California's Drought and the Energy-Water Nexus

Developing Water Supply Increase Strategies Through Examination of Energy Consumption

Written by Anna Epstein
Advised by Professor Ralph Bradburd

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Introduction

Home to a large and steadily growing population and economy, California is well known for its sunny beaches, expansive mountain ranges, and numerous natural wonders. Drawing residents and visitors alike, the state's allure in part explains California's continuously growing thirst for fresh water. To date, technologies have been successfully developed and implemented that, under normal conditions, have allowed California to adequately satisfy its demand for water. However, while these water supply mechanisms have typically fulfilled the state's needs, times of drought place increased strain on water supplies, and although droughts are a recurring aspect of California's climate, the state's most recent drought was the harshest on record (Hank et al, 2015). From 2011 to 2014, less precipitation fell than during any three-year span since 1895, and this, combined with above average temperatures, served to exacerbate the drought's effects (Hank et al, 2015). The year 2014 was particularly brutal – the hottest year on record with snowpack levels 5% of their annual average (California DWR, 2015). While in the past few months, precipitation has returned to more typical levels, total water supply in the state has not yet recovered. Even if water levels do return to average in the coming months, droughts will likely increase in frequency and severity as the effects of climate change manifest themselves. States prone to drought, such as California, must begin creating robust water supply strategies to maintain their booming population, flourishing economy, and cherished environments.

Statewide, agricultural water use accounts for 80% of California's total consumption, with significant opportunities for reductions in demand (Vara, 2015). Savings could be found through mechanisms such as increased efficiency of irrigation methods or production of crops with lower water requirements, to name a few. Despite this, the opportunities for reducing agricultural water use remain largely unexploited due to the political pressures from the powerful agricultural interest groups in the state. One of the most prominent of these groups is the Westlands Water District, representing some of the wealthiest and most politically influential farmers in California (Wines et al, 2015). In 2014 the group spent six times its 2010 expenditures in Washington, DC when Congress began discussing potential policy actions concerning the state's water supply. The group also bankrolls a number of subsidiary organizations through which it influences the media (Wines et al, 2015). In these cases and others, the state's strong agricultural lobby has thus far successfully blocked significant measures to reduce agricultural water consumption.

Given the complex politics surrounding agricultural water use that limit implementation of improved conservation practices, I have instead chosen to focus on residential water supply as an area of potential savings.[1] There exist many opportunities for increased water conservation in this sector, which accounts for approximately 20% of California's total water consumption. In some cases, this water conservation could occur *directly* through behavioral changes such as reducing the use of water for landscaping or increasing the efforts to control leaks in water pipes. In other cases, water can be conserved through efforts to replace existing residential appliances with those designed to use water more sparingly; these efforts have both direct *and* indirect effects on water consumption due to their energy usage. Approximately 20% of California's electric

[1] In examining residential use and throughout the paper I will be focusing on surface water supplies. While groundwater possesses an enormous opportunity for study and savings, its use is not currently regulated by the state, making it difficult to know exactly how much is being used, at what rates, and by whom.

energy consumption is used to transport and treat water (California Energy Commission). This is a staggering amount, especially when one takes into account the fact that significant amounts of water are consumed in the process of energy production. The interconnectedness of the two resources poses a fascinating area of study for potential improvements in the consumption efficiencies of both. This energy-water nexus is the specific focus of my thesis research.

The Energy-Water Nexus

Although the interconnectedness of water and energy may not be immediately apparent, energy production necessitates large quantities of water, and water supply and transport require large amounts of energy. In 2010, 583 billion cubic meters (bcm) of freshwater were extracted globally for energy production, accounting for 15% of the world's total water withdrawals (International Energy Agency, 2012). Of this total, 66 bcm, 11% of the total water withdrawn, was consumed, evaporated or otherwise prevented from returning to the watershed after its use. This value represents 1.65% of the world's total water withdrawals for any end use (International Energy Agency, 2012). Given increasing global demand for energy, this value is not insignificant and will likely continue to grow.

Energy is a modern necessity and energy production involves consumption of water in all stages of its lifecycle: fossil fuel extraction, transport, and processing; power plant operation; and increasingly, irrigation of biofuel crops. Water is of course a necessity as well, and just as some water must be consumed in the production of energy, some energy is required for the withdrawal, processing, and distribution of water. This interdependency does not represent inefficiency; however, the fact that water and energy utilities operate separately, combined with the fact that water is rarely priced at its true value, leaves open the possibility that water and energy needs could be met in ways that reduce consumption of both. These potential savings could also considerably lower greenhouse gas emissions generated through energy production processes if either the energy devoted to supplying water or the water consumed in the production of energy is significant.

Given that California uses about a quarter of its total energy consumption for the purpose of providing water, the state's energy use and water consumption clearly have the potential to be interdependent. California derives its energy from a variety of sources ranging from fossil fuels to renewables. While the portfolio is diverse, the vast majority of the sources consume some degree of water over the course of their lifecycles. The relative abundances of each energy type in California's energy portfolio are demonstrated in Figure 1 below.

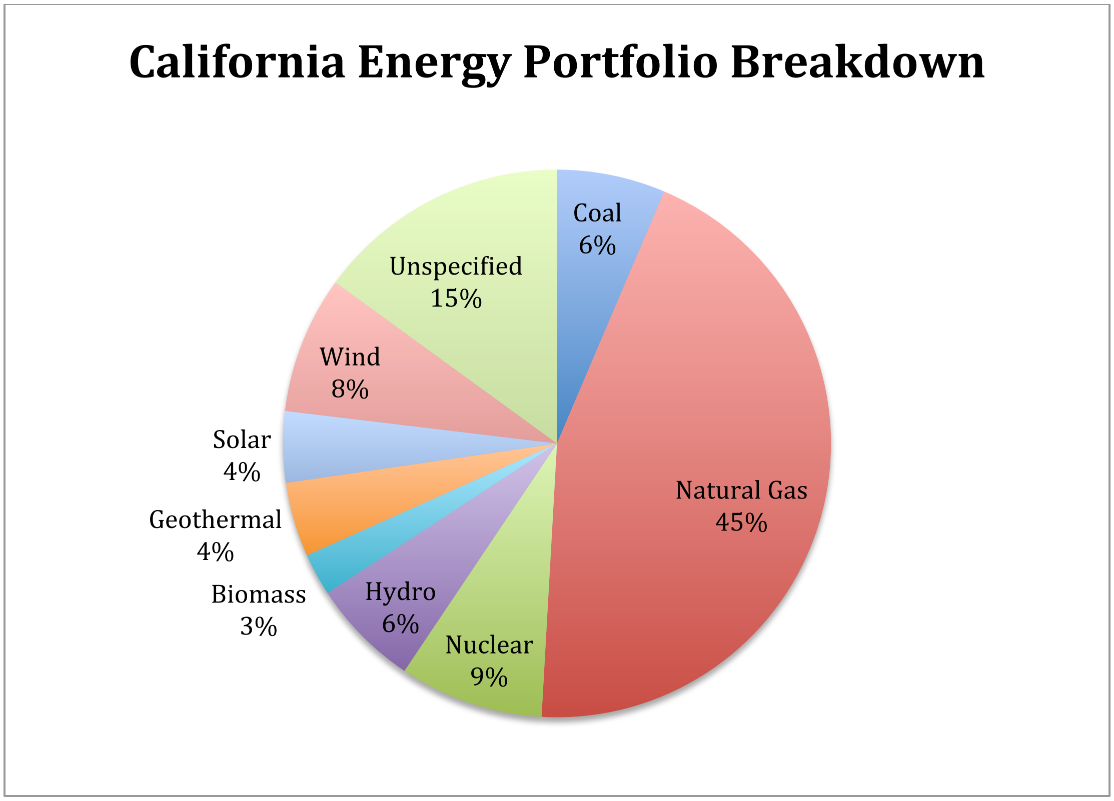

Figure 1: Pie Graph representation of the various components of California's energy portfolio and each energy type's relative proportion.

Wind and solar, which together comprise 12.3% of the state's power mix, use little water beyond the amount necessary during their construction. Geothermal and biomass both require larger quantities for successful operation, but at only 6.9% of the California energy portfolio, they are not large enough producers to render efficiency improvements effective. Hydroelectric power provides 6.4% of California's energy, and while not directly consumptive in its use of running water to turn turbines, it does lose water to evaporation from the large reservoirs its dams create. As I will discuss later in this paper, this evaporative loss is significant and deserves closer attention. Coal, natural gas, and nuclear generated electricity are the primary fossil fuel sources that power the state. They all require significant water inputs in their extraction and combustion stages and together comprise 59.4% of the state's power mix. Of these three, natural gas is by far the largest contributor, generating approximately 45% of the state's energy.

There are a number of sources of natural gas including conventional and shale, and depending on the type of gas as well as the number of times a well is tapped, its extraction can consume large quantities of water. In arid regions where potable water is at a premium, allocating it to natural gas wells may not represent its best use. However, only 10% of the natural gas burned in California power plants comes from wells in California itself. Thus when considering only California's water supply, the natural gas *extraction* process does not represent a significant use of water; however, natural gas *combustion* does.[2]

Thermoelectric Power Plants

While almost all stages of the energy production life cycle consume some amount of water, the stage involving conversion of energy into electricity in power plants consumes by far the most. In thermoelectric power plants, energy production generates an immense amount of heat that must be removed from the cycle. To accomplish this, plants use large quantities of water to absorb the heat and remove it from the plant. Thermoelectric plants typically use one of three methods of heat removal. The first is once-through cooling, an effective but water-intensive process that passes water through the plant and discharges it into nearby bodies of water (Lopez, 2015). This hot water can harm the ecosystems of the local watershed, causing this method of removal to come under attack by advocacy groups.

[2] It is somewhat arbitrary to draw the line at the California border; however, with my focus specifically on water use in the state and the need to draw an edge somewhere, the state line appears the best option.

The second method, recirculating cooling, was developed by utilities in response to increased regulation enacted to protect local ecosystems from the harms imposed by once-through cooling. With recirculating cooling, hot water is exposed to ambient air in cooling towers or, less frequently, in cooling ponds (Lopez, 2015). This causes a large percentage of the water to evaporate, reducing the amount of hot water that then returns to nearby sources and limiting the environmental damage caused by its influx. However, this method drastically increases the amount of water lost to evaporation. While recirculating cooling only withdraws approximately 1.25% to 5% of the water used for once-through cooling, it consumes 86% to 100% of its withdrawals (Union of Concerned Scientists, 2012). This percentage of consumption is much greater than the 2% to 5% consumption of once-through systems, meaning much less water returns to the local watershed for in situ use or downstream users (Lopez, 2015). Recirculating cooling systems are predominant in the western United States despite their significant water consumption (Union of Concerned Scientists, 2012).

The third method of power plant heat removal uses air to cool the plant and thus requires no water withdrawals (Union of Concerned Scientists, 2012). Known as dry cooling, it is a less efficient method of heat removal especially at high ambient temperatures due to the diminished thermal gradient between the air outside and that used to cool the plant. This decrease in efficiency requires more fuel per unit of electricity, which can result in increased indirect water consumption through its use in fuel production (Union of Concerned Scientists, 2012). However, in water-scarce regions this method’s inefficiencies may still represent a better option than one of the directly water-intensive cooling methods (Lopez, 2015).

Hydroelectric Power Plants

Among energy generation methods, thermoelectric power plants stand out as obvious consumers of water given their significant cooling needs; however, hydroelectric power plants, through evaporative losses, consume large amounts of water as well. Typically these plants are constructed on rivers to generate hydroelectric power by harnessing the kinetic energy of running water. Dams control the storage and flow of this water, channeling it through turbines that generate electricity, before it continues downstream. Since the water flowing through the dam is not lost and can be used by downstream ecosystems or consumers, its use is not considered consumptive (Torcellini et al, 2003). However, hydroelectric dams still result in significant water losses due to evaporation from the reservoirs that abut them (Torcellini et al, 2003). When engineers construct a dam on a river, they also create a large, standing body of water behind it. In arid regions such as California, the hot climate combined with the large surface area renders such reservoirs susceptible to high rates of evaporation. Relative to the counterfactual rates of the flowing river, these reservoirs lose significant amounts of water to the atmosphere (Torcellini et al, 2003). In water-abundant regions these losses are not significant relative to the overall water supply; however, in California they represent a non-trivial amount of the energy production cycle's indirect consumption of water.

Because of the potential for significant consumptive losses in energy production, determining approximately how much water is consumed in electrical generation is a necessary first step towards reducing these losses. In a study conducted in 2003, the National Renewable Energy Laboratory weighed the evaporative losses of thermoelectric and hydroelectric plants in California per kilowatt-hour (kWh) produced of each type. They found that the state's thermoelectric plants produce 72,800 million kWh/year, with 0.05 gallons of water consumed per kWh produced (Torcellini et al, 2003). Hydroelectric plants produce less of the state's energy, only 9,130 million kWh/year, but consume 20.87 gallons of water per kWh produced (Torcellini et al, 2003). The weighted average of the two production types results in total water consumption of 4.64 gallons per kilowatt-hour (Torcellini et al, 2003). This baseline value is critical to examining indirect water consumption of different water supply strategies given their energy requirements. There may be opportunities for improving the state's water supply and demand imbalance if the interconnectedness of water and energy are more fully examined and the different uses of electricity involved in supplying water more carefully considered. I will now discuss California's primary water delivery system, the energy it requires, and the subsequent water it consumes indirectly.

Current Water Supply Mechanisms: The State Water Project

To understand the rationale for California's current water supply mechanisms, we must begin with the regional imbalances in water supply and demand *within* the state. In northern California, precipitation is typically high and snowmelt from the mountains feeds the local watersheds, while in the southern region of the state the climate is more arid, resulting in lower amounts of precipitation and less snowmelt. This difference in the natural regional abundance of water would be of little consequence if the majority of California residents lived in the north. However in reality, two thirds of the state's population resides in southern California while two thirds of the precipitation falls in the north (Klein et al, 2005). This imbalance led to a number of policy decisions regarding water transport and supply in the early 1900's that still hold much relevance today. The most notable of these were the decisions to transport water over hundreds of miles and thousands of vertical feet from the north to the south. The California State Water Project represents the most significant current source of urban water to southern California.

The idea for a massive water transport system that would carry water from Sacramento to the southern region of the state was initially conceived in 1919 (California Department of Water Resources). Plans for its construction continued into the early 1930's, until the Great Depression rendered revenue bonds unmarketable and thus funding nonexistent (California Department of Water Resources). The project lay dormant for the next thirty years until 1960 when the Burns-Porter Act passed the state legislature and provided funding for the system. Construction began rapidly after that and the California State Water Project began delivering water to southern California in 1973 (California Department of Water Resources).

The State Water Project (SWP) is comprised of canals, aqueducts, rivers, pipelines, and reservoirs that stretch a total of 701 miles from north of Sacramento to the San Diego municipality (California Department of Water Resources, 2011). While many portions of the SWP transport water solely due to gravitational pull, a number of prominent geological features that impede the southward flow and thus necessitate pumping. Most notably, the SWP passes over the Tehachapi Mountains in southern California prior to reaching its final destination. These mountains require the SWP to pump water vertically 1,926 feet to cross the summits and to allow the route to continue (California Department of Water Resources, 2011). This lift is the highest of any water delivery system in the world and requires a substantial amount of energy (California Department of Water Resources, 2011). Because of its immense distance and pumping requirements, the system as a whole represents the largest single consumer of electricity in California, using approximately 2% to 3% of the state's total annual consumption (NRDC, 2004).

While the SWP's yearly electrical consumption rate is high, it would be more than doubled if the hydroelectric power produced by the dams located along its extent were not included. The project requires on average approximately 11.5 billion kWh of electricity each year to move water from the north to the south (NRDC, 2004). Of this total requirement, 6.5 billion kWh are generated from the flowing water of the system itself, necessitating the purchase of the remaining approximately 5 billion kWh from the grid (NRDC, 2004). If we assume that approximately 4.64 gallons are consumed in the process of electric generation for each kWh on the grid –the state average – the SWP indirectly consumes approximately 23,200 million gallons per year through its energy use. With average yearly deliveries of over 782,000 million gallons, the indirect water consumption through the SWP's energy use represents approximately 2.97% of the total annual water supplied by the system (California DWR, 2011).

This calculation of indirect water loss must be considered carefully however, as it may not represent the full extent. Large portions of the system – including reservoirs behind dams, aqueducts, and canals – are open to the air, driving evaporative losses. Some of the most prominent areas where this evaporation may happen are the reservoirs created for hydroelectric and stable supply purposes. The SWP has 21 primary reservoirs along its extent, the largest of which has a surface area of 15,810 acres (California DWR, 2011). These reservoirs, in addition to the many miles of open-air canals and aqueducts, render water susceptible to evaporation. This water, also known as "carriage water," is lost in the transport process, yet requires energy to pump it until it evaporates, wasting valuable energy that indirectly consumes water with it (NRDC, 2004). While no formal analyses of the system's total evaporative losses have been calculated, the SWP estimates losses at approximately 5% (NRDC, 2004). Given the system's average annual deliveries of approximately 782,000 million gallons, the SWP's estimated evaporative losses are 39,100 million gallons each year. Combined with the indirect water consumption from electrical requirements, the project loses approximately 8% of its annual supply, or approximately 62,300 million gallons per year.

The project's immense scale is matched by an immense operating budget of $900 million each year (NRDC, 2004). Given this value and the SWP's average annual deliveries of 782,000 million gallons, the cost to provide southern California with water this way is approximately $1,150 per million gallons.[3] However, this cost takes into account neither the indirect water losses through the SWP's electrical requirements, nor the system's evaporative losses during conveyance. These losses, totaling approximately 62,300 million gallons annually, decrease the net amount of water provided by the SWP, reducing true deliveries to approximately 719,700 million gallons per year. With this value for net annual deliveries, the cost of water from the SWP equals approximately $1,250 per million gallons. This modified cost of water more accurately depicts the true costs of SWP provisions, and can be used as a baseline standard with which to compare costs of alternative mechanisms of increasing California's effective water supply.

[3] This value covers just the annual operating costs, not the installation or structural costs.

For much of its lifetime the SWP has served southern California consumers well, providing the vast majority of the region's much needed water supply with a great deal of reliability. However due to significant and prolonged drops in precipitation and corresponding snowpack, the primary sources of the SWP's supply have diminished. The reduced precipitation has not only affected the SWP, but also lessened water supplies elsewhere in the state. With dwindling supply in their local reservoirs, an increased number of consumers are turning to sources such as the SWP, placing an even greater strain on its diminished supplies. With these resource pressures in place and the potential for future droughts highly likely, California policymakers have begun looking for alternative mechanisms to increase the state's total accessible water supply. While an array of options is available, policymakers appear to have selected desalination as their primary method of choice.

Desalination

Desalination, which involves removing dissolved ions and small particulate matter from saline water, has in recent years become an increasingly important source of potable fresh water. Desalination occurs naturally as a part of the hydrologic cycle. When water vapor that has fallen as rain moves over the ground and into the subsurface, it dissolves salt and other minerals and ions on its route back to the oceans. However, when oceanic water evaporates and becomes water vapor, it leaves behind all but its hydrogen and oxygen molecules. This water vapor forms clouds that eventually condense to produce fresh rainwater, thus completing the cycle.

Humans have succeeded in recreating this natural process. One of the earliest recorded mentions of water purification comes from Aristotle, who wrote about seawater distillation in 320 BCE. While the technology remained relatively unsophisticated for much of the time since the ancient Greeks, in the 1940's it began to develop significantly. During World War II, military troops stationed in arid regions needed safe and reliable access to water. Research and development during this time produced commercial desalting units that used thermal energy to distill water. After the war, scientists began exploring osmotic processes as a means of desalination (International Desalination Organization, 2015). This research spurred innovations that led to reverse osmosis desalination, the technology used in approximately 60% of installed capacity today (International Desalination Organization, 2015).

Desalination Technology

Reverse osmosis involves demineralizing water by forcing it through a semi-permeable membrane that allows water to pass but blocks dissolved ions in the water from doing the same. In nature, osmosis is the process of water traveling from a lower saline concentration to a higher one. It requires no energy and is integral to a number of lifecycle processes; for example, osmosis plays a key role in nutrient transfer across cellular membranes. In reverse osmosis, water is forced to travel in a direction opposite to the natural gradient, producing freshwater but requiring significant energy inputs to do so. The process typically leaves 95% to 99% of the dissolved salts behind in a highly concentrated brine called the "concentrate" and produces potable water known as the "permeate" (Puretec, 2016). The filter blocks contaminants from passing through based on their size and charge. Most filters block any particle with a molecular weight greater than 200; for comparison, water has a molecular weight of 18. The higher a contaminant's charge the less likely it is to pass through the filter. Overall, reverse osmosis constitutes an effective means of producing freshwater from saline, especially given the number of existing technologies for purifying the permeate and reusing or disposing of the concentrate.

The most basic reverse osmotic process is a "one stage" or "single pass" system. In this design, "feed water" brought in from the ocean enters a tank while pumps force it through the semi-permeable membrane. Tanks on the other side collect the permeate and transport it away while the remaining concentrate is collected and disposed of. There also are further options beyond this once-through system that allow plants to treat the water more fully. In a "double pass" system water flows through a membrane, generating permeate that is then passed through another membrane, purifying it to a higher quality (Puretec, 2016). Similarly, another plant option lies in a "two stage" system. Here water again passes first through one membrane after which the permeate and concentrate are collected. The concentrate then passes through another membrane in an attempt to glean any additional potable water. In this system, "concentrate recycling" occurs to gain as much benefit from the feed water as possible. Each of the above options allow plants the flexibility to desalinate water to their desired levels or to combine processes to maximize purity and percentage filtered. However, the amount of energy required to reverse the natural osmotic processes by pumping water through the membranes is significant. The high energy inputs of the desalination process means that desalinated water comes at a high energy price, one that should not be overlooked when considering the viability of this technology as a solution to a warming climate, increased and prolonged droughts, and arid regions' water demands.

Desalination in California

As a result of increasing scarcity of naturally occurring freshwater in many parts of the world and reductions in the cost of desalinating water, arid and drought stricken regions are increasingly turning to desalination to meet their potable water needs. Globally there are over 17,000 desalination plants producing more than 21.1 billion gallons per day (International Desalination Organization 2015). These plants are located in 150 countries and supply more than 300 million people with some, if not all, of their daily water needs (International Desalination Organization, 2015). Currently California has 17 plants either operating, partially constructed, or in the exploration and planning phases; nine are along the northern coast of the state, two in the central region, and six in the south. A number of these plants were constructed in the 1990's and 2000's during severe droughts, but given their high operating costs, were mothballed or decommissioned when rainfall amounts increased again. These are among the plants in consideration for re-commission.

One newly constructed desalination facility, and the only plant currently operating in the state, is the Claude "Bud" Lewis Carlsbad Desalination Plant. Located just outside of San Diego, the plant went online December 14, 2015 and possesses not only the largest capacity in the state, but in the entire western hemisphere (Fagan, 2014). The plant is expected to produce 50 million gallons of water per day – or 18,250 million gallons per year – which will supply approximately 110,000 customers throughout the San Diego area. The plant cost approximately one billion dollars to construct, an investment that in combination with the daily operating costs will necessarily have an impact on the water bills of San Diego residents over the next few years. While the plant has received much press for its high capacity and costs, it has also gained attention for its employment of an array of energy recapture and efficiency mechanisms. However, despite these efforts, the Carlsbad Desalination plant still uses a significant amount of electric energy.

Just north of Carlsbad along the California coast another desalination plant will begin production in September 2016. Santa Barbara's Charles E. Meyer Desalination Plant was originally built in the late 1980's with a projected capacity of 2,444 million gallons per year, with the potential for expansion to production of 3,259 million gallons annually (City of Santa Barbara, 2015). After opening in March of 1992 the plant operated through June of the same year before it was placed on standby mode due to large amounts of rainfall that rendered the plant's product superfluous. However on July 21, 2015, the Santa Barbara City Council issued a contract to reopen the plant (Magnoli, 2015). While initial construction costs totaled $34 million, reactivation of the plant will cost an estimated $55 million with annual operating costs of approximately $5 million (Magnoli, 2015). The plant will have a yearly production capacity of 1,018 million gallons that will be used not as a regular water supply, but instead as a resource in times of drought, covering approximately 30% of the city's water demands.

By comparing these two plants and conducting analyses of their potential gross and net water productions as well as their costs per unit of water, we can compare a newly built, state-of-the-art plant with one that is being retrofitted and brought back into commission after decades offline. This will allow us to calculate a range of efficiencies and costs within which any given California desalination plant will likely fall. This range can then be used to compare desalination efficiencies and costs with those of other potential water supply mechanisms.

Energy and Water Calculations

As discussed above, the reverse osmotic process requires significant energy inputs. The electric energy used in the desalination process is generated in a variety of ways, and those generation processes themselves consume water. Information on the desalination plant's reported energy use and water output, combined with information on the sources of the energy necessary to power the plant and the water intensity of each of those sources, allows us to calculate the indirect water consumption involved in the operation of the plant, and thus its "net water output."

The Carlsbad plant was constructed with a capacity of approximately 50 million gallons – or 189,270 cubic meters – per day. The plant uses 3.6 kWh to produce each cubic meter of water, resulting in approximately 684,000 kWh/day of energy usage. Given that the indirect amount of water embodied in any kWh on the grid in California is equal to 4.64 gallons, the total amount of indirect water consumed in producing the energy necessary to operate the plant is 3,173,760 gallons per day, 6.35% of the output of the reported production of the plant. While this number may not represent a prohibitive amount, it is not insignificant.

While the Santa Barbara desalination plant was initially constructed with annual capacity as high as 3,259 million gallons per year, the mothballed then recomissioned plant is expected to produce 1,018 million gallons, or 3,125 acre-feet, annually. Engineers expect the plant to use 5,300 kWh to produce each acre-foot, resulting in annual energy requirements of 16,562,500 kWh. Given the 4.64 gallons of water embodied in any given kWh on the grid, the Santa Barbara desalination plant would indirectly consume 76.85 million gallons per year through its energy usage. Compared with annual gross production of 1,018 million gallons per year, this indirect consumption represents approximately 7.55% of the plant's output. A comparison of the consumption and production values of both desalination plants is listed in Table 1 below.

Table 1: Comparison of relative production and consumption values of the Carlsbad and Santa Barbara Desalination Plants.

	Carlsbad Desalination	Santa Barbara Desalination
Gross Water Production	18,250 million gallons per year	1,018 million gallons per year
Energy Consumption	249,660,000 kWh	16,562,500 kWh
Indirect Water Consumption	1,158 million gallons per year	76.85 million gallons per year
Net Production	17,092 million gallons per year	941.15 million gallons per year
Percentage of Gross Production Indirectly Consumed	6.35%	7.55%

From considering the two plants' energy use and water outputs, we can set a reasonable range of values for approximately what percentage of gross water production is indirectly consumed through desalination plants' energy requirements. While values between 6.35% and 7.55% are not large enough to render desalination technology as a whole inefficient, nevertheless they are worth taking into account when designing water management strategies. In California's current state of severe drought, water use must be carefully considered and evaluated. If there are no better options for producing water for the state, then this water consumption can simply be taken as a necessary cost. However, if there exist alternative sources of meeting California's water needs that do not require as much energy and thus have less associated indirect water consumption, they may be worth exploring in further detail.

Cost Calculations

While desalination offers the advantage of a stable means of water supply,[4] it has disadvantages as well; the one most commonly cited is cost. Given the sophistication of its technology, a plant's construction requires significant initial investments in addition to continued maintenance inputs throughout its lifetime. These costs are typically recovered in the form of prices that are higher than many other water sources. Based on current electricity cost estimates, the price of the Carlsbad desalination plant's water in 2016 has been set at $6,540 to $7,264 per million gallons (San Diego County Water Authority, 2016). The Santa Barbara plant's price is slightly lower; given the estimates for the initial production level, the cost of water is expected to start at $4,296 per million gallons (Magnoli, 2015). When considering this technology as a significant piece of a water management strategy, these costs must be carefully considered, especially when the price of water from a region's primary source, such as the State Water Project, is so much lower. Because the Carlsbad plant will only produce approximately 7% of San Diego's total consumption, its high price is averaged with lower prices of the remaining supply. This pricing policy blunts consumer perceptions of the impact of desalination's high price per unit of water. However if desalination fulfilled a larger portion, or even all, of a region's supply, the price of water would be significantly higher. This elevated cost is frequently passed on to the consumer, resulting in price increases where desalination technology is used.

Because the Carlsbad desalination plant's output was introduced to the San Diego water supply at the end of 2015, the City of San Diego's Water Department implemented

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[4] There certainly exists value in stability; however, the calculations to put a dollar amount on it are complex and beyond the scope of this paper.

water rate increases that began on January 1, 2016 and will continue through 2020. Citing the need to reduce water imports (85% of the city's water supply previously came from northern California and the Colorado River), to increase drought-proof supply mechanisms, and to invest in new water delivery infrastructure such as pipes and pump stations, the city incorporated some of the costs of these investments in the price increase (San Diego Public Utilities Department, 2015). In the city's press releases and media coverage of the desalination plant, many estimates placed the increased annual costs at approximately $5 per household per monthly bill, a seemingly modest amount for a stable source of water in an arid region. However, closer examination of the planned increase suggests this modest figure may be misleading.

In an example of the adjustments to the water bill of a single-family home, the City of San Diego estimated that a typical residential house that uses 12 hundred cubic feet[5] per month would see a 9.1% or $6.44 increase in the monthly bill, stating that the exact increase is subject to varying levels of consumption (San Diego Public Utilities Department, 2015). While this is true for the rate increase from 2015 to 2016, it neglects to mention that over the following four fiscal years, the price will continue to increase (San Diego Public Utilities Department, 2015). In order to properly quantify the full cost that the Carlsbad desalination plant will impose on consumers, we should compare what consumers paid in 2015 to what they will pay in 2020 if their consumption remains the same.

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[5] The San Diego water pricing system uses cubic feet as its volumetric unit of choice. A cubic foot is defined as the amount of water contained within a cube of length, width, and height all equal to one meter, and is equivalent to approximately 264 gallons.

Assume, as the City of San Diego did, that a single-family home possesses a ¾ inch meter and consumes 12 hundred cubic feet (hcf) per month, the equivalent of 300 gallons per day. The San Diego water utility's bill is comprised of two parts, the meter charge (base fee) and the commodity rate (cost per hcf consumed), both of which will increase over the next five years (San Diego Public Utilities Department, 2015). The base fee does not change with amount of water consumed, while the commodity rate is based on a tiered use system; the price per hcf increases with consumption (San Diego Public Utilities Department, 2015). In 2015, the base fee for this home would equal $20.31 per month, with a commodity rate of $15.584 per hcf for the first four hcf per month, and $34.912 per hcf for the next 8 hcf per month: a total commodity rate of $50.496 per month. The annual cost of water with 2015 rates would equal $849.672. In 2020, after four years of gradual increase, the home's base fee would equal $29.46 per month. The commodity rate for the first four hcf would equal $21.54 per hcf per month and $48.248 per hcf per month for the next eight hcf. These together would bring the home's total annual cost to $1,190.976. The escalation in prices represents a $341.304 or approximately 40% increase in the cost of water just five years in the future. This is not an insignificant figure for consumers in the San Diego area. Table 2 below compares the costs for 2015 and 2020 below.

Table 2: Comparison of water rates for San Diego consumers in 2015 and 2020 after the inclusion of desalinated water into the municipal supply.

	2015	2020
Monthly Base Fee	$20.31	$29.46
Commodity Rate per hcf for the first 4 hcf (Tier 1)	$15.58	$21.54
Commodity Rater per hcf for the next 8 hcf (Tier 2)	$34.91	$48.25
Total Annual Cost	$849.67	$1,190.98
Percent Increase from 2015	0%	40%

Potential Effects of Increased Price on Water Consumption

While the substantial increase in prices, largely due to the new desalination plant, is clearly not an appealing prospect for water utility customers, it does not imply that the policy decision to build a plant – or even to undertake other alternative policy options – is a poor one. In fact, an increase in price alone can spur water conservation simply through mechanisms of supply and demand. When supply decreases but demand remains the same, the price ought to increase. However, in California, water prices are fixed significantly below this point. By keeping water artificially inexpensive, consumers do not feel any pressure to conserve (McArdle, 2015); they plant green lawns in the desert and let water flow while brushing their teeth, but give no thought to this waste because they are shielded from incurring its full burden.

Examination of the price elasticity of demand for residential water use in California suggests that the resource's demand is relatively inelastic; consumers are unlikely to significantly decrease their water consumption due to an increase in price (Dale et. al., 2009). While this suggests that price increases should be coupled with non-price based conservation initiatives, there still exist some benefits to raising the price of water relative to alternative policy mechanisms (Dale et. al., 2009). By allowing the price of water to better represent its true scarcity value given by supply and demand, consumers would be allowed the freedom to choose their methods of conservation based on personal utility functions (McArdle, 2015). For example, a consumer may find greater value in maintaining a small vegetable garden rather than washing clothes as frequently, or vice versa; either way, he is allowed the opportunity to conserve based on personal preferences. This freedom is not always possible when the price is kept low and mandated restrictions are imposed. In this scenario, certain conservation methods are enforced, regardless of consumers' desires.[6] While restrictions are at times unavoidable, they may not be the best solution when the option of allowing prices to increase and thereby dictate consumption remains available and relatively unexplored. If California were to raise water prices as one of its many conservation strategies, the state could see significant, voluntary reductions in consumption that could reduce the need for government regulation in an efficient and simple manner.

Desalination and the Environment

While the high costs associated with desalinated water are one area of dissatisfaction with the technology, its impact on the surrounding environment is another contested issue. Concern regarding environmental harm generally focuses on three areas of the desalination process: the intake, the effluent, and the carbon footprint. Despite screens that cover the intake pipes, where water is drawn from the ocean and conveyed to the plant, marine organisms too large to pass through are pulled against it and frequently killed in a process known as impingement (Cooley et al, 2013). Those organisms small enough to pass through are invariably killed during the water processing. The plants' effluent also poses hazards to the marine environment as the highly concentrated salt brine mixed with other chemicals from the plant is poured into the nearby ocean and estuaries. Because its density is even much greater than seawater, the brine sinks to the ocean floor and spreads to depths where little wave action can occur to facilitate mixing. Little is known about the long term effects this solution may have on marine and estuary environments. Fossil fuel combustion to power the plants raises a number of concerns as

[6] Given that water is essential to life, any price increase could not be prohibitive to the poor. If prices were allowed to rise, a set amount of water could be sold at a lower than market rate, allowing access to those for whom any price increase would be disastrous.

well. In a time when greenhouse gas emissions must be significantly reduced worldwide, increased use of such an energy intensive water supply process has caused a great deal of opposition to the technology.

Despite these concerns, California appears to be launching desalination as its strategy of choice. In preparation for the state's increase in desalinated water supply, the California legislature adopted rules in May 2015 that facilitate construction of plants, but also minimize harm to aquatic ecosystems (Fimrite, 2015). One rule requires desalination intake to occur subsurface, or below the seafloor, whenever possible, thus lessening risk of impingement. Another limits the salinity of outflow, requiring plants to dilute the effluent with treated wastewater prior to releasing it (Fimrite, 2015). These policies are the first steps in California's march towards widespread desalination usage. Although they do attempt to mitigate environmental damages, the harms associated with this technology are still present and should be carefully considered when making decisions about a plant's construction and use.

Despite desalination's appeal as a stable water supply mechanism, its high construction and operational costs, significant indirect water consumption associated with its energy requirements, and numerous environmental concerns all suggest that desalination might not in face be the silver bullet strategy California policymakers so desperately seek. Other less costly and potentially more successful means of increasing the state's effective water supply are available, and should be given adequate consideration before the state commits to widespread implementation of desalination infrastructure.

<u>Residential Energy Efficiency Improvements: Hot Water Heaters</u>

Given the amount of indirect water lost through consumption of electricity, improved energy efficiency represents a potentially significant source of reduction in water demand. There are opportunities for improving energy efficiency in all sectors, but in this section, I am going to focus on residential energy consumption.

Nationwide, space heating/cooling is the single largest residential use of electricity, accounting for approximately 47% of home energy expenditures (US Energy Information Administration, 2009). The second largest source of residential electricity demand is water heating (US Energy Information Administration, 2009). Using on average 18% of a US household's energy, the hot water heater represents a significant power consumer (US Energy Information Administration, 2009). In California in particular, because home heating and cooling demands are lower than the US average, water heating takes up even more of the residential energy pie, accounting for 25% of home energy consumption, only 6 percentage points less than heating/cooling (US Energy Information Administration, 2009).

Options for Water Heater Technology

Given recent energy efficiency improvements in water heater technology, significant electrical energy savings, and therefore reductions in indirect water consumption, can be attained if inefficient "standard models" are replaced with newer water heaters. Standard electric storage hot water heaters are the most common type of home water heating system (US Department of Energy, 2016). This type has a tank with a capacity ranging from 20 to 80 gallons of water that is kept at a constant temperature, ready for use at a moment's notice. These heaters use electric-resistance heat, in which an electric current flows through an element of high electrical resistance, converting that electricity directly into heat, which is then transferred to the water (US Department of Energy, 2016). In these systems water is released from the top of the tank when a faucet or other use is engaged, and is replaced at the bottom by cold water to ensure a full tank and steady supply of hot water (US Department of Energy, 2016).

While capable of supplying large quantities of hot water, the standard models are highly energy intensive. Programed to maintain a certain temperature, they constantly heat water – even when the tap is not running – and thus constantly consume energy. In addition to the electric input required to simply maintain the water temperature, the water entering the tank to replace the hot water leaving is cold, requiring additional energy to reach the set point temperature (US Department of Energy, 2016). While some of these losses can be lessened through better insulation and subsequent heat retention, nevertheless the need for constant energy input results in high electricity requirements for standard models.

A number of alternatives to the standard electric storage water heaters exist, all of which consume less energy and thus yield monetary and water savings.[7] Tankless and other demand-type heaters heat water only as it is used, removing the need for a tank and the energy consumption that comes with it. As water moves to the faucet, it passes through an electric unit that heats the water before reaching the tap, providing hot water

[7] Of note: In this comparison of various hot water heaters, I only include electric models. This paper focuses on the connection between water supply and electricity, and although the majority of California homes use natural gas to power their hot water heaters, a comprehensive calculation of the indirect water costs of that power source was outside the scope of this paper. Due to the currently low price of gas, homeowners may be tempted to switch to natural gas-powered hot water heaters. However, from an environmental perspective, natural gas use can result in significant water consumption and environmental damage, and may not ultimately represent a beneficial switch.

with between 8% and 34% greater efficiency than a standard electric storage model (US Department of Energy, 2016). Although tankless and other demand-type water heaters are far more energy efficient, they do not provide as much hot water as quickly as a standard model; this is their disadvantage relative to an electric storage water heater. Solar is another type of hot water heater that provides significant energy savings when compared to standard electric storage tanks. The numerous options for solar heating allow for flexibility while working approximately 50% more efficiently than conventional heaters (US Department of Energy, 2016). Though also more cost effective than a standard model when considering annual energy consumption, these heaters have significantly greater initial installation costs, and this has limited their market penetration (US Department of Energy, 2016).

Of all the alternatives to conventional electric storage water heaters, the heat pump water heater (HPWH) technology is the most energy and cost effective, reaching efficiencies two to three times those of standard electric models (US Department of Energy, 2016). These water heaters achieve this degree of efficiency by using electricity to transfer heat rather than create it (US Department of Energy, 2016). They work like a refrigerator in reverse, pulling heat from the ambient air into the tank where a refrigerant fluid is alternately condensed and evaporated in a closed loop (Wilson, 2012). The phase changes of the refrigerant capture and release the energy, thereby transferring heat from the air outside into the tank's water (Wilson, 2012). Because of their use of ambient air, HPWHs are most efficient in warm environments, and because of the mechanism by which they heat water, they also provide indirect benefits to the homes in which they are located. By pulling in the warm air, HPWHs dehumidify their surroundings, reducing or eliminating the need for a dehumidifier and thus saving energy (US Department of Energy, 2016). They also expel cool air as a byproduct of the heat transfer, which in warmer regions, such as southern California, may even help to reduce the amount of energy used to cool homes, saving even more energy, and indirectly, water (US Department of Energy, 2016). Because they do withdraw heat from the ambient air, HPWHs may necessitate increased home heating requirements in the winter; however, in regions such as southern California, there exist few times in which this should pose a serious tax on the heating system. By using electricity to move heat from the ambient air to the water as opposed to creating heat itself, heat pump water heaters are far more energy efficient than standard models and provide significant indirect water savings potential.

Heat pump water heaters are not without their disadvantages. Because of their mode of heat transfer, HPWHs require at least 1,000 cubic feet of air space around them (US Department of Energy, 2016). Given this space constraint, not every home may be able to take advantage of this technology. They also produce more noise than other types of water heaters; however, given their need for space many HPWHs are placed in basements or garages, limiting the extent to which the noise is heard (Wilson, 2012). Finally, the rate at which they produce hot water falls short in comparison to standard models. While a conventional storage hot water heater can heat 20 gallons of water an hour, a HPWH, with current technology, can only heat approximately 8 gallons per hour (Shapiro et al, 2012). With a large tank this difference in rates would be minimized; however if demand is high or a large tank is infeasible, at times a heat pump water heater alone may not be sufficient.

To accommodate for their slower rates of production, current HPWHs are designed with hybrid capabilities. In the event of high demand, HPWHs can switch into electric-resistance mode, the same heating method used by conventional water heaters, combined with continued heat pumping (Shapiro et al, 2012). This produces greater quantities of hot water, although at reduced efficiency, so when demand is met the water heater reverts back to heat pump only mode (Shapiro et al, 2012). This feature allows for flexibility and is beneficial not only in times of high demand, but also if the ambient air is too cold to be effective for heat transfer or if there is a malfunction with the heat pump. Although they consume more electricity during these occasions when they operate as electric resistance water heaters, the hybrid heat pump and electric-resistance heating capabilities ensure continued hot water supply.

Comparison of Water Consumption, Energy Intensity, and Costs

The cost, energy, and indirect water savings of HPWHs when compared to standard electric models are significant. On average, a standard model's annual energy consumption equals approximately 4,857 kWh per year (Energy Star, 2008).[8] With an expected lifetime of 13 years, average annual cost of operation $505, and initial installed cost of $650, the annual total direct financial cost for a standard electric hot water heater is approximately $555 (Energy Star, 2008). For a HPWH, the average annual energy consumption equals 2,195 kWh per year (Energy Star, 2008). With a life expectancy of ten years, average annual cost of operation $228, and initial installed cost of approximately $1,500, the annual total direct financial cost for a heat pump water heater

[8] I recognize that this study is some years out of date; however, I could not find any more recent studies on the comparative costs.

equals approximately $378 (Energy Star, 2008).[9] Despite the higher installed costs, the HPWH's total annual direct financial costs are approximately $177 less than a standard model's because of the significantly lower energy requirements. When we take indirect water consumption into account, the HPWH appears even better by comparison. Considering its annual kWh requirements and the 4.64 gallons of water per kWh consumed indirectly through the energy production process, a standard water heater in California consumes 22,536.48 gallons of water per year. HPWHs in contrast require only 10,184.80 gallons of indirect water consumption per year, approximately 12,351.68 gallons per year fewer than a standard model. Thus, a HPWH not only saves money, but water as well. This offers a win-win opportunity for California. Table 3 below compares the standard and heat pump water heaters.

Table 3: Comparison of the annual energy and water consumptions and costs of standard and heat pump water heaters. As seen below, the HPWH consumes less water and energy, and has a lower direct financial cost, making it an overall beneficial option.

	Standard Water Heater	Heat Pump Water Heater
Annual Energy Consumption	4857 kWh	2195 kWh
Annual Direct Financial Cost	$555	$378
Annual Indirect Water Consumption	22,536.48 gallons	10,184.80 gallons

In California, approximately two million homes power their hot water heaters with electricity, the vast majority of which are standard models (US Energy Information Administration, 2009). If even half of these homes were to switch to a HPWH, annual indirect water savings would total 12,352 million gallons per year. The Carlsbad desalination plant – factoring in the water lost through its energy requirements – produces

[9] Of note: these calculations are based on DOE test procedure and calculations that assume inlet water temperature of 58 degrees Fahrenheit, maintenance temperature of 135 degrees Fahrenheit, daily hot water demand of 64.3 gallons, 365 days per year of use, and energy costs of $0.104 per kWh.

17,092 million gallons per year: only 4,740 million gallons more annually. While this difference is enough water to supply approximately 29,000 homes for a year, it comes with an annual price tag of $54 million in operation costs alone. By contrast, the replacement of one million standard electric-resistance models with HPWHs would generate $17.7 million in savings each year. This switch in water heater technology would save California water, energy, and money, making it an attractive option with few drawbacks.

Water Heater Standards and Regulations

Historically, HPWHs faced significant difficulties in entering the market, largely due to their significantly higher initial cost. The first HPWHs were developed in the 1950's, but because of reliability issues and the low energy costs of the time, they generated little demand (Pacific Northwest National Laboratory, 2015). Energy prices rose in the 1970's, spurring a revival of research and development of the technology, but, before the models reached the market, energy prices fell, bringing HPWH demand down with them (Pacific Northwest National Laboratory, 2015). In recent years, rising energy costs as well as increased awareness of carbon emissions have again spurred the development of this technology. The values used in the above cost and efficiency calculations originate from a 2008 Energy Star assessment of available technologies conducted in preparation for the first-ever hot water heater standards, effective January 1, 2009. Under the Energy Star criteria, conventional electric-resistance storage tanks were not eligible for Energy Star qualification (Energy Star, 2009). HPWHs were included among the qualifying products, motivating many large manufacturers such as GE to begin developing HPWHs, rendering the technology more accessible and recognizable with brand name companies and Energy Star labels.

The Energy Star standards are based on a water heater's energy factor (EF), the efficiency metric calculated based on the amount of hot water produced per unit of fuel consumed. It takes into account three additional factors: recovery energy, or how efficiently heat is transferred to the water; standby losses, or the percentage of heat lost from the tank per hour; and cycling losses, or the loss of heat as water moves through the tank or pipes (US Department of Energy, 2015). Standard electric models typically have EF of approximately .9-.95 (Energy Star, 2008). For HPWHs, the initial standards were set with EF greater than or equal to 2.0, a value typical of almost all HPWHs. In April 2015 Energy Star updated its hot water heater guidelines. The new standards distinguished between large and small tanks, requiring EF of greater than or equal to 2.00 for tanks 55 gallons or less, and EF of greater than or equal to 2.20 for tanks greater than 55 gallons (Energy Star, 2015). As with the 2009 standards, these energy factors are minimum requirements for any electric storage water heater, and because HPWHs are the only type that can attain energy factors that high, the label effectively pushes manufacturers towards this more efficient type, driving supply, which will likely stimulate consumer demand.

In addition to the increase in the Energy Star label's efficiency standards, in August 2015 the Department of Energy updated the federal hot water heater standards from the previous 2004 criteria. In 2004 all electric storage water heaters, under which conventional and HPWHs fall, had a minimum EF equal to .97 – (0.00132 x tank volume) (US Department of Energy, 2015). Under the new mandate, electric storage water heaters with tank volume of 55 gallons or less must have EF equal to .96 – (0.0003 x tank volume), while heaters with tank volumes of greater than 55 gallons must have EF equal to 2.057 – (.00113 x tank volume) (US Department of Energy, 2015). While the standards remained approximately the same for smaller heaters, the mandate renders it impossible to meet the standards for large heaters with anything but a HPWH. Historically, heat pump water heaters have faced challenges with market penetration. But with Energy Star certification only possible for HPWH and increased federal standards for large water heaters, many incentives now exist for manufacturers to produce HPWH en mass.

Given that the mandates effectively force the purchase of HPWH, at least for large tanks, the government has implemented a number of incentives to help homeowners with the initial costs and speed the market rate of installation. Throughout California utility companies are offering for the purchase of a HPWH. For example, PG&E, a large energy provider in the state, is currently offering a $500 rebate for purchase of this type of heater if it is made in 2016. In addition, there is a federal tax credit of $300 for heat pump water heaters purchased this year. These incentives could significantly reduce the initial installed costs associated with the technology and make the product a less burdensome investment for California homeowners.

While progress has been made in the energy efficiency of water heaters and HPWH are lauded for their energy and money saving effects, little to none is being said about the effect of these savings on water supply. Given the residential water restrictions throughout the state and the significant push towards increasing the effective water supply through conservation means such as showering less and allowing lawns to brown, it would seem that California residents and policymakers should take advantage of water saving opportunities such as this that do not come with an overall cost, but instead a net savings. If the state reimbursed the installation costs of these water heaters or at least covered the difference in price between heat pump and standard models, they would not only save water, but would do so in a way that also benefited their constituents. While brown lawns, fewer showers, and higher water bills to cover the costs of desalination plants may be necessary to ensure adequate water supply for the state, other options that provide net benefits should be fully pursued first.

Evaporative Loss Mitigation: Aquatain

Gains in household energy efficiency are not the only means of increasing the effective water supply; other improvements to water use efficiency can also yield significant savings. Important gains in water conservation are available through improvements in the efficiency of water use, storage, and distribution. Improvements can be made throughout water's supply chain, including minimization of evaporative losses in reservoirs, reduction of leaks in municipal pipe delivery systems, and increased development and use of wastewater recycling. In the dry California climate, evaporative losses from bodies of water exposed to the air are significant, and water storage or transportation infrastructure that exposes water to the ambient air likely loses a significant amount of water to evaporation. While this water vapor is not gone in the context of the global hydrologic cycle, it is lost to local water users.

Evaporation Reduction Strategies in New Infrastructure

As California designs and invests in new infrastructure with greater awareness of the diminishing water sources available, it can do a great deal to minimize evaporative losses. Reservoirs can be built deeper so as to hold large amounts of water but with reduced surface areas, thus decreasing sun and wind exposure, both of which contribute to evaporation. Vegetation to shade the reservoir perimeter as well as wind barriers can also be incorporated in designs to combat evaporative loss. Aqueducts can also benefit from modified designs; while typically open to the air, by covering or enclosing the water, significant amounts of evaporative loss can be prevented. While this construction would require more building supplies than a typical aqueduct, it would reduce ambient exposure and subsequent losses. As engineers and urban planners continue to develop water-related infrastructure, they can mitigate evaporative losses in their designs and thereby increase the effective supply of water.

Evaporation Reduction Strategies in Existing Infrastructure

California already possesses a significant amount of legacy water supply infrastructure that would be too difficult or costly to retrofit with large, infrastructural modifications. Thus, alternative methods of reducing evaporative losses must be developed. One promising solution is Aquatain. This liquid, comprised of mostly silicone polymers, spreads across surfaces of bodies of water and forms a clear, thin layer that inhibits evaporation. Originally designed as a mosquito control mechanism, polydimethylsiloxane – the primary silicone polymer in the substance – has a significantly lower surface tension than the water it covers (Green Flow, 2013). By decreasing surface tension, two critical stages of the mosquito lifecycle are disrupted, successfully eliminating their propagation. Researchers subsequently realized that their silicone polymer product, with its ability to effectively spread across surfaces of water, could also serve to reduce evaporation rates. Because one of the characteristics of silicones is their permeability to vapor, the product as originally formulated was ineffective at preventing evaporation (Strachan, 2016). However when additional polymers were added to the product, sealing the polydimethylsiloxane's silicone lattice, it achieved evaporation savings of approximately 50% (Strachan, 2016) (Aquatain, 2016). By preventing gas exchange and thus inhibiting production of water vapor, the polymer layer effectively keeps water in its liquid state and accessible to consumers.

While it has not yet been applied in a large-scale project, calculations of Aquatain's potential effect on bodies of water in the western United States are encouraging. A 2012 proposal to the US Bureau of Reclamation outlined the case for using Aquatain on the entirety of Lake Mead in order to decrease the amount of evaporative loss experienced there each year. Located in southern Nevada, Lake Mead has been an exemplar of effects of the ongoing drought on standing bodies of water. The reservoir loses approximately 293,265 million gallons each year to evaporation – a 7.5-foot annual drop in the surface of the lake – and while at capacity it has a surface area of 160,000 acres, recently that average has fallen to only 125,600 acres (US Bureau of Reclamation, 2012). Using this value in its calculations' assumptions, the 2012 proposal found that to effectively cover the lake and maintain the polymer layer's integrity, 10,000 gallons of Aquatain would need to be applied every ten days, or approximately 36.5 times a year (US Bureau of Reclamation, 2012). In compiling the costs of doing so, the proposal included the capital, operations, repair, and replacement requirements for each of two airplanes that would apply the product, gasoline for the planes, purchase of Aquatain, payment for the two pilots, and costs of monitoring and reporting on conditions of the lake (US Bureau of Reclamation, 2012). Over a fifty-year period, total costs would be $1,846,000,000 (US Bureau of Reclamation, 2012). This amount is not insignificant; however, given the long time frame, high potential for water savings, and large costs associated with other water supply mechanisms, it is not prohibitive.

Because Aquatain's exact efficacy is unknown, as is the exact amount of evaporative loss from Lake Mead each year, a sensitivity analysis provides a range of values by which to evaluate the product. To find the upper limit, the evaporative loss value is taken to be 305,485 million gallons per year, the average annual evaporative loss over the past fifty years at Lake Mead. An efficacy rate of 50% is also used, which is the amount the company claims the product saves (Aquatain, 2016). Given these values, 152,743 million gallons per year are saved. Assuming the costs outlined in the proposal, the cost per million gallons of water saved using Aquatain is $241.71.

For a more conservative estimate, I assume 260,680 million gallons per year as the estimate of annual evaporative loss, and 30% as the reduction in evaporative loss, significantly less effective water retention (US Bureau of Reclamation, 2012). With these values, Aquatain would keep approximately 78,204 million gallons per year in Lake Mead. In this case, again assuming the proposal's costs, the cost per million gallons of water saved using Aquatain is $472.10. Although this cost is approximately double that achieved using Aquatain's upper limit of efficacy, both values fall far below the costs per million gallons of water pumped through the State Water Project or from desalination. Additionally, while this proposal does use values from Lake Mead in Nevada, similar reservoirs exist throughout California and would likely result in similar predictions of decreased evaporative losses. A comparison of the upper level and conservative estimates of Aquatain for evaporation reduction is in Table 5 below.

Table 5: Sensitivity analysis determining the upper and lower levels of savings that could be reasonably expected through use of Aquatain on Lake Mead.

	Upper Limit of Effectiveness	Lower Limit of Effectiveness
Annual Evaporative Loss	305,485 million gallons	260,680 million gallons
Percentage Efficacy of Aquatain	50%	30%
Amount of Water Saved	152,473 million gallons	78,204 million gallons
Cost per Million Gallons Saved	$241.71	$472.10

Not only are the costs associated with this product and its application attractively low, the amount of total water saved is also significant. With conservative estimates, Lake Mead is projected to retain 78,204 million gallons per year that would otherwise evaporate. The Carlsbad desalination plant produces approximately 18,250 million gallons per year, only 23.3% of the amount that might be saved from evaporation at Lake Mead. This value for desalination also does not take into account the indirect water lost in the production of energy used at the Carlsbad plant. Factoring in the approximately 1.3 million gallons per day indirectly consumed by the plant, the net annual production of the Carlsbad plant totals approximately 17,092 million gallons per year, 21.9% of Aquatain's savings at Lake Mead. Because Aquatain does not require any significant electric input in its application, a similar adjustment for indirect water consumption is unnecessary. Thus both the amount of water added to the accessible supply and the cost per unit to provide it achieved through decreasing evaporative losses with Aquatain appear to be superior to at least some alternatives in use or under consideration. The comparison above is of a single – albeit expansive – reservoir with the largest desalination plant in the western hemisphere, one with state-of-the-art efficiency: if Aquatain were applied on a wide array of California reservoirs, pools, ponds, and lakes, its impact on the state's water supply could be even greater.

Aquatain and the Environment

Aquatain appears to represent an appealing option for increasing total accessible water supply in California; however, not a great deal is known about its potential environmental or ecosystem effects. Several studies have been conducted on various aspects of the product, from its manufacturing process to its degradation in the environment. According to the company that produces Aquatain, the silicones that comprise the product are used in a variety of other common applications, including cosmetics and food (Aquatain, 2016). The company also claims that silicones degrade in the environment into harmless silicates that do not bioaccumulate, and cause no significant concerns in a number of toxicity studies (Aquatain, 2015). Perhaps more compelling, in 2009 the National Science Foundation International tested the product for toxicity and harmful effects in drinking water; Aquatain passed, allowing its use on drinking water sources in the United States (Green Flow, 2013).[10]

While these findings are comforting, they do not necessarily mean that Aquatain is entirely without negative effects on aquatic ecosystems and organisms. It does not appear that any significantly scaled studies have been conducted in the field. These would prove helpful to test for any harmful and unexpected effects on aquatic ecosystems or species, especially given the original product's goal of disrupting the mosquito lifecycle. Given silicones' greatly reduced surface tension, mosquitos cannot survive in treated bodies of water. However it would seem that mosquitos are not the only organisms that

[10] Of note: "This standard established minimum requirements for chemicals, the chemical contaminants, and impurities that are added to drinking water from drinking water treatment chemicals. Contaminants produced as by-products through reaction of the treatment chemical with a constituent of the drinking water are not covered by this standard." Thus any byproducts of Aquatain are not covered in this assessment.

benefit from the high surface tension of water. While this product is an effective means of combatting malarial or Zika fever vector propagation, non-target species may also suffer as a result.

In addition, the product is described as "produced from polymers which are highly impermeable to gasses including water vapor" (Strachan, 2016). This inhibition of the transfer of gasses is what renders Aquatain so effective at reducing evaporative loss. However, it seems as though reducing the exchange of gases, including oxygen, could negatively affect the health and functioning of aquatic ecosystems that exist in or near the treated body of water. Furthermore, with limited evaporation and release of water vapor comes limited heat transfer from water to air, inhibiting the exchange up to 15-20% (Aquatain, 2016). The subsequent increase in water temperature may negatively affect ecosystems or their constituents, especially those that exist primarily near the surface where water temperatures are highest. It is worth noting however, that reduced depth of streams, rivers, lakes, and other bodies of water due to evaporation *also* contributes to increased water temperature, and thus can also result in ecosystem damages. An examination of the differences in water temperature under each of these scenarios, and their relative impacts on the aquatic ecosystems therein, is necessary.

Given these concerns and lack of substantial field study, the precautionary principle may be warranted. In bodies of water that do not support aquatic life, such as swimming pools, use of the product may be a beneficial and seemingly safe means of saving water. However, caution must be taken when considering widespread implementation of Aquatain. With the high potential for gains to the effective supply of water but also high possibility of environmental harm, it would be worthwhile for

California to fund research designed to determine the likely extent of Aquatain's environmental harm. This study would provide improved information for policy makers regarding whether or not, where, or how often to use Aquatain in California.

Areas of Further Study

Beyond hot water heaters and Aquatain, there exist a number of additional areas of water and energy use that may prove to be cost effective means of increasing effective water supply. Household water conservation practices, if applied at a large scale, could provide substantive improvements in efficiency. For example, clothes washers comprise approximately 17.5% of a home's direct water usage. Models manufactured prior to 2003 are significantly less efficient than newer models, especially those with Energy Star certification. If replacement of older models occurred, similar to the hot water heater example, significant increases in efficiency may be found. Improvements beyond the home could also lead to increases in the overall water supply. Leaks in municipal pipe systems lead to losses of on average 6% to 15% of the water they carry, resulting in decreased delivery as well as increased energy requirements necessary to maintain water pressure in the pipes. While overhauls of municipal pipe systems are expensive and losses can only be reduced, not eliminated, improved efficiency of these transport systems has the potential to increase the state's effective water supply. As California continues to develop its water supply management strategies and creates a more diversified water portfolio, taking these potential efficiency improvements into consideration may reveal cost effective means of improving supply to California consumers.

Conclusions

Southern California's primary water supply mechanism is the State Water Project, providing a net amount of approximately 719,700 million gallons of water each year at a cost of $1,250 per million gallons. While the SWP has been effective throughout its lifetime, it does have a few drawbacks, namely its high energy intensity, as well as its dependence on average levels of precipitation to provide water to its many users. As periods of drought increase in frequency and severity, California policymakers have begun exploring alternative options to help alleviate stress on the SWP and ensure greater water security. These decision makers appear to have selected desalination as their primary approach, bringing mothballed facilities back online and constructing new plants as well. With wide ranges of production volume, desalination technology provides a reliable source of water, but at a cost. In the new Carlsbad plant, large energy requirements and debt amortization render the price of water much higher than other sources. While it produces a significant net amount of 17,092 million gallons of water each year, it comes at a cost of $6,540 to $7,264 per million gallons.

The results of my research suggest that California should consider addressing its water supply and demand through means other than desalination, given that a number of these alternative methods increase the effective water supply with significantly fewer costs. On Lake Mead alone, Aquatain could save from 78,204 to 152,473 million gallons each year from evaporative loss at a cost of only $241.71 to $472.10 annually per million gallons. This option, if applied on a large scale in California, could lead to significant reductions in evaporative losses and provide the state with large amounts of water it would have otherwise lost as vapor. If, in the end, environmental concerns rule out widespread application of Aquatain, there remain other alternatives to desalination to explore. Some of these alternatives involve straightforward residential consumer behavioral changes, such as taking shorter showers or watering lawns more efficiently, which would directly reduce water consumption. Efforts to reduce leakage in water distribution would similarly result in direct decreases in water consumption.

The energy-water nexus suggests that opportunities for *indirect* reductions in water use exist as well. Energy efficiency improvements can increase effective water supply, reduce fossil fuel consumption, and actually save money. By replacing just one million standard electric water heaters with heat pump models, a net amount of 12,352 million gallons of water could be saved annually, with energy savings of 2.662 billion kWh per year and monetary savings of $17.7 million annually. This action would benefit all, especially if the available state and federal rebates were provided to their full extent. As California continues to develop a robust water supply portfolio, policymakers must not neglect the interconnectedness of water supply and energy production as a significant opportunity for savings.

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Appendix A: Glossary of Terms from the US Geological Survey

Consumptive Use (or Water Consumption)	"That part of water withdrawn that is evaporated, transpired by plants, incorporated into products or crops, consumed by humans or livestock, or otherwise removed from the immediate water environment."
Domestic or Residential Water Use	"Water used for household purposes, such as drinking, food preparation, bathing, washing clothes, dishes, and dogs, flushing toilets, and watering lawns and gardens."
Freshwater	"Water that contains less than 1,000 milligrams per liter (mg/L) of dissolved solids; generally, more than 500 mg/L of dissolved solids is undesirable for drinking and many industrial uses."
Hydrologic Cycle	"The cyclic transfer of water vapor from the Earth's surface via evapotranspiration into the atmosphere, from the atmosphere via precipitation back to earth, and through runoff into streams, rivers, and lakes, and ultimately into the oceans."
Kilowatt Hour	"A power demand of 1,000 watts for one hour"
Water Use	"Water that is used for a specific purpose, such as for domestic use, irrigation, or industrial processing. Water use pertains to human's interaction with and influence on the hydrologic cycle, and includes elements, such as water withdrawal from surface- and groundwater sources, water delivery to homes and businesses, consumptive use of water, water released from wastewater-treatment plants, water returned to the environment, and instream uses, such as using water to produce hydroelectric power."
Water Withdrawal	"Water removed from a ground- or surface-water source for use."

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