataset/i08-groundwaterdepthseasonal-points

California Department of Water Resources. (2023b). SGMA Data Viewer. *SGMA Portal.* https://sgma.water.ca.gov/webgis/?appid=SGMADataViewer#currentconditions

California Department of Water Resources. (2023c). What we do. *California Department of Water Resources.* https://water.ca.gov/What-We-Do

California Natural Resources Agency. (2022, August). *Retrieved January 12, 2023, from https://resources.ca.gov/-/media/CNRA-Website/Files/Initiatives/Water-Resilience/CA-Water-Supply-Strategy.pdf*

California Regional Water Quality Control Board. (2013). NOTICE OF PUBLIC HEARING PROPOSED REISSUANCE OF WASTE DISCHARGE REQUIREMENTS (National Pollutant Discharge Elimination System Permit). *California Regional Water Quality Control Board.* https://www.waterboards.ca.gov/losangeles/board_decisions/tentative_orders/individual/npdes/Oxnard%20WWTP/Oxnard%20WTP%20Renewal%20Notice%20for%20Posting-rev2%20accepted.pdf

California State Water Resources Control Board. (2022). Information for Public Drinking Water Systems. SWRCB.gov. https://www.waterboards.ca.gov/drinking_water/certlic/drinkingwater/publicwatersystems.html

California State Water Resources Control Board. (n.d.). Water conservation. SWRCB.gov. Retrieved February 18, 2023, from https://www.waterboards.ca.gov/water_issues/programs/conservation_portal/

California Water Boards. (2018). *Water Boards Structure.*

https://www.waterboards.ca.gov/about_us/water_boards_structure/

Centre, UNEP - International Environmental Technology, and United Nations Environment Programme. 1997. *Source Book of Alternative Technologies for Freshwater Augmentation in Latin America and the Caribbean*.

Chappelle, C., & Hanak, E. (2015). California's Water Quality Challenges. *Public Policy Institute of California*, *October*. http://www.ppic.org/publication/californias-water-quality-challenges/

Chan, A. (2014, December 12). *The future of direct potable reuse in California: Overcoming public.* Retrieved January 3, 2023, from https://repository.usfca.edu/cgi/viewcontent.cgi?article=1101&context=capstone

Centers for Disease Control and Prevention. (2020, January 16). *Health implications of drought*. Centers for Disease Control and Prevention. Retrieved January 20, 2023, from https://www.cdc.gov/nceh/drought/implications.htm

City of Bakersfield. (2021). 2020 Urban Water Management Plan. *City of Bakersfield.* https://wuedata.water.ca.gov/getfile?filename=/public%2Fuwmp_attachments%2F1242078483%2F2020%20COB%20UWMP%20Final%20-%20December%202021.pdf

City of Bakersfield. (2023). Planning & Land Use Map. *GIS Mapping Portal.* https://cob.maps.arcgis.com/apps/webappviewer/index.html?id=9fbb25e825e3425a84e7dea631e42f7b

City of Fresno. (2021). 2020 Urban Water Management Plan. *Fresno Department of Public Utilities.* https://cityoffresno.wpenginepowered.com/publicutilities/wp-content/uploads/sites/16/2021/07/Fresno-2020-UWMP_Final_2021-07-21.pdf

City of Fresno. (2022). City Limits. *City of Fresno GIS Data Hub.* *https://gis-cityoffresno.hub.arcgis.com/search?tags=boundaries*

City of Oxnard. (2017). Advanced Water Purification Facility Indirect Potable Reuse Engineering Report. *City of Oxnard.* https://www.oxnard.org/wp-content/uploads/2018/08/Vol1_Oxnard-Title22EngineeringReport_Final.pdf

City of Oxnard. (2020). Oxnard Local Limits Evaluation Reports. *City of Oxnard.* https://www.oxnard.org/wp-content/uploads/2021/04/Oxnard-Local-Limits-Evaluation-Report.pdf

City of Oxnard. (2021). 2020 Urban Water Management Plan. *City of Oxnard Water Division.* https://www.oxnard.org/wp-content/uploads/2021/11/Oxnard-2020-Urban-Water-Management-Plan_20211110_w-Appendices.pdf

City of Oxnard. (2022). 2030 General Plan Goals & Policies. *City of Oxnard Planning Division.* https://www.oxnard.org/wp-content/uploads/2017/06/Oxnard-2030-General-Plan-Amend-12.2022-SMc.pdf

City of Oxnard. (2023). City Council District Map. *City of Oxnard Spatial Data Portal.* https://oxnard.maps.arcgis.com/apps/webappviewer/index.html?id=829b8def3cb74113bda0659bc87df746

Costa, Ana Rita, and Maria Norberta de Pinho. 2006. “Performance and Cost Estimation of Nanofiltration for Surface Water Treatment in Drinking Water Production.” *Desalination* 196(1–3): 55–65.

Crockett, A B. 1997. “Water and Wastewater Quality Monitoring.” : 39–57.

Del-Pilar-Ruso, Y., la Ossa Carretero, J. A. D., Casalduero, F. G., & Lizaso, J. L. S. (2007). Spatial and temporal changes in infaunal communities inhabiting soft-bottoms affected by brine discharge. *Marine Environmental Research*, *64*(4), 492–503. https://doi.org/10.1016/j.marenvres.2007.04.003

Diffenbaugh, N. S., Swain, D. L., & Touma, D. (2015). Anthropogenic warming has increased drought risk in California. *Proceedings of the National Academy of Sciences*, *112*(13), 3931–3936. https://doi.org/10.1073/pnas.1422385112

Environmental Protection Agency. (n.d.). Salt. *EPA.* Retrieved January 15, 2023, from https://www.epa.gov/risk/salt

Environmental Protection Agency. (2004). Understanding the Safe Drinking Water Act Roles and Responsibilities. *EPA.* https://www.epa.gov/sites/production/files/2015-04/documents/epa816f04030.pdf

Environmental Protection Agency. (2022). Summary of the Clean Water Act. *EPA.* Retrieved March 2, 2023, from https://www.epa.gov/laws-regulations/summary-clean-water-act

Environmental Protection Agency. (2023). About the Drinking Water State Revolving Fund (DWSRF) Set-Asides. *EPA*. Retrieved March 1, 2023, from https://www.epa.gov/dwcapacity/about-drinking-water-state-revolving-fund-dwsrf-set-asides

Environmental Protection Agency. (n.d.). EPA Water Reuse. Retrieved March 15, 2023, from https://www.epa.gov/waterreuse/basic-information-about-water-reuse#:~:text=Water%20reuse%20can%20provide%20alternatives,composed%20of%20previously%2Dused%20water.

Fanourakis, Sofia K., Janire Peña-Bahamonde, Pasan C. Bandara, and Debora F. Rodrigues. 2020. “Nano-Based Adsorbent and Photocatalyst Use for Pharmaceutical Contaminant Removal during Indirect Potable Water Reuse.” *npj Clean Water* 3(1): 1.

“FAQS: Claude Bud Lewis Desalination Plant.” 2020. https://www.carlsbaddesal.com/faqs.htm

Fountain, H. (2022, July 21). *A painful deadline nears as Colorado River Reservoirs Run Critically Low*. The New York Times. Retrieved March 20, 2023, from https://www.nytimes.com/2022/07/21/climate/colorado-river-water-cuts.html

Fournier, E. D., Keller, A. A., Geyer, R., & Frew, J. (2016). Investigating the Energy-Water Usage Efficiency of the Reuse of Treated Municipal Wastewater for Artificial Groundwater Recharge. *Environmental Science and Technology*, *50*(4), 2044–2053. https://doi.org/10.1021/acs.est.5b04465

Fox Canyon Groundwater Management Agency. (2019). Groundwater Sustainability Plan for the Oxnard Subbasin. *Fox Canyon Groundwater Management Agency.* http://pwaportal.ventura.org/WPD/FoxCanyon/GroundwaterReports/Oxnard/signed_final_oxnard%20subbasin%20gsp.pdf

Gacia, Esperança et al. 2007. “Impact of the Brine from a Desalination Plant on a Shallow Seagrass (Posidonia Oceanica) Meadow.” *Estuarine, Coastal and Shelf Science* 72(4): 579–90.

Gumerman, Robert C., Russell L. Culp, and Robert M. Clark. 1979. “The Cost Of Granular Activated Carbon Adsorption Treatment in the US.” *Journal - American Water Works Association* 71(11): 690–96.

Guo, T., Englehardt, J., & Wu, T. (2014). Review of cost versus scale: Water and wastewater treatment and reuse processes. *Water Science and Technology*, *69*(2), 223–234. https://doi.org/10.2166/wst.2013.734

Gibler, J. 2005. Water for People and Place: Moving Beyond Markets in California Water Policy . Oakland: Public Citizen.

Hanak, E. (2010). Show Me the Water Plan: Urban Water Management Plans and California’s Water Supply Adequacy Laws. *Golden Gate University Environmental Law Journal*, *4*(1), 69–89.

Hancock, N. (2018, August 15). *Ultrafiltration, nanofiltration and reverse osmosis*. Safe Drinking Water Foundation. Retrieved March 20, 2023, from https://www.safewater.org/fact-sheets-1/2017/1/23/ultrafiltrationnanoandro

Hansen, J. A., Jurgens, B. C., & Fram, M. S. (2018). Quantifying anthropogenic contributions to century-scale groundwater salinity changes, San Joaquin Valley, California, USA. *Science of the total environment*, *642*, 125-136.

Heihsel, Michael, Manfred Lenzen, and Frank Behrendt. 2020. "Desalination and Sustainability: A Triple Bottom Line Study of Australia." *Environmental Research Letters* 15(11).

Katsoyiannis, Ioannis A., Silvio Canonica, and Urs von Gunten. 2011. "Efficiency and Energy Requirements for the Transformation of Organic Micropollutants by Ozone, O3/H2O2 and UV/H2O2." *Water Research* 45(13): 3811–22. http://dx.doi.org/10.1016/j.watres.2011.04.038

Keller, A. A., Su, Y., & Jassby, D. (2022). Direct Potable Reuse: Are We Ready? A Review of Technological, Economic, and Environmental Considerations. *ACS ES&T Engineering*, *2*(3), 273–291. https://doi.org/10.1021/acsestengg.1c00258

Kelley, R L, and R L Nye. 1984. "Historical Perspective on Salinity and Drainage Problems in California." *California Agriculture* 38: 4–6.

Kern River Groundwater Sustainability Agency. (2022). Groundwater Sustainability Plan. *KRGSA.* http://www.kernrivergsa.org/?page_id=966

Law, Ian B. 2007. "Indirect Potable Reuse - Learnings from the Singapore NEWater Scheme." *Meat and Livestock Australia Limited*: 1–61.

McGivney, William, and Susumu Kawamura. 2008. Cost Estimating Manual for Water Treatment Facilities *Cost Estimating Manual for Water Treatment Facilities*.

Medellín-Azuara, Josué et al. 2022. "Economic Impacts of the 2021 Drought on California Agriculture." *University of California, Merced*.

Mickley, Michael. 2018. "Desalination and Water Purification Research and Development Program Report No. 207." *Reclaimation managing water in the west* (207): 56. https://www.usbr.gov/research/dwpr/reportpdfs/report207.pdf.

Minnesota Rural Water Association. 2001. "Chapter19: Membrane Filtration." *Minnesota Water Works Operations Manual*: 1–12. http://www.mrwa.com/WaterWorksMnl/Chapter 19 Membrane Filtration.pdf.

Mosley, Luke M. 2015. "Drought Impacts on the Water Quality of Freshwater Systems; Review and Integration." *Earth-Science Reviews* 140: 203–14. http://dx.doi.org/10.1016/j.earscirev.2014.11.010.

Mount, Jeffrey, Emma Freeman, and Jay Lund. 2014. "Water Use in California: The Facts." (July).

Nickles, C. (2013). *Layperson's Guide To California Wastewater*. www.watereducation.org

Olmstead, Alan L., and Paul W. Rhode. 2018. "Agriculture in American Economic History." *The Oxford Handbook of American Economic History* 1: 159–82.

Omerspahic, Mustafa, Hareb Al-Jabri, Simil Amir Siddiqui, and Imen Saadaoui. 2022. "Characteristics of Desalination Brine and Its Impacts on Marine Chemistry and Health, With Emphasis on the Persian/Arabian Gulf: A Review." *Frontiers in Marine Science* 9(April): 1–12.

Orange County Sanitation District. 2007. "Groundwater Replenishment System." (Proposition 13).

Orange County Sanitation District. (2020). *Ocean Outfall Inspection*. https://www.ocsan.gov/Home/Components/News/News/4344/

Orange County Sanitation District. (2022). *GWRS - new water you can count on*. https://www.ocwd.com/gwrs/

Oregon State University. (n.d.). *Prism Climate Group, Oregon State U*. PRISM Climate Group, Northwest Alliance for Computational Science and Engineering. Retrieved January 20, 2023, from https://www.prism.oregonstate.edu/

Pace, C., Balazs, C., Bangia, K., Depsky, N., Renteria, A., Morello-Frosch, R., & Cushing, L. J. (2022). Inequities in Drinking Water Quality Among Domestic Well Communities and Community Water Systems, California, 2011-2019. *American Journal of Public Health*, *112*(1), 88–97. https://doi.org/10.2105/AJPH.2021.306561

Panagopoulos, A., & Haralambous, K. J. (2020a). Environmental impacts of desalination and brine treatment - Challenges and mitigation measures. *In Marine Pollution Bulletin* (Vol. 161). Elsevier Ltd. https://doi.org/10.1016/j.marpolbul.2020.111773

Panagopoulos, A., & Haralambous, K. J. (2020b). Environmental impacts of desalination and brine treatment - Challenges and mitigation measures. *Marine Pollution Bulletin*, *161*, 111773. https://doi.org/10.1016/J.MARPOLBUL.2020.111773

Park, K., Kim, J., Yang, D. R., & Hong, S. (2020). Towards a low-energy seawater reverse osmosis desalination plant: A review and theoretical analysis for future directions. In *Journal of Membrane Science* (Vol. 595). Elsevier B.V. https://doi.org/10.1016/j.memsci.2019.117607

Pauloo, R. A., Fogg, G. E., Guo, Z., & Harter, T. (2021). Anthropogenic basin closure and groundwater salinization (ABCSAL). *Journal of Hydrology*, *593*, 125787.

Pearson, Jeffrey L., Peter R. Michael, Noreddine Ghaffour, and Thomas M. Missimer. 2021. “Economics and Energy Consumption of Brackish Water Reverse Osmosis Desalination: Innovations and Impacts of Feedwater Quality.” *Membranes* 11(8).

Pistocchi, A. et al. 2020. “Can Seawater Desalination Be a Win-Win Fix to Our Water Cycle?” *Water Research* 182.

Plappally, A. K., & Lienhard V, J. H. (2012). Energy requirements for water production, treatment, end use, reclamation, and disposal. *Renewable and Sustainable Energy Reviews*, *16*(7), 4818–4848. https://doi.org/10.1016/j.rser.2012.05.022

Plumlee, Megan H. et al. 2014. “Costs of Advanced Treatment in Water Reclamation.” *Ozone: Science and Engineering* 36(5): 485–95.

“Producing and Consuming Power.” 2022. *California Department of Water Resources*. https://water.ca.gov/What-We-Do/Power (March 20, 2023).

PUB - Singapore’s National Water Agency. (2022). *NEWater*. https://www.pub.gov.sg/watersupply/fournationaltaps/newater

Quon, H., Sperling, J., Coughline, K., Greene, D., Miara, A., Akar, S., Talmadge, M., Stokes-Draut, J. R., Macknick, J., & Jiang, S. (2022). Pipe Parity Analysis of Seawater Desalination in the United States: Exploring Costs, Energy, and Reliability via Case Studies and Scenarios of Emerging Technology. ACS ES and T Engineering, 2(3), 434–445. https://doi.org/10.1021/acsestengg.1c00270

Roberts, D. A., Johnston, E. L., & Knott, N. A. (2010). Impacts of desalination plant discharges on the marine environment: A critical review of published studies. *Water Research*, *44*(18), 5117–5128. https://doi.org/10.1016/j.watres.2010.04.036

Scottsdale Water. 2022. “Recycled Water.” https://www.scottsdaleaz.gov/water/recycled-water.

Scruggs, C. E., & Thomson, B. M. (2017). Opportunities and Challenges for Direct Potable Water Reuse in Arid Inland Communities. *Journal of Water Resources Planning and Management*, *143*(10), 04017064. https://doi.org/10.1061/(ASCE)WR.1943-5452.0000822

Snyder, S. A.; von Gunten, U.; Amy, G.; Debroux, J. F. Use of Ozone in Water Reclamation for Contaminant Oxidation; Report No. WRF-08-05; Alexandria, VA, 2014

Soliman, M. N., Guen, F. Z., Ahmed, S. A., Saleem, H., Khalil, M. J., & Zaidi, S. J. (2021). Energy consumption and environmental impact assessment of desalination plants and brine disposal strategies. *Process Safety and Environmental Protection*, *147*, 589–608. https://doi.org/10.1016/J.PSEP.2020.12.038

State Water Project. (2022). California Department of Water Resources.

SUEZ. *Fundamental Biological Engineering Processes Applicable to Water Treatment*. https://www.suezwaterhandbook.com/water-and-generalities/fundamental-biological-engineering-processes-applicable-to-water-treatment.

Swain, Daniel L., Baird Langenbrunner, J. David Neelin, and Alex Hall. 2018. "Increasing Precipitation Volatility in Twenty-First-Century California." *Nature Climate Change* 8(5): 427–33. http://dx.doi.org/10.1038/s41558-018-0140-y.

Szczuka, Aleksandra et al. 2021. "Removal of Pathogens and Chemicals of Emerging Concern by Pilot-Scale FO-RO Hybrid Units Treating RO Concentrate, Graywater, and Sewage for Centralized and Decentralized Potable Reuse." *ACS ES&T Water* 1(1): 89–100.

Tariqi, Arianna Q., and Colleen C. Naughton. 2021. "Water, Health, and Environmental Justice in California: Geospatial Analysis of Nitrate Contamination and Thyroid Cancer." *Environmental Engineering Science* 38(5): 377–88.

The Metropolitan Water District of Southern California. (2021). *2020 Urban Water Management Plan: City of Oxnard*. *June*, 143pp.

The Water Research Foundation. (n.d.). Potable Reuse.

Tow, E. W., Hartman, A. L., Jaworowski, A., Zucker, I., Kum, S., AzadiAghdam, M., Blatchley, E. R., Achilli, A., Gu, H., Urper, G. M., & Warsinger, D. M. (2021). Modeling the energy consumption of potable water reuse schemes. *Water Research X*, *13*, 100126. https://doi.org/10.1016/j.wroa.2021.100126

Tow, Emily W., Ronan K. McGovern, and John H. Lienhard V. 2015. "Raising Forward Osmosis Brine Concentration Efficiency through Flow Rate Optimization." *Desalination* 366: 71–79. http://dx.doi.org/10.1016/j.desal.2014.10.034.

Ullrich, P. A. et al. 2018. "California's Drought of the Future: A Midcentury Recreation of the Exceptional Conditions of 2012–2017." *Earth's Future* 6(11): 1568–87.

United States Census Bureau. (2022). QuickFacts, Fresno City California. *United States Census Bureau.* https://www.census.gov/quickfacts/fact/table/fresnocitycalifornia/POP010220

U.S. Energy Information Administration. (2022). Form EIA-861M (formerly EIA-826), Monthly Electric Power Industry Report. *United States Energy Information Administration.*

https://www.eia.gov/electricity/monthly/epm_table_grapher.php?t=epmt_5_6_a

United States Geological Survey. (2008). Elevation in the Western United States (90 meter DEM). *ScienceBase.* https://www.sciencebase.gov/catalog/item/542aebf9e4b057766eed286a

United States Geological Survey. (2021). National Land Cover Database (NLCD) 2019 Products (ver. 2.0, June 2021). *ScienceBase.* https://www.sciencebase.gov/catalog/item/5f21cef582cef313ed940043

Vandenberg, L. N., Colborn, T., Hayes, T. B., Heindel, J. J., Jacobs, D. R., Lee, D. H., Shioda, T., Soto, A. M., vom Saal, F. S., Welshons, W. V., Zoeller, R. T., & Myers, J. P. (2012). Hormones and endocrine-disrupting chemicals: Low-dose effects and nonmonotonic dose responses. In *Endocrine Reviews* (Vol. 33, Issue 3, pp. 378–455). https://doi.org/10.1210/er.2011-1050

Voutchkov, N. (2018). Energy use for membrane seawater desalination – current status and trends. In *Desalination* (Vol. 431, pp. 2–14). Elsevier B.V. https://doi.org/10.1016/j.desal.2017.10.033

"Water Conservation and Production Reports." 2023. *California State Water Resources Control Board*. https://water.ca.gov/What-We-Do (March 20, 2023).

WaterReuse Research Foundation. 2015. *Framework for Direct Potable Reuse*. https://watereuse.org/wp-content/uploads/2015/09/14-20.pdf.

Wilson, Zoë, and Bill Pfaff. 2008. "Religious, Philosophical and Environmentalist Perspectives on Potable Wastewater Reuse in Durban, South Africa." *Desalination* 228(1–3): 1–9.

Zhou, Dong et al. 2015. "Development of Lower Cost Seawater Desalination Processes Using Nanofiltration Technologies - A Review." *Desalination* 376(1219): 109–16. http://dx.doi.org/10.1016/j.desal.2015.08.020.

11 Appendices

11.1 Groundwater Energy Equations

Equation 11.1 - Friction Factor Equation (Fournier et al. 2016)

$$f = \frac{0.25}{[log(\frac{k}{3.75D}) + \frac{5.74}{Re^{0.9}}]^2}$$

Equation 11.2 - Total Pipe Loss Equations (Fournier et al. 2016)

$$K_t = k_f + \frac{fz}{D}$$

Equation 11.3 - Pump Energy Calculation (Fournier et al. 2016)

$$E_{pump} = \frac{x_{pump} K_t v^2}{3600\eta}$$

11.2 Unit Process Energy Data

Table 11-1: *Tabulated unit process energy data with sources.*

Process	SEC (kWh/m^3)	Variance	Source
Biological Activated Carbon	0.257	0.0165	Snyder et al., 2014
Brackish Water Desalination	1.80	0.600	Plappally et al., 2014
Coagulation	0.550	0.0225	Tow et al., 2014
Granular Activated Carbon	0.370	-	Gumerman et al., 1979
Microfiltration	0.210	0.00384	Plappally et al., 2014 Tow et al., 2014
Nanofiltration	1.06	0.0765	Tow et al., 2014
Ozonation	0.0134	0.000733	Plappally et al., 2014 Tow et al., 2014 Katsoyiannis et al. 2011
Reverse Osmosis	1.75	0.562	Plappally et al., 2014 Tow et al., 2014
Seawater Desalination	4.03	2.09	Plappally et al., 2014
Ultrafiltration	0.202	0.00309	Plappally et al., 2014 Tow et al., 2014
UV Oxidation	0.0362	0.000293	Plappally et al., 2014 Tow et al., 2014 Katsoyiannis et al., 2011

11.3 Unit Process Economic Data

Table 11-2: *Tabulated economic data from Guo et al. 2014 for the William's Power Log Rule.*

Process	CAPEX			OPEX		
	a	b	c	a	b	c
Coagulation	0.222	1.516	3.071	0.347	1.448	2.726
Granular Activated Carbon	0.722	1.023	3.443	1.669	0.559	2.371
Reverse Osmosis	0.966	0.929	3.082	0.543	1.253	2.786
Ultrafiltration	1.003	0.830	3.832	1.828	0.598	1.876

Table 11-3: *Tabulated economic data with sources for the Power Law.*

Process	CAPEX		OPEX		Source
	a	b	a	b	
Biological Activated Carbon (10 min EBCT, ≤ 10 MGD)	2.92	-0.52	0.074	-0.19	Plumlee et al., 2014
Biological Activated Carbon (10 min EBCT, 10 - 80 MGD)	1.43	-0.17	0.059	-0.044	Plumlee et al, 2014.
Biological Activated Carbon (20 min EBCT, ≤ 10 MGD)	3.03	-0.48	0.085	-0.16	Plumlee et al., 2014
Biological Activated Carbon (20 min EBCT, 10 - 80 MGD)	1.52	-0.15	0.070	-0.036	Plumlee et al., 2014
Brackish Water Desalination	0.011936	0.71659	-	-	Bhojwani et al., 2019
Microfiltration	3.57	-0.22	0.3	-0.22	Plumlee et al., 2014
Nanofiltration	7.14	-0.22	0.44	-0.13	Plumlee et al., 2014
Ozonation	2.26	-0.54	0.0068	-0.051	Plumlee et al., 2014.
Seawater Desalination	9.3423	0.7177	2.9129	0.6484	McGivney et al. 2008
UV Oxidation	0.474	-0.056	0.038	-0.052	Plumlee et al., 2014

11.4 Model Results

Table 11-4. *Model results for each flow rate for the City of Oxnard.*

Flow Rate Scenario	Technology	Energy Requirement	Capital Cost	O&M Cost
Upper Bound (~13 MGD)	Direct Potable Reuse	2.22 ± 0.56	6.05 +3.025/-1.815	0.72 +0.36/-0.216
	Indirect Potable Reuse	2 ± 0.56	4.39 +2.195/-1.317	0.6 +0.3/-0.18
	Groundwater Desalination	2.89 ± 0.6	2.11 +1.055/-0.633	0.52 +0.26/-0.156
	Ocean Desalination	4.03 ± 2.09	6.25 +3.125/-1.875	1.63 +0.815/-0.489
Normal (~6.3 MGD)	Direct Potable Reuse	2.22 ± 0.56	7.66 +3.83/-2.298	0.82 +0.41/-0.246
	Indirect Potable Reuse	2 ± 0.56	5.05 +2.525/-1.515	0.64 +0.32/-0.192
	Groundwater Desalination	2.89 ± 0.6	2.6 +1.3/-0.78	0.53 +0.265/-0.159
	Ocean Desalination	4.03 ± 2.09	7.67 + 3.835/-2.301	2.1 +1.05/-0.63
Lower Bound (~3.1)	Direct Potable Reuse	2.22 ± 0.56	9.99 +4.995/-2.997	0.96 +0.48/-0.288
	Indirect Potable Reuse	2 ± 0.56	5.8 + 2.9/-1.74	0.69 +0.345/-0.207
	Groundwater Desalination	2.89 ± 0.6	3.17 +1.585/-0.951	0.55 +0.275/-0.165
	Ocean Desalination	4.03 ± 2.09	9.37 +4.685/-2.811	2.7 + 1.35/-0.81

Table 11-5. *Model results for each flow rate for the City of Bakersfield.*

Flow Rate Scenario	Technology	Energy Requirement	Capital Cost	O&M Cost
Upper Bound (~18 MGD)	Direct Potable Reuse	2.22 ± 0.56	5.49 +2.745/-1.647	0.69 +0.345/-0.207
	Indirect Potable Reuse	2 ± 0.56	4.12 +2.06/-1.236	0.58 +0.29/-0.174
	Groundwater Desalination	3.31 ± 0.6	1.93 +0.965/-0.579	0.52 +0.26/-0.156
	Ocean Desalination	4.03 ± 2.09	5.7 +2.85/-1.71	1.45 +0.725/-0.435
Normal (~9.1 MGD)	Direct Potable Reuse	2.22 ± 0.56	6.69 +3.345/-2.007	0.76 +0.38/-0.228
	Indirect Potable Reuse	2 ± 0.56	4.7 +2.35/-1.41	0.62 +0.31/-0.186
	Groundwater Desalination	3.31 ± 0.6	2.34 +1.17/-0.702	0.52 +0.26/-0.156
	Ocean Desalination	4.03 ± 2.09	6.91 +3.455/-2.073	1.85 +0.925/-0.555
Lower Bound (~4.6 MGD)	Direct Potable Reuse	2.22 ± 0.56	8.62 +4.31/-2.586	0.88 +0.44/-0.264
	Indirect Potable Reuse	2 ± 0.56	5.37 +2.685/-1.611	0.66 +0.33/-0.198
	Groundwater Desalination	3.31 ± 0.6	2.84 +1.42/-0.852	0.54 +0.27/-0.162
	Ocean Desalination	4.03 ± 2.09	8.38 +4.19/-2.514	2.35 +1.175/-0.705

Table 11-6. *Model results for each flow rate for the City of Fresno.*

Flow Rate Scenario	Technology	Energy Requirement	Capital Cost	O&M Cost
Upper Bound (~27 MGD)	Direct Potable Reuse	2.22 ± 0.56	4.87 +2.435/-1.461	0.65 +0.325/-0.195
	Indirect Potable Reuse	2 ± 0.56	3.81 +1.905/-1.143	0.57 +0.285/-0.171
	Groundwater Desalination	2.58 ± 0.6	1.72 +0.86/-0.516	0.51 +0.255/-0.153
	Ocean Desalination	4.03 ± 2.09	5.08 +2.54/-1.524	1.26 +0.63/-0.378
Normal (~13 MGD)	Direct Potable Reuse	2.22 ± 0.56	6.05 +3.025/-1.815	0.72 +0.36/-0.216
	Indirect Potable Reuse	2 ± 0.56	4.39 +2.195/-1.317	0.6 +0.3/-0.18
	Groundwater Desalination	2.58 ± 0.6	2.11 +1.055/-0.633	0.52 +0.26/-0.156
	Ocean Desalination	4.03 ± 2.09	6.25 +3.125/-1.875	1.63 +0.815/-0.489
Lower Bound (~6.5 MGD)	Direct Potable Reuse	2.22 ± 0.56	7.57 +3.785/-2.271	0.82 +0.41/-0.246
	Indirect Potable Reuse	2 ± 0.56	5.02 +2.51/-1.506	0.64 +0.32/-0.192
	Groundwater Desalination	2.58 ± 0.6	2.57 +1.285/-0.771	0.53 +0.265/-0.159
	Ocean Desalination	4.03 ± 2.09	7.6 + 3.8/-2.28	2.08 +1.04/-0.624