ELIMINATING WATER SCARCITY IN SAN DIEGO COUNTY

By

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ABSTRACT OF THE THESIS

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Due to climate change, semi-arid regions like San Diego County in Southern California will see more frequent and extreme drought events. An increasing demand for water combined with a decreasing amount of available water supply could lead to stress on the freshwater resource in this region. Alternative sources of water will be needed to supply the necessary water to the region. San Diego County is a region that is already using desalination technology and recycled water. Unless desalination and recycled water start supplying an increased share of water to San Diego County, the area will not be able to sustain its inhabitants going forward. Desalinated water should be allocated to the residential sector to supply most of the direct consumption; this will free up freshwater sources for the agriculture sector. The agriculture sector should utilize recycled water at capacity, and then be supplemented by the freshwater sources. By using a water allocation model to calculate economic surplus both with and without alternative water sources, this thesis will show that desalination and recycled water will create diversification in the water portfolio for San Diego County, eliminating the water scarcity issue.

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Chapter 1: Introduction

The effects of climate change are expected to have a significant impact on water availability throughout the world, especially for regions already experiencing water supply stress. Coastal communities typically have high population densities, high population growth rates, growing demand for water, and scarce surface and freshwater resources (Mo, Wang, & Zimmerman, 2014; Tarroja et al., 2014). Due to climate change, these coastal areas are expected to experience less precipitation. This could lead to water scarcity in these vulnerable regions. Finding a solution to the issue of water scarcity will mean looking to alternative sources of water because the current supply is under stress. With 80% of the global population living near the coastal area (within 60 miles of the coast) and 97% of the total water on earth having an average 3.5% salinity content, finding a solution to water scarcity means utilizing the most abundant source of water on the planet: salt-water ("Desalination," 2015).

Semi-arid coastal regions like San Diego County are especially at risk of water scarcity. The quantity of water demanded in San Diego County will only increase with population growth in the region, the increase in standard of living, and the growing agricultural and industrial industries (Khawaji, Kutubkhanah, & Wie, 2008). This increasing demand for water resources combined with a decreasing amount of available water supply will result in the water resource becoming more and more stressed. We can define water scarcity as, "… a lack of access to, or unavailability of, sufficient, clean, affordable, and reliable potable water and sanitation" (Gerlak & Wilder, 2012; Jamie McEvoy, 2014). Amidst the threat of water scarcity, San Diego County is currently working towards a water secure future. Water security can be defined as, "… the sustainable availability of adequate quantities and qualities of water for resilient societies and ecosystems in the face of uncertain global change" (Scott et al., 2013). Achieving water security means meeting the following targets: basic human needs; food security; conserving and preserving ecosystems; sharing the resource; managing risk; valuing water; and managing water properly (Savenije & Van der Zaag, 2008). In order to adapt to an uncertain future, water management is key (Jamie McEvoy, 2014). Properly allocating the alternative water resources in the region is a priority that needs to be addressed.

There is a need now, more than ever, to efficiently use water resources in this region. The focus of this paper will not be mitigation efforts for climate change - instead, it will focus on adaptation methods. There are multiple options available to adapt to the changing climate, which can be broken down into demand-side approaches and supply-side approaches. Southern California has been utilizing demand-side approaches for a few years by setting restrictions on water uses. Despite the decreasing trend in per-capita water use, water is still a stressed resource throughout the region. There is a threshold to the amount that people can reduce their consumption and use. This limitation, coupled with rapid population growth and an agriculture sector heavily dependent on water, will create even more pressure on the water resource.

Despite water conservation efforts, the competition for water use amongst water scarcity conditions will deem existing sources unable to supply sufficient water to the region. The only water supplier SDCWA (San Diego County Water Authority) imports about 90% of San Diego's water supply from the Colorado River Basin and from

Northern California (“Carlsbad Desalination Plant,” 2017). The rest comes from conservation efforts, recycled water, groundwater, surface water, and now desalination. Desalination is the removal of salt and other particles from sea, ocean, or brackish water.

Desalination is a fairly new technology utilized in San Diego County. The Carlsbad Desalination Facility was finished in December 2015 and is located next to the Encina Power Station about 35 miles north of the City of San Diego. It can provide 69,074,983.89 m^3 of clean drinking water per year, which is only enough for 400,000 people or about 12% of the total population of 3.3 million people in San Diego County. The population is projected to be over 4 million by 2050 (“Population Of San Diego County,” 2017). If the increased production of desalinated water becomes economically viable, then desalination could help mitigate the pressure on the water systems in San Diego County.

Agriculture, the energy sector, and ecosystems all rely on water in San Diego County, each for different uses. So, different types of source water can be used for different purposes. This paper positions that the optimal use of desalinated water is for the residential sector because it is highly purified and the source is close to the end users. If desalinated water were to be used in the agriculture sector, minerals would need to be added to the desalinated water. The mineralization of desalinated water would increase the cost of water significantly. There is another solution for the agriculture sector, and that is recycled or reclaimed wastewater. Recycled water is already being used as a small share of the water supply in San Diego County for non-potable uses. Recycled water should be treated and transported at capacity for use in the agriculture sector because the nutrients in this water source are better suited for this sector. However, even at capacity, the quantity of recycled water in San Diego County will not be enough to meet the demand of the entire agriculture sector. But by using desalinated water in the residential sector, this will free up the freshwater resource for the agricultural sector located more inland in San Diego County. Unless desalination and recycled water are used to supply San Diego County with the necessary water it needs, the area will not be able to sustain its population going forward.

Although desalination has been utilized more widely in other areas in the world, such as Israel, San Diego County will be used as the case study in this thesis for many reasons. With almost 40% of U.S. citizens living on or near the coast, San Diego County is a good case study to review because water in Southern California has a local and national importance; the area is the second most concentrated metropolitan region in the U.S.; it is already experiencing water scarcity and has responded to this issue. San Diego County has expanded their supply of water by looking to desalination at the Carlsbad Desalination Facility as well as wastewater recycling to supply residents with water. Since this has already been established in this region, a better understanding of the implications of these technologies going forward will be explored in this paper.

Desalination and treated wastewater can be used together to help mitigate the water shortage and provide a reliable, local source of water for San Diego County. This paper will mathematically model the water markets in San Diego County and introduce desalination and recycled water into the water supply mix. It will show the optimal allocation of these two sources and show the policy implications, economic and environmental costs, and benefits. This paper states that the introduction and optimization of desalinated water will give sufficient supply of potable drinking water for San Diego

County residents because the water will be high-quality and the distance the water will be transported will not be far from the source, the Carlsbad Desalination Facility. Using treated wastewater for drinking water would be too expensive because of the additional purification treatments required, and it is not currently approved for direct consumption. However, the treated wastewater will be best used for agriculture because recycled water has more of the necessary nutrients needed for crop irrigation. The high-quality desalination water is not needed for irrigation purposes. These statements somewhat contradict Mo et al. (2014) to which this paper will respond. Mo et al (2014) compares the two different sources of alternative water and because of the energy intensity of the desalination process, concludes that using recycled water exclusively will solve the water scarcity issue. This thesis will differ by showing that using both desalination and recycled water simultaneously for different uses is the best allocation of the alternative sources of water. The reasons are that recycled water is limited by the capacity of wastewater generated in a region, recycled water needs further treatments and much higher costs to become drinking water quality, and that the size of the agriculture sector is small compared to the residential sector.

This thesis is organized as follows: Chapter 2 discusses the literature review and explains the process of reverse osmosis, the benefits and environmental costs of desalination and recycled water, how the climate is changing, and why there is a need for alternative water sources. Chapter 3 explores the water allocation model in detail, where we assume two end users, agricultural and residential sectors, with three water sources: freshwater, desalination, and treated wastewater. Chapter 4 shows the equilibrium outcome of the model. Chapter 5 describes the data and the calibration of the water allocation model. Chapter 6 reveals the results of the analysis and further makes a point that once desalination and recycled water are both added to the supply mix for San Diego County, the problem would no longer be a resource scarcity issue but rather a resource management issue. Chapter 7 is the policy discussion where managing the water supply and the policy implications will be discussed further. Chapter 8 is the conclusion and suggestions for further research.

Chapter 2: Literature review

2.1 Reverse Osmosis (RO) Technology

Desalination is the method of separating salts, minerals, and other particles from a water source (Commission & others, 2004). The types of water that can be used are: seawater, brackish water, recycled or reclaimed water, runoff water from agricultural uses, and others (Commission & others, 2004). The Pacific Ocean water along the coast of California has an average salinity of 32 to 34 ppt (parts per thousand) (Commission & others, 2004). Seawater typically has a lower salinity level than ocean water at a little over 20 ppt and brackish water has a salinity level of about 5 to 20 ppt (Commission & others, 2004). Brine is the super-saline solution that is left over from the desalination process that contains salts as well as chemicals from the pretreatment process (Fritzmann, Löwenberg, Wintgens, & Melin, 2007).

Thermal desalination was the original method of desalination but due to high energy costs, the switch to Reverse Osmosis (RO) technology happened in 1964 ("Desalination," 2015). The principle of osmosis is that molecules in a solvent (water) move from the less concentrated solution to a higher concentrated solution through a semi-permeable membrane ("Reverse Osmosis," 2017). During RO, a high-pressure force is exerted on the source water allowing the water to flow from high to low concentration through a semi-permeable membrane ("Desalination," 2015). This is very energy intensive, but not as much as thermal desalination. However, 40% of the world's desalination facilities use thermal technology (Anderson et al., 2008).

RO is the most prevalent desalination technology used today. The global water production capacity from desalination is 24.5 million m^3/day (Lattemann & Höpner, 2008). The first stage of the Carlsbad RO desalination process is pretreatment of the ocean water. The feed-water is pumped through filter tanks in layers of anthracite, sand, and gravel to remove algae, organic materials, and other particles from the feed-water (“Desalination,” 2015). The second stage is a secondary pretreatment of the feed-water to prevent the RO membranes from fouling (“Desalination,” 2015). Some typical chemicals involved are ferric chloride, sulfuric acid, anti-scalants, and sodium bisulfite (Khawaji et al., 2008). This stage involves microfiltration to remove smaller particles. After this stage, the only things left in the feed-water are salt and other minerals. RO is the third stage where over 2,000 pressure vessels with over 16,000 RO membranes catch the salts and minerals. The salt gets left behind membrane and freshwater is ready to go to the next stage of the process. During this process, one stream of freshwater goes on to become drinking water and another reject stream is the brine that gets diluted and put back into the Pacific Ocean via pipelines (Khawaji et al., 2008). Stage four of the process is the post-treatment where certain minerals are added back to the water and a disinfectant/chlorine further cleans the water. Stage five is when the water moves to product water storage tanks and travels about 10 miles to the SDCWA Second Aqueduct in San Marcos where the water blends with their supply and then can be delivered to the 3.3 million San Diego County residents in 24 water agencies (“Five steps to fresh, clean water,” 2017).

2.2 Negative Effects of Desalination

Because of the long distance traveled, importing water from the Colorado River to San Diego County is on average 50 times more energy intensive than supplying water to

Northern California (Fang, Newell, & Cousins, 2015). However, local sources of water can produce a large carbon footprint as well, depending on the energy intensity of the water processing, its location in relation to the end destination, and on the type of energy source used to power the facility (Fang et al., 2015). The treatment phase, distribution and transportation all play a role in the carbon footprint calculation. The Los Angeles Department of Water and Power (LADWP) and Inland Empire Utilities Agency (IEUA) were studied, and the IEUA desalination of water had a higher carbon footprint than recycled water; this is not surprising because the RO process for desalination to remove nitrates and suspended solids is a very energy intensive process (Fang et al., 2015). Some problems with this arise.

Desalination will also have negative consequences on the environment; this is discussed in the literature extensively. There will be a number of potential environmental impacts, both direct and indirect, from the desalination of seawater. A Red Brine Phenomena caused from ferric hydroxide used during the RO pretreatment stage may cause a red hue to the source water (Newlin, Jenkins, & Lund, 2000). The impingement and entrainment of ocean organisms caused by the desalination plant's intake of water may cause premature death of aquatic life and indirectly affect the local water's ecosystem. The initial impact of laying the pipes is temporary but has the potential to leave permanent damage (Einav, Harussi, & Perry, 2003). Public access, coastal resources, pollution, and overfishing are possible negative effects of using ocean water as the source for desalination (Einav et al., 2003). The coastal area where a desalination plant is located will turn into an industrial zone and most likely not be used for tourism or maritime recreation (Einav et al., 2003).

Adverse effects on land use may also occur (Einav et al., 2003). Impact on any aquifer may also occur if there is leakage from the desalination plant that seeps into the underground water (Einav et al., 2003). Noise pollution is another concern for any local businesses and residents (Einav et al., 2003). Noise from an RO plant can reach up to 90 decibels (Fritzmann et al., 2007). Locating the Carlsbad Desalination facility next to the Encina Power Plant means this power plant will need to provide the desalination facility with energy, thus increasing its energy output. The carbon footprint of desalination needs to be considered. The indirect effect of intensive energy use from the RO process may increase greenhouse gas (GHG) levels in the atmosphere (Einav et al., 2003). The release of more GHG emissions can worsen climate change (Fang et al., 2015). If climate change worsens, more drought events will occur, thus exacerbating the very problem that desalination was remedying.

The outfall of the discharge stream of brine solution back into the source water creates some adverse impacts. Chemical discharges of chlorine, ozone, other biocides, coagulants, acids, anti-scalants, and others that were used in the pretreatment process are mixed into the brine stream. Also, the brine solution is about twice the salinity concentration than the salinity of the source water (Commission & others, 2004). This could cause a number of unforeseen ramifications in the ocean ecosystem. Aquatic life nearby the discharge pipe will either need to adapt to higher salinity levels, move further away from the discharge pipe, or be killed by this higher salinity level.

2.3 Benefits of Desalination

Using desalination to supplement the water supply for San Diego County frees up the surface and groundwater resource for agricultural use. Because of the seemingly endless supply of ocean and sea water, desalination is seen as the drought-proof solution and acts as a hedge against water shortage (District, 2005). The quality of desalinated water is very pure, resulting in softer water, which is good for households and industrial uses (Einav et al., 2003). Newlin (2000) estimated an annual benefit from desalination of $1.1 billion per year for a normal wet-year and about $2 billion per year during a drought-year. There is also a reduced reliance on imported water and a more secure and abundant water source.

Job creation is another benefit of desalination. About 2,500 jobs were created and $350 million was spent during the construction of the Carlsbad Facility. And there is an estimated $50 million in annual spending for San Diego County that will be from the Carlsbad facility ("Carlsbad Desalination Plant," 2017). The next few sub-sections will discuss the other alternative water source, recycled water.

2.4 The Current State of Recycled Water in Society

Reclaimed water is defined as wastewater that is treated and purified for reuse in various non-potable water uses. Currently water reuse is being used in water stressed areas such as Japan, Australia, California and Florida for groundwater recharge (Leflaive, 2009). Southern Europe, Canada, and the U.S. are using water reuse for irrigation purposes (Leflaive, 2009). With shortages in the North East part of China, water reuse may become a major component of the water supply (Leflaive, 2009). The main determinants for water reuse are: increased demand, water shortage, affordability, practicality in regards to it being a local source, and the restrictions of public policy (Leflaive, 2009). In California, treated wastewater is used for agricultural irrigation (46%), landscape irrigation (21%), groundwater recharge (14%), and other uses (19%)

(Leflaive, 2009).

Regulation requires the use of an alternative pipe to be installed in buildings, which is a major cost component. Regulation also calls for high effluent standards for water reuse. Now may be a good time to build up infrastructure in certain areas for water recycling because the current pipe systems may need to be replaced or updated.

2.5 Benefits and Costs of Recycled Water

The following will be the benefits of water reuse for the environment: it reduces the demand for freshwater; diversifies the water supply; reduces GHG emissions; reduces amount of wastewater in the environment; increases ability to adapt to population and consumption changes. Treated wastewater also has lower salinity levels and will cause less damage to the environment and agriculture than using ocean water for agricultural irrigation (Einav et al., 2003).

Some downsides to water reuse are: the uncertain regulatory network that will assess water quality; any additional public costs for the projects; the issue with providing subsidies; and other concerns associated with the legal terms of decentralized infrastructure and tariffs (Leflaive, 2009). One of the biggest obstacles to overcome with water reuse is public acceptance of potable reuse. The water reuse in Australia, Europe, and the U.S. has been successful with indirect potable reuse where treated wastewater is put into a body of water before its potable use (Leflaive, 2009).

In San Diego, 5% of the water supply in 2015 came from recycled or reclaimed water. San Diego looks favorably upon water reuse and sees it as a part of its sustainable future ("Increasing San Diego County's Water Supply Reliability through Supply

Diversification," 2015; Leflaive, 2009). In San Diego County, the current approved uses for reclaimed water are for irrigating: parks, golf courses, landscaping, playgrounds, schoolyards, and other common areas ("Recycled Water," 2015). It can also be used for recreational purposes in certain bodies of water and for industrial uses ("Recycled Water," 2015).

2.6 Recycled Water and Desalination for a Sustainable Water Future

The willingness of water reuse adoption has been studied in many articles (Dolnicar & Schäfer, 2009). Water reuse for drinking and food preparation was rejected by more than 50% of respondents in Dolnicar and Schafer (2009) but is more accepted in irrigation and public space uses. In regards to price, there is no real consensus on how the price of freshwater and recycled water affects demand but Thomas and Syme (1988) found that prices of freshwater had little effect on treated wastewater adoption (Dolnicar & Schäfer, 2009; Thomas & Syme, 1988). Contrary to this, Marks et al (2003), Alhoumound et al. (2003), and Hurlimann and McKay (2007) all conclude that prices do matter. Quality and cost seem to be the major acceptance factors for water reuse (Alhumoud, Behbehani, & Abdullah, 2003; Dolnicar & Schäfer, 2009; Hurlimann & McKay, 2007; J. Marks, Cromar, Fallowfield, & Oemcke, 2003). There is a strong acceptance rate for using grey water (clean wastewater from clean household use) and storm-water for residential landscape purposes and for toilet use (Dolnicar & Schäfer, 2009; J. S. Marks, 2006). In contrast, fifty-two percent of respondents accept desalinated seawater for all water uses (Dolnicar & Schäfer, 2009; J. S. Marks, 2006).

Municipal wastewater is the main source of recycled water, which is part of the reason for its non-acceptance for reuse for drinking or food preparation (Dolnicar &

Schäfer, 2009). RO creates very high-quality water (Dolnicar & Schäfer, 2009). The quality of water from RO technology is typically better than most bottled water (Dolnicar & Schäfer, 2009). Seawater (>35 g/L), as source water for desalination, can contain hundreds the amount of dissolved solids than in municipal wastewater (0.1 to 1 g/L) for water recycling (Dolnicar & Schäfer, 2009). Because of the higher concentration of particles in seawater, it requires more energy than municipal wastewater to clean it. In turn, the cost for desalination is more than double that of treated wastewater (Côté, Siverns, & Monti, 2005; Dolnicar & Schäfer, 2009). Water recycling is less energy intensive, emits fewer GHGs and has a lesser impact on the environment than seawater desalination (Dolnicar & Schäfer, 2009). These studies have significant implications for water management and policy regarding alternative water source adoption.

2.7 Climate Change in California

In order to understand how climate change will affect San Diego County watersheds, an understanding of the current climate needs to be discussed ("Desalination," 2015). In San Diego County, the precipitation from the winter months is stored and delivered to the arid and semi-arid regions in the summer months. Most precipitation occurs from November to April, but most demand is during the summer and early fall (Tarroja et al., 2014). When demand for water is high, the melting snow from the mountains provides water to the dry regions. California has built infrastructure so that water can be conveyed from its sources in the northern California mountain regions and the Colorado River Basin, to its high-demand areas in the coastal regions. Conveyance to Southern California is very energy intensive due to the distance the water needs to be transported (Tarroja et al., 2014). Climate change may cause disruption to this water transfer process and bring about water scarcity.

Warming and drying in the region has already been documented. From 1979 to 2008, a 1.5-degree Celsius increase and a 3cm reduction in precipitation have been observed in California. Southern California desert areas are projected to be over 2 degrees Celsius hotter by 2050 (Bachelet, Ferschweiler, Sheehan, & Strittholt, 2016; Bell, Sloan, & Snyder, 2004; Snyder, Sloan, & Bell, 2004). Some animals and vegetation could adapt to this warming, but some may not be able to (Bachelet et al., 2016). The consensus among the literature is that the average temperatures in California are predicted to increase over time (Berg & Hall, 2015; Duffy et al., 2006; Pierce et al., 2013). Variability in precipitation is expected to increase throughout the state, with more dry days and more periods of heavy rainfall (Berg & Hall, 2015).

Extreme weather conditions have increased in Southern California and the San Diego region; this seems to be the trend going forward (AghaKouchak, Cheng, Mazdiyasni, & Farahmand, 2014; Damberg & AghaKouchak, 2014; Seager, 2007; Tarroja et al., 2014). Warmer temperatures are expected to reduce the amount of snowfall and may melt the mountains' snow earlier in the season than usual. In April 2015, the smallest snowpack in the past seven decades occurred, only supplying about 5% of the typical amount of water ("Climate Change," 2017). Spring floods and runoff are expected to increase as more rain instead of snow occurs as the temperatures rise. Rivers are expected to dry due to the increased evaporation rates from the warmer temperatures. The groundwater sources may experience less recharge causing more stress on the water resource in the future.

The water year (WY) October 2013 to September 2014 was one of the top three driest years for California in the past 440 years (Diaz & Wahl, 2015; Griffin & Anchukaitis, 2014). Since 2000, parts of California have had lower precipitation, on average, than previous time periods. Drought is a temporary lack of precipitation characterized by uncertainty in frequency, duration, and intensity in precipitation (Pereira, Oweis, & Zairi, 2002). The 2014 drought was considered a very rare event as it relates to the Palmer Drought Severity Index (PDSI) and the standardized precipitation-evapotranspiration index (SPEI) (Diaz & Wahl, 2015; Griffin & Anchukaitis, 2014). The PDSI is a proxy for soil moisture near the Earth's surface (Williams et al., 2015). The PDSI is used as the main method for monitoring drought in the U.S. (Williams et al., 2015). What made the 2014 drought so rare was that from November to April during that time, California had the warmest temperatures on record (AghaKouchak et al., 2014). The 2014 drought event in California experienced 75% less precipitation than typical and according to the SPEI, about 60% of the state was in a time of extreme drought meaning the dry and hot conditions were very extreme (Diaz & Wahl, 2015). Average precipitation for California in 2014 was 243.6 mm but in 1977, California only received 163.1 mm average precipitation (AghaKouchak et al., 2014). The 1924 drought was the worst drought in recorded history, followed by the 1977 drought and then the 2014 drought (Diaz & Wahl, 2015; Griffin & Anchukaitis, 2014). Climate change will increase the frequency and duration of these extreme drought events in the San Diego region.

The recurrence period of precipitation levels similar to the California 2014 drought is about 24 years (AghaKouchak et al., 2014). The recurrence period for the extreme temperature similar to the 2014 temperatures in California is every 120 years

(AghaKouchak et al., 2014). The recurrence period for the combined extreme drought with the extreme heat similar to the 2014 event is every 200 years (AghaKouchak et al., 2014). The duration of these extreme drought events may also increase. There is a 50% chance of droughts lasting over 5 consecutive years in the next half century (Cayan et al., 2010). Climate change may increase the chance for the combination of extreme heat and drought occurring simultaneously. This could have devastating consequences. Increased drying due to increased evapotranspiration rates and decreased precipitation could also occur (Bureau of Reclamation, 2007). Drought combined with higher surface temperatures can cause serious public health and safety issues as well as risks for agriculture.

For the southern part of the state, precipitation variability is projected to increase by mid-century, with the possibility of causing extreme winter rainfall events, floods, and extreme summer drought events to increase (Davis & Chornesky, 2014). The hot-dry scenario in Dale et al. (2015) projects a 25% decrease in precipitation, hydropower facility water flow decreasing by 25% while urban demand for water is expected to rise 3% and the demand for agriculture is to rise by 6% (Dale et al., 2015). Imported water would need to increase by about 35% in those years (Dale et al., 2015). The problem with imported water is the intense competition for this water and the inability to recharge and replenish at an acceptable rate.

The projected trend is towards a warming climate, increases in evapotranspiration, reduction in snowpack due to rain replacing snowfall, and an overall drying of the state (Bureau of Reclamation, 2007). Some climate change adaptation measures that California has taken can be seen in the Water Conservation Act of 2009 in which it states goals for a

20% reduction in per capita water use by 2020 and support for the Integrated Regional Water Management (IRWM) planning groups (Davis & Chornesky, 2014). Pricing schemes, tax increases, and efficiency of water transportation (improving pipes and transportation infrastructure to minimize leakage) are all ways to influence the demand for water. Policy changes, management restructuring, and consumer behaviors are all slowly changing but even this will not make up for the water needed to satisfy the growing population and reduced precipitation availability from climate change conditions (Davis & Chornesky, 2014; Gleick & MacDonald, 2010; Sabo et al., 2010). The seven states involved in the Colorado River Compact are very aware of the need for adaptation measures for the impending change in climate (Davis & Chornesky, 2014; Sabo et al., 2010).

The 2014 drought in California prompted the need for water-use restriction and reduction in groundwater usage (Famiglietti, 2014; Harter, Dahlke, & others, 2014; Williams et al., 2015). Some negative impacts were crop failures, (Howitt, Medellín-Azuara, MacEwan, Lund, & Sumner, 2014; Williams et al., 2015), wildfires and tree mortality (Williams et al., 2015). Consensus among the literature shows the effects of a warming climate would create severe situations in areas with heat waves and low precipitation because it would speed up potential evapotranspiration (PET) and create more severe dry conditions (AghaKouchak et al., 2014; Griffin & Anchukaitis, 2014; Williams et al., 2015). The warm temperatures increase the rate of evaporation, which is a damaging situation for California's lucrative agricultural industry e.g. (Amos et al., 2014; Borsa, Agnew, & Cayan, 2014; Scanlon et al., 2012; Seager et al., 2015). This cost California $2.2 billion in damages and losses and 17,000 lost jobs in the agricultural sector (Howitt et al., 2014; Seager et al., 2015).

2.8 The Need for Alternative Water Sources

Water scarcity is a concern in regions both lacking and abundant in rainfall. Decreasing amounts of precipitation and increasing average temperatures creates a water scarcity problem, which may be seen more clearly in the next few decades (Maloney et al., 2014; Seager, 2007; Vano et al., 2014). Almost two-thirds of the global population will be affected by water scarcity (J. Alcamo, Henrichs, & Rosch, 2000; Joseph Alcamo, Döll, Kaspar, & Siebert, 1997; Raskin, Gleick, Kirshen, Pontius, & Strzepek, 1997; Rijsberman, 2006; Seckler, 2003; J. Wallace, 2000; J. S. Wallace & Gregory, 2002).

Many urban arid and semi-arid regions are currently water stressed. NASA's GRACE satellites have been monitoring aquifers, naturally occurring underground water reservoirs, and has shown that about 33% of them are being depleted more rapidly than they are being replenished (McEvoy, 2015). Desalination could be a technical, supply-side solution to reducing some of the pressure on groundwater in coastal communities such as San Diego County (McEvoy, 2015). There are also concerns that adding desalination to the mix will just cause an increase in demand for water (McEvoy, 2015).

Critics of desalination argue that desalination is a "Band-Aid" approach to a more institutional and management/planning problem that allows us not to curtail our consumption and better manage our resources, but to just increase supply to fulfill demand (Jamie McEvoy, 2014). However, California already has water-use restrictions in place to try to reduce consumption and reduce the amount of unnecessary water wasted. Added environmental stress from the warming climate, an increase in major drought events, and an ever-increasing demand for water from a growing population will prompt the need for not only better management and planning, but additional sources of water in order to have sufficient supply.

Competing demand for the limited freshwater prompts the need for alternative sources of water (Savenije & Van der Zaag, 2008). Storm-water recapture, recycled water, groundwater recharge, and desalination are alternative water sources used to expand the local water supply in Southern California. An IRWM approach needs to be considered in order to holistically address the problem (Savenije & Van der Zaag, 2008). The four dimensions to the IRWM approach are: the water resources, the water users, the spatial scale, and the temporal scale. The water resources dimension looks at the entire hydrological cycle and includes stocks and flows, water quality and quantity, rainfall amount, soil moisture, rivers, lakes, streams, aquifers and all waterways and their return flows (Savenije & Van der Zaag, 2008). These include salt water, fossil groundwater, blue and green water. Blue water is the water mostly in lakes and rivers while green water refers to water in the soil and fossil water refers to deep underground aquifers that can easily be exploited and overdrawn at the expense of future use (M. Falkenmark & M. Lannerstad, 2005). The water users dimension includes industrial use, agricultural use, household use, fishing industry, ecosystem, transportation, recreation, environmental, etc. (Savenije & Van der Zaag, 2008). The spatial scale refers to the distribution of water resources and its uses including watersheds, arid plains, basins, and others (Savenije & Van der Zaag, 2008). This can be international, national, district, or local level. The temporal scale refers to the availability and demand of water throughout different seasons. Floods, droughts, and other patterns of seasonality need to be taken into consideration as well as peak demands. Most of these dimensions are taken into consideration with the water allocation model used in this paper.

Chapter 3: The Economic Model

This water allocation model was specified for San Diego County. Uppercase letters represent stock variables and lowercase letters represent flow variables. The underground aquifer supply can hold a maximum of M units of water. San Diego has four main sources of water: surface, desalination, recycled, and imported water, that make up 11%, 3%, 5%, and 81% of the total water supplied to San Diego County, respectively (Mo, 2014). This surface water level is replenished by random rainfall, ε. This is a stochastic model where time is in years, *t*. Although time is an important factor, its notation is initially dropped for brevity. Next will be a discussion on the aquifer level.

Aquifer water cannot go below a certain allowable level. The extraction of water from the local source brings about a social cost because low aquifer water levels may lead to groundwater contamination. To model this, we assume the aquifer cannot drop below $\bar{Y}$, and

$$Y \geq \bar{Y} \tag{1}$$

The state variable is the water level at the beginning of the year and is described by Y $\in [\bar{Y}, M]$. The total amount of water supplied in a given period is described by y $\in [0, Y]$.

The model assumes two sectors; the agricultural and residential sectors, denoted by the subscript *s* and will be identified as either *ag* or *res*, respectively. Freshwater, desalination, and recycled water are the three water sources represented by the subscript *i* for use *s*. The three sources will be identified as either freshwater, desalination, or recycled as *fresh, desal, or rec,* respectively. The amount of water supplied to end users in each sector is defined as $y_{s,i}$, where we assume that $y_{ag,desal} = 0$ and $y_{res,rec} = 0$. We assume *rec* water is not consumed by the residential users and *desal* is not consumed by the agriculture sector. Desalination produces highly purified water, which is better for residential consumption rather than agricultural use. If desalinated water were to be used for irrigation purposes, minerals would need to be added back into the water, which would make production of desalinated water even costlier. The agricultural sector can use the lower quality recycled water for crop irrigation, whereas using recycled water for drinking would need additional purification and incur higher costs. So, we are going to assume that recycled water will be used in the agricultural sector and the desalinated water will be used for drinking water in the residential sector.

The quantity of water demanded differs by source and sector, but can be aggregated to get the total water demanded in San Diego County. The quantity of water source *i* demanded in sector *s* is such that,

$$q_{s,i} = \sum_i q_{s,i} \tag{2}$$

The maximum economic surplus occurs at equilibrium where the supply of recycled water to the agriculture sector is equal to the quantity of recycled water that is demanded. This condition is represented as follows,

$$y_{ag,rec} = q_{ag,rec} \tag{3}$$

The total amount of water collected from the ocean and used in the desalination process to be consumed in the residential sector is equal to the quantity of water demanded, represented by

$$y_{res,desal} = q_{res,desal} \tag{4}$$

All desalination water goes to the residential sector because it is better suited for residential consumption due to the high purity of that water. The total cost of bringing desalinated water to users in the residential sector is modeled by multiplying the cost of desalination by the quantity of water supplied after going through desalination. The total water supplied to the residential sector is divided by the fraction of purified water from one unit of ocean water, β. The cost of desalination is the conveyance cost. The total cost of providing water to consumers is

$$TC_{s,i} = \frac{c_{s,i}}{2} \cdot y_{s,i}^2 \tag{5}$$

where the constant $c_{s,i} > 0$. The total cost of desalination for use *s* is

$$TC_{res,desal} = \frac{c_{res,desal}}{2} \cdot y_{res,desal}^2 \tag{6}$$

The marginal cost for purified water is the derivative of the TC equation. We assume that districts are price takers, so the price of water for the residential consumers must equal the marginal cost of agricultural water and the marginal cost of residential freshwater. We assume a linear marginal cost function and a quadratic cost function. The derivative of the cost equation from Eq. 5 is:

$$MC_{s,i} = c_{s,i} \cdot y_{s,i} \tag{7}$$

The cost equations were omitted for recycled water. We assumed the amount of recycled water consumed is a function of the region's capacity to collect and purify the wastewater, and this capacity is held constant at $y_{ag,rec}$. Recycled water will be allocated to agricultural use due to health concerns with direct consumption of recycled wastewater. We assume it is consumed at capacity and that recycled water is cheaper than desalination.

Half of the total water supplied to the Carlsbad facility is used as freshwater to residents and the remainder is brine that gets diluted and deposited back to the water source (ocean) or used in production of related goods. The brine is represented by (1 - β) that needs to be either cleaned or repurposed. The unit cost of the brine treatment is k and the total cost of treatment is

$$TC_{brine} = k \cdot \frac{(1-\beta)}{\beta} \cdot y_{res,desal} \tag{8}$$

The change in total residential sector water supply when desalination is introduced into the model is represented by Equation (9). This represents the current period excess water that is left over after quantity demanded is subtracted:

$$\dot{Y} = \sum_s \sum_i y_{s,i} - \sum_s \sum_i q_{s,i} \tag{9}$$

The following optimization, Equation (10), represents the demand of water over time subtracting the cost of providing desalination and the environmental cost of the brine solution. The following is the objective function, or the social planner's problem where time is explicitly reintroduced and the objective function is modeled over a finite horizon of *T periods*

$$Max_{\{y_{s,i},q_{s,i}\}_{i\epsilon\{res,ag\},s\epsilon\{fresh,rec,desal\}}} \sum_{t=0}^{T} e^{-rt} \{\sum_s \sum_i (\int_0^{q_{s,i,t}} D_{s,i}^{-1}(q)dq - \frac{c_{s,i}}{2} \cdot y_{s,i,t}^2)$$

$$-k \cdot \frac{(1-\beta)}{\beta} \cdot y_{res,desal,t}\} \tag{10}$$

subject to Eqs. (9), non-negative control variables and the conditions (3) and (4) – that is, we assume the constraints are $y_{ag,desal} = 0$ and $y_{res,rec} = 0$, and the constraints of the non-negative stock variables $Y_t|_{t=0} = Y^0 > \bar{Y}$ where Y^0 is the initial condition or the starting point of the aquifer level. The stock is taken at a certain level in the aquifer.

Eq. 10 maximizes the area of the objective function with respect to supply and the constraints of the model to obtain net economic surplus, subtracting the environmental damages.

Chapter 4: The Equilibrium Outcome

In the following, $q_{s,i}$ and $y_{s,i}$ are choice variables for the water used and supplied by sector *s* and use *i*. State variable, *Y* is the amount of available water. The optimization is solved by the Lagrangian equation:

$$\Im = \sum_s \sum_i \left(\int_0^{q_{s,i,t}} D_{s,i}^{-1}(\theta) d\theta - \frac{c_{s,i}}{2} \cdot y_{s,i,t}^2 \right) - k \cdot \frac{(1-\beta)}{\beta} \cdot y_{res,desal,t} \tag{11}$$

$$+\lambda_Y \cdot \left(\sum_s \sum_i y_{s,i,t} - \sum_s \sum_i q_{s,i,t} \right) + \mu_Y \cdot (Y - \bar{Y})$$

$$+\sum_s \sum_i {\upsilon_{s,i,t}}^q q_{s,i,t} + \sum_s \sum_i {\upsilon_{s,i,t}}^y y_{s,i,t}$$

$$+\vartheta_{ag}(y_{ag,rec} - q_{ag,rec}) + \vartheta_{res}(y_{res,desal} - q_{res,desal})$$

where λ_Y, μ_Y, $\upsilon_{s,i}$, ϑ_{ag}, and ϑ_{res} are the assumed non-negative state variables and the Kuhn-Tucker multiplier of the non-negative constraint as well as the non-negative control variables and the conditions (3) and (4).

Assuming an internal solution, the first-order-conditions (F.O.C.) of Eq. (11) with respect to $q_{s,i}$ and $y_{s,i}$, for $i \neq desal$, yield

$$D_{s,i}^{-1}(q_{s,i}) = c_{s,i} \tag{12}$$

This is an internal solution. The price of water $D_{s,i}^{-1}(q_{s,i})$ equals the unit cost $c_{s,i}$, and since recycled water costs less than freshwater, $c_{s,rec}$, $<$, $c_{s,fresh}$, the marginal value of water in agriculture is determined by the use of freshwater in agriculture. The assumption is that desalination will not be used in agriculture because it will be too expensive whereas recycled water's best use is for irrigation.

The F.O.C. of Eq. (11), with respect to $q_{res,desal}$, yields

$$D_{res,desal}^{-1}\left(q_{res,desal}\right) = c_{res,desal} + k \cdot \frac{(1-\beta)}{\beta} \tag{13}$$

Eq. (13) states the normalized price of desalinated water, $\frac{D_{res,desal}^{-1}\left(q_{res,desal}\right)}{\beta}$ is equal to the sum of: (i.) production and conveyance costs associated with desalinated water being supplied for *s,* (ii.) the post-treatment cost for the brine discharge.

The F.O.C. with respect to the state variables *Y* is,

$$\dot{\lambda_Y} - r\lambda_Y = \mu_Y \tag{14}$$

The equation above implies that given $Y_t > \bar{Y}$, the relative change in the value of state variable overtime equals that of the discount rate *r*; that is, $\frac{\dot{\lambda_Y}}{\lambda_Y} = r$.

Chapter 5: Data and Calibration

Data from San Diego County is used to calibrate the demand, cost, and supply equations in the previous two sections. San Diego County is used as the case study in this thesis for the following reasons. For one, San Diego County is an arid, water stressed region that is dependent on other regions in order to supply its consumers with sufficient water. Going forward, with increasing temperatures and more frequent drought events, the region will become even more water stressed. San Diego County already has a desalination facility, the Carlsbad facility that supplies some water to residents. Increasing the use of desalination could help to transform the region from water scarce to water abundant. This region also has active residential and agriculture sectors. Recycled water is also already used in the region for certain restrictive uses. For all of these reasons, San Diego County makes a great case study for this thesis and can imply similar solutions to other regions throughout the country. The following sub-sections will describe the current landscape of San Diego's water supply mix, energy supply mix, information on the Carlsbad facility, and calibration of the demand curves for the residential and agriculture sectors as well as calibration for the general model of this paper.

5.1 San Diego County profile

Figure 1 is a map of San Diego County in Southern California. The residential sectors which would receive desalinated water are located near the coastline, while the agriculture sectors are located more inland. These inland areas would utilize recycled water instead of desalinated water. The city of Carlsbad is highlighted on this map which is where the Carlsbad Desalination facility is located.

Figure 1. Map of San Diego County

Source: (Mcgirr and Batterbury, 2016)

The current energy use in San Diego County is: 53.57% natural gas, 15.08% nuclear, 12.84% hydro-power, 7.40% coal, 4.41% geothermal, 2.79% wind, 1.76% biomass, 1.38% oil, 0.30% solar, and 0.47% other fossil fuels (Mo et al., 2014). Although alternative uses of energy are not in the model because we wanted to focus on water use, it is an important component going forward because if renewable energy could provide all necessary energy needs for the energy intensive desalination process, then the environmental footprint of desalination could be reduced significantly. The following will be a rank of water sources and their relative energy intensity from highest to lowest for San Diego: desalinated seawater, imported water from northern California, desalinated brackish water, imported water from the Colorado River, reclaimed water/wastewater, and local surface water (Mo et al., 2014). For San Diego County, the RO process is very energy intensive so it makes sense that it ranks highest on the list. There is a 75 MJ and 2.2 kg CO_2e reduction if we replace $1m^3$ of desalinated seawater with reclaimed water in SD (Mo et al., 2014). However, due to water use restrictions on reclaimed water, desalination and reclaimed water are not seen as interchangeable. We assume desalinated water is used for direct consumption in the residential sector and reclaimed water is used in irrigation for the agriculture sector.

The cost of water depends on its source. Water imported from northern California is more expensive than water received from the Colorado River because the water from the north needs to travel over mountains, which is very energy intensive. We can assume that residents will use desalinated water as long as it is cheaper than other sources. However, this changes with the reality of climate change. With climate change, water would become scarcer. And since other regions depend on the Colorado River, which supplies San Diego County with 81% of its total supply, there will be increased competition for this water source, therefore increasing prices. Desalinated water would only cost each household an additional $5 per month, on average ("Carlsbad Desalination Plant," 2017). Desalination would provide a stable, reliable source of water and residents may be willing to pay a premium for this secure water source at present (Commission &

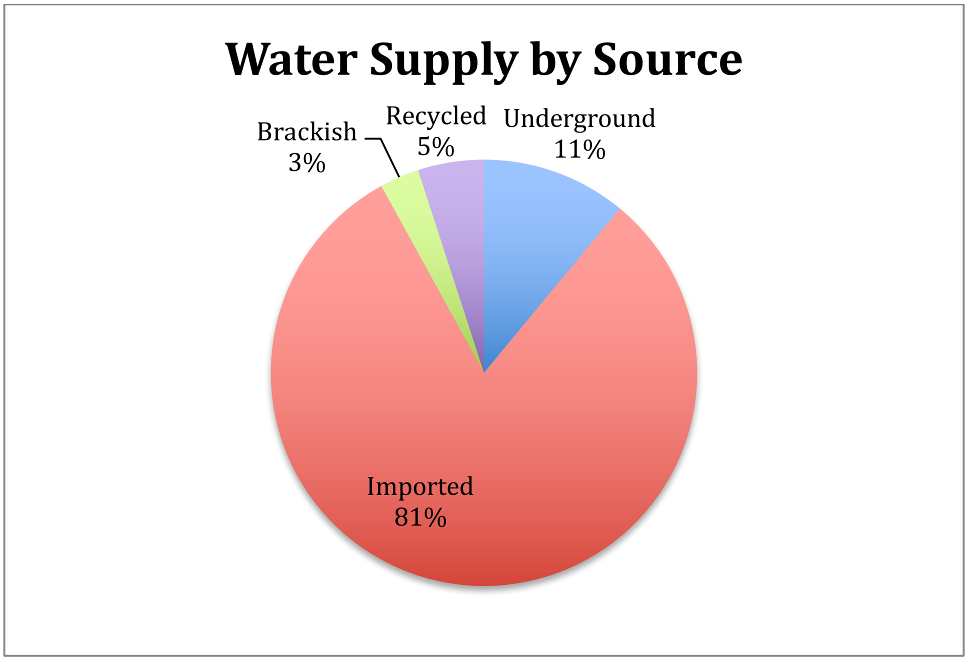
others, 2004).

The Carlsbad Desalination Facility is the only active desalination facility in San Diego County. Data is available on this plant so it was used in this paper as a representative desalination plant. There is a 30-year purchasing agreement for all of the desalinated water output between the San Diego County Water Authority (SDCWA) and Poseidon Water, which funded the desalination plant. The plant can supply about 400,000 people per year by producing 69,074,983.89 m^3 of water. It is located in Carlsbad, California next to the natural gas and oil-powered electricity plant, the Encina Power Plant ("Carlsbad Desalination Plant," 2017). The increase in annual energy consumption due to the Carlsbad plant is about 224,000 MWh (Messner, Miranda, Young, & Hedge, 2011). The Carlsbad facility works on a 2 to 1 ratio where 2 gallons of seawater is required to make 1 gallon of drinking water (Commission & others, 2004).

5.2 Calibration of the Model

All parameters were calibrated to 2015 values. All prices and costs are in terms of 2015 dollars. The supply of water in San Diego is made up of imported water, underground water, recycled water, and brackish or desalinated water. Figure 2 shows a pie chart with the share of the water supply with data obtained from Mo et al. (2014).

Figure 2. San Diego County's water supplied by source



The information provided in Figure 2 was used in the calibration of the model. The Carlsbad facility in San Diego currently desalinates 3% of the total supply of water to be consumed by San Diego County residents. The capacity of this facility is 12% of the total supply (Mo et al., 2014). Recycled water makes up 5% of the mix and the current capacity is 50 MGD (million gallons daily) ("Carlsbad Desalination Plant," 2017). The imported water comes from the Colorado River Basin. Based on a survey, residents would be willing to pay a higher price for a cleaner, more sustainable and secure water source such as desalination (Commission & others, 2004). At a certain price, desalination could meet the needs of residents, which frees up the water resource and the underground water becomes marginal.

All measurements were converted to cubic meters (m^3). The share of cleaned water after the desalination process is 50%, meaning the desalination process cleans half of the water that was input and this can be sent to the end users. The other 50% of the outcome is the brine. Brine is a saline solution that could either be diluted and discharged back into the Pacific Ocean, be used and sold as melting salt, or used to make other products. The percentage share of brine after desalination is represented by the variable, β = 0.5 because 1 unit of ocean water produces 0.5 units of clean water. To calculate price for brine in terms of $\$/m^3$, the price for a gallon of brine is \$0.15/gallon and 1 gallon is equal to 0.00378541 m^3. These numbers were multiplied to get the final result.

Supply must equal demand at equilibrium. This was shown in Eq. 4, $y_{res,desal} = q_{res,desal}$.

The following conditions were used to calibrate the cost equations. The total cost of supplying desalinated water to end-users was found by solving an internal solution. It is modeled by the quadratic function in Eq. 5. The different costs associated with desalination that are included in the total cost are the production and conveyance of water. Other costs are capital expenditures, maintenance, and electricity costs. As production increases, total cost increases. The brine treatment is separate from the total cost. The transportation cost of water to end users is charged by the SDCWA which distributes water to residents. The linear marginal cost curve for desalinated water shown in Eq. 7 is the derivative of the quadratic total cost equation. We assume a linear marginal cost because maintenance and electricity costs increase at the margin as production volume increases (WateReuse Desalination Committee, 2012). We assume districts in San Diego County are price takers, such that the MC of freshwater for drinking is equal to the price for water in the residential sector. In order for the economic surplus to be maximized, the MC of the production of desalination needs to equal the marginal benefits of consumption. The cost equations were omitted for recycled water. We assumed recycled water is a function of the amount of wastewater collected. Recycled water is also assumed to be cheaper than desalinated water. The next sub-section will show the demand equation calibration.

5.3 The Demand Solution Calibration

Data was collected from the San Diego County Water Authority (SDCWA) on the quantity of water consumed in the agricultural and residential sector from 2000 to 2015 for all 24 districts in San Diego County. For the agriculture sector, the only districts used in these calculations were the following: City of Escondido, Fallbrook Public Utility District, Rainbow Municipal Water District, Vallecitos Water District, Valley Center Municipal Water District, and Yuima Municipal Water District. Other districts either did not have agricultural water use or did not have significant amount of use. The quantity demanded from each district was then converted from acre-feet (af) to m^3 by multiplying the quantities in acre-feet (af) by the conversion rate, 1233.48.

Then the district quantities were summed to have total quantity used by the residential sector and the agricultural sector. The demand model was calibrated using 2015 prices and quantities to predict historical prices. The demand function for sector *s* and use *i* is represented by the intercept, $\alpha_{0,s,i}$, subtracting the product of the slope and price of water for the respective sector, $\alpha_{1,s,i} \cdot P_{s,i}$. The inverse demand equation is as follows,

$$P_{s,i} = \alpha_{0,s,i} - \alpha_{1,s,i} \cdot Q_{s,i} \tag{15}$$

The elasticity of demand for water is the responsiveness to changes in price. Elasticity is defined as the inverse slope multiplied by the price and quantity of water demanded. The general equation for elasticity is: $\eta_{s,i} = \frac{1}{\alpha_{1,s,i}} \cdot \frac{P_{s,i}}{Q_{s,i}}$. The elasticity of demand, gathered from the literature, for the agriculture sector and residential sector, respectively, are -0.79 and -0.3 (Jenkins, Lund, & Howitt, 2003; Schoengold, Sunding, & Moreno, 2006). The elasticity of demand for water in the residential sector was documented in the literature as a range from -0.1 to -0.5, so the average value was chosen (Jenkins et al., 2003). This was tested in the sensitivity analysis, which will be discussed in the results section of this paper. The elasticity of demand for water in the agriculture sector was taken from Schoengold et al. (2006) reported the elasticity for San Joaquin Valley in California, which was the closest value attainable that was comparable to San Diego County at the time this paper is published. These two regions are similar in that they both are heavily dependent on underground water sources. The elasticity of demand for water in the residential sector is slightly more inelastic than the elasticity of demand for water in the agriculture sector because the residential needs water for essential purposes, whereas farmers are more likely to reduce their water use as price changes.

In Eq. 16, the slope for sector *s* and use *i* was calculated internally, by multiplying the inverse of the elasticity, multiplied by the price and quantity of water demanded. The intercept is the same across districts because of the use of a single elasticity of demand and a single price across districts, and when solving for the intercept, the quantity of water demanded is cancelled out. The intercept is calculated in Eq. 17:

$$\alpha_{1,s,i} = -\frac{1}{\eta_{s,i}} \cdot \frac{P_{s,i}}{Q_{s,i}} \tag{16}$$

$$\alpha_{0,s,i} = P_{s,i} - \frac{1}{\eta_{s,i}} \cdot P_{s,i} \tag{17}$$

Demand was calculated for each district in San Diego County for the Agriculture and Residential sectors from 2011 to 2015 ("Board Documents," 2017). Although each district has reported the quantity of water used, prices only were available from 2011 onward. The price of water used to calibrate the model for the agriculture sector and residential sector, respectively, was a constant \$0.70 per m^3 and \$1.11 per m^3 ("Board Documents," 2017). The prices were obtained from the SDCWA and the prices for agricultural and residential water for 2015 were used to calibrate going backwards, historically in the data to calculate the different demand equations. The prices were reported in \$ per acre-feet, so these prices were multiplied by the conversion rate 1233.48 to convert to \$ per m^3. Table 1 shows the actual prices obtained from the SDCWA.

Table 1: Actual prices for Agriculture and Residential Water from 2011 to 2015 in terms of dollars per m^3.

Year	**Actual Price for Agriculture Water (\$/m3)** ("Board Documents," 2017)	**Actual Price Residential Water (\$/m3)** ("Board Documents," 2017)
2011	\$0.60	\$0.86
2012	\$0.64	\$0.93
2013	\$0.64	\$1.02
2014	\$0.70	\$1.06
2015	\$0.70	\$1.11

The difference between the average of the calculated prices and the actual prices for both the agriculture and residential sectors will be shown in Table 2.

Table 2: The percent difference of the average calculated price from the actual price of water for both residential and agriculture sectors.

Year	Percent Difference from Actual Price of Water (Residential Sector)	Percent Difference from Actual Price of Water (Agriculture Sector)
2011	108.11%	54.00%
2012	78.094%	32.68%
2013	42.681%	5.65%
2014	-19.36%	-22.10%
2015	No change	No change

The calculated demand curves were not too accurate at estimating the actual price for water at earlier time periods. Data on price was limited and were not available before the year 2011. The model was most accurate at predicting the price the agriculture sector paid for water in 2013 and 2015. However, the lack of accuracy is due to limited data. Another limitation was assuming each district in the residential sector paid the same price for water, and that the same district in the agriculture sector paid the same price for water. Taxes for water were also not included due to lack of available data, which could have an effect on the inaccuracy.

Only equations for certain districts were calculated based on their relevance and available data. Table 3 below defines the parameters that were used to calibrate the maximization equation found in the Economic Model section of this paper. To summarize, the demand parameters were found by aggregating the individual district demand curves. The supply of desalinated and recycled water was calculated from existing data. The share of clean water after the desalination, or output, is half of the input, or the seawater.

Table 3: Parameters used to calibrate the model

z	Symbol	Value	Units
Share of clean water after desalination	β	0.5	Fraction
Total supply of water	$y_{s,i}$	5.43E+08	m^3/year
Cost of supplying desalination to end users	$c_{res,desal}$	2.62E-08	$/$m^3$
Price / m^3 of brine ("How much does it cost?," 2015)	k	5.68E-04	$/$m^3$
Total desalinated water supply	y_{desal}	1.1536E+07	m^3/year
Supply of reclaimed water (Mo et al., 2014)	y_{rec}	2.95E+07	m^3/year
Aggregate demand	Q_s	5.9003e+08	m^3
Residential demand	q_{res}	542,401,614.1	m^3
Agricultural demand	q_{ag}	47,631,570.29	m^3

Now that the calibration and data has been discussed, the next section will show the results of the model and sensitivity analysis.

Chapter 6: Results

Introducing desalination and recycled water into the supply mix relieves the scarcity problem and brings the issue of water management to the center of focus. Desalinated water is consumed in the residential sector because of the cost structure. In the short run, the price of water in the agriculture and residential sector will equate agriculture and residential marginal cost, respectively. Recycled water is at capacity and is restricted by the amount of wastewater collected. This amount of recycled water is not enough to supply the agriculture sector. Desalination and recycled water could help eliminate the water scarcity problem in San Diego County. In theory, desalination could provide the residential sector with all of its water needs due to the seemingly infinite amount of ocean water available. Because of this fact, desalination could help free up the freshwater resource for the agriculture sector. A question for the future is whether the capacity of desalination could increase and to what extent.

In Table 4, the key parameters used in the model calibration are listed. For the sensitivity analysis, each variable was changed, ceteris paribus, and the changes in key variables - the economic surplus with desalination and recycled water, the economic surplus without desalination and recycled water, the supply of desalination, the cost of brine, the cost of desalination, and the cost of natural gas - were documented in the baseline solutions Table 5. The economic surplus with recycled and desalinated water means the total economic surplus benefits in dollars that would come from a solution of the model where desalination and recycled are taken out and only freshwater (imported and underground water) remains. A supply without the alternative water sources would lead to a reduction in economic surplus and a stressed water resource. This situation is not ideal and will be shown in this sensitivity analysis.

Table 4: Calibrated parameters, their values and the positive and negative 10% and 20% changes used in the sensitivity analysis.

Parameters	Calibration	10% Change	-10% Change	20% Change	-20% Change
Elasticity of demand for water in Agriculture	-0.79	-0.869	-0.711	-0.948	-0.632
Price of water in Agriculture	\$0.70 / m^3	\$0.77 / m^3	\$0.63 / m^3	\$0.84 / m^3	\$0.56 / m^3
Elasticity of demand for water in Residential	-0.3	-0.33	-0.27	-0.36	-0.24
Price of water in Residential	\$1.11 /m^3	\$1.22 /m^3	\$0.99/m^3	\$1.33 /m^3	\$0.88 /m^3
Cost of Brine Treatment	\$0.000567812 /m^3	\$0.000624593 /m^3	\$0.00051103/m^3	\$0.000681374/m^3	\$0.000454249/m^3
MC for Agriculture	\$1.46E-08	\$1.60965E-08	\$1.31698E-08	\$1.75598E-08	\$1.17065E-08
MC for Residential	\$2.04E-09	\$2.24299E-09	\$1.83517E-09	\$2.4469E-09	\$1.63126E-09

kWh needed in Desalination process	3.5 kWh	3.85 kWh	3.15 kWh	4.2 kWh	2.8 kWh
Desalination Unit Cost	5.74E-08	6.31634E-08	5.16791E-08	6.89055E-08	4.5937E-08
Discount factor	0.95	N/A	0.855	N/A	0.76
Standard Deviation of Rainfall	400,000	440,000	360,000	480,000	320,000

Table 5: Baseline solutions for the key variables.

Key Variables	**Baseline Solution**
Economic surplus with desalination and recycled water	$4,720,840,415
Economic surplus without desalination and recycled water	$4,681,969,357
Supply of desalinated water	9,369,398.662 m^3
Cost of brine treatment	$5,320.052308
Cost of desalination	$0.538 / m^3
Cost of natural gas	$0.0448 / MMBTU

The baseline solutions found in Table 5 are the starting points from which the analysis of the changes in key variables in the model will be compared to. The results coincide with predictions because the economic surplus with desalination and recycled water at 2015 capacity levels is higher than the economic surplus without desalinated and recycled water by $38,871,058. Without desalination and recycled water in the supply mix there will be a loss of potential benefits of over $38 million. If the capacity of the Carlsbad desalination facility and the capacity for recycled water were higher than their share of the supply source of water in 2015, then this difference would be much greater. Nonetheless, these results show that desalination and recycled water frees up some of the freshwater resource and relieves some of the pressure of the water supply.

Figure 3 shows the aggregate demand and supply curves in the residential sector (Eq. (7) for the supply and Eq. (15) for the demand curves). Consumer surplus is the triangle above the price of $1.11 yet below the demand curve and producer surplus is the triangle below the equilibrium price but above the supply curve. When climate change enters the picture, we can look to Figure 4 because it shows the loss of consumer benefits by the dashed line area. Water scarcity would cause supply to shift to the left, thus raising price and decreasing the economic surplus. Without desalination and recycled water in the supply mix under water scarcity conditions, this will be a loss of about $38 million (see also Table 5).

Figure 5 shows the demand and supply for the agriculture sector. At first, the supply curve for the agriculture sector is perfectly inelastic at the capacity for recycled water. Then the supply curve changes to represent the linear MC of the freshwater resource (Eq. (7)).

Figure 3. Residential Sector Aggregate Demand and Supply

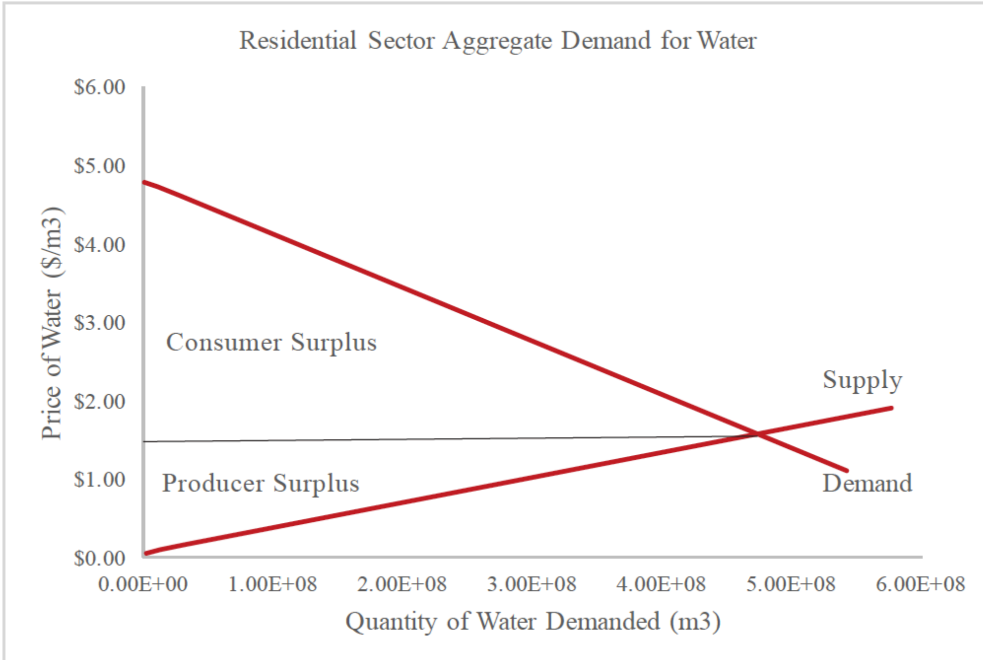


Figure 4. Residential Sector Economic Surplus Changes

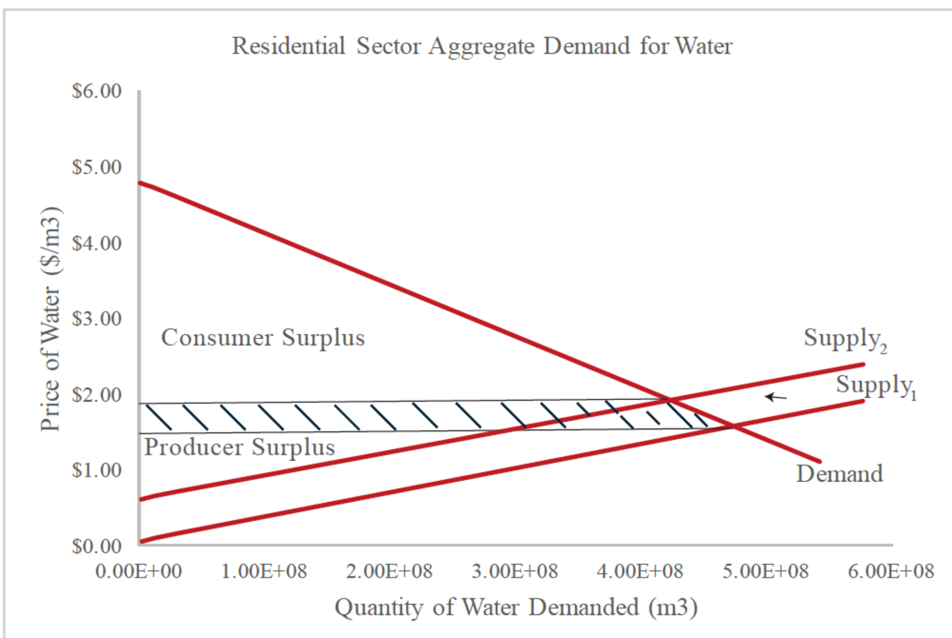
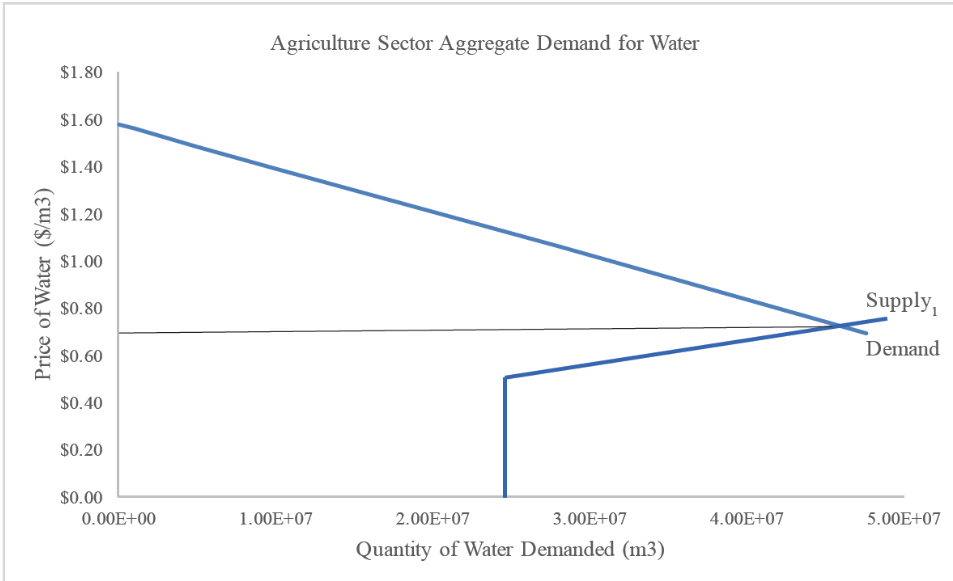


Figure 5. Agriculture Sector Aggregate Demand and Supply



The total quantity of water supplied in San Diego County in 2015 is 543,000,000 m^3. The total desalinated water supplied in 2015 is 11,536,000 m^3 per year. The capacity of the Carlsbad Desalination Facility is 69,074,983.89 m^3 of clean drinking water per year. The Carlsbad Desalination Facility can provide San Diego County with about 12% of its total water supply. So, unless the capacity of the facility can increase its productivity, then additional desalination facilities would need to be built in the region in order for desalination to completely supply the entire region with clean drinking water (our baseline scenario required that desalination will supply 9,369,398.662 m^3 – see Table 5).

Tables 6 through Table 9 are the results of the sensitivity analysis. For these tables, the values in parenthesis are the percent changes from the baseline solution. And due to rounding errors, small changes may not be reported. The baseline solutions are shown in the column titled “0%.

Table 6: Sensitivity analysis of the change in elasticity of demand for water use in the agriculture sector.

Variables	Changes in elasticity of demand for water in the agriculture sector				
	-20%	**-10%**	**0%**	**10%**	**20%**
Economic surplus with desalination and recycled water	$4,721,886,326 (0.02%)	$4,721,601,390 (0.02%)	$4,720,840,415	$4,720,143,770 (-0.01%)	$4,719,503,630 (-0.03%)
Economic surplus without desalination and recycled water	$4,683,015,268 (0.02%)	$4,682,730,332 (0.02%)	$4,681,969,357	$4,681,272,712 (-0.01%)	$4,680,632,572 (-0.03%)
Supply of desalinated water	No change	No change	9,369,398.66 m^3	No change	No change
Cost of brine treatment	No change	No change	$5,320.05	No change	No change
Cost of desalination	No change	No change	$0.538 / m^3	No change	No change
Cost of natural gas	No change	No change	$0.0448 / MMBTU	No change	No change

Table 6 shows the changes in key variables when the elasticity of demand for agriculture was increased and decreased by 10% and 20%. The baseline solutions are shown in the column titled "0%" meaning no change in the elasticity of demand for water in the agriculture sector. The price elasticity of demand is expected to be negative because it follows the law of demand, as price increases, quantity demanded decreases. There were slight changes from the baseline solutions in the economic surplus with and without desalination and recycled water. As the elasticity is changed positively, the elasticity becomes more elastic and thus leads to decreases in consumer surplus as shown by the results of a -0.01% and -0.03% changes in economic surplus with and without desalination and recycled water when the elasticity is changed by 10% and 20%, respectively. So, when the elasticity was increased, both economic surpluses decreased. As the elasticity decreased by 10% and 20%, both economic surpluses increased by 0.02%. The more elastic the demand for water becomes, the more the consumer surplus decreases. This is because as the demand for water in the agriculture sector becomes more elastic (meaning farmers are more sensitive to price changes), farmers more readily decrease water use if prices rise and increase water use if prices decline.

Table 7: Sensitivity analysis of the change in elasticity of demand for water use in the residential sector.

Variables	**Changes in elasticity of demand for water in the residential sector**				
	-20%	**-10%**	**0%**	**10%**	**20%**
Economic surplus with desalination and recycled water	$4,721,167,403 (0.01%)	No change	$4,720,840,415	No change	$4,720,541,544 (-0.01%)
Economic	$4,682,308,385	No change	$4,681,969,357	No change	$4,681,659,482

surplus without desalination and recycled water	(0.01%)				(-0.01%)
Supply of desalinated water	9,357,359.48 (-0.13%)	9,375,021.51m^3 (-0.06%)	9,369,398.66 m^3	9,375,021.51 m^3 (0.06%)	9,380,402.60 m^3 (0.12%)
Cost of brine treatment	\$5,313.22 (-0.13%)	\$5,323.25 (-0.06%)	\$5,320.05	\$5,323.25 (0.06%)	\$5,326.30 (0.12%)
Cost of desalination	\$0.5373 (-0.13%)	\$0.5476 (-0.06%)	\$0.538 / m^3	\$0.5702 (0.06)	\$0.5386 (0.12%)
Cost of natural gas	No change	No change	\$0.0448 / MMBTU	No change	No change

The changes in the economic surplus both with and without desalination and recycled water when the elasticity of demand for water in the residential sector was changed was slightly less than the changes in the agriculture demand elasticity. This is because water demand in the residential sector is more inelastic than water demand in the agriculture sector. So changes in the elasticity of a good that is more elastic than another good results in larger changes in economic surplus. Changing the residential price elasticity also affected the supply of desalinated water, the brine treatment cost, and the cost of desalination.

Table 8: Sensitivity analysis of the change in the unit cost of desalination.

Variables	Changes in the unit cost of desalination				
	-20%	**-10%**	**0%**	**10%**	**20%**
Economic surplus with desalination and recycled water	\$4,724,847,738 (0.08%)	\$4,722,628,013 (0.04%)	\$4,720,840,415	\$4,719,369,955 (-0.03%)	\$4,718,139,131 (-0.06%)
Economic surplus without desalination and recycled water	\$4,683,711,671 (0.04%)	\$4,682,746,573 (0.02%)	\$4,681,969,357	\$4,681,330,027 (-0.01%)	\$4,680,794,886 (-0.03%)
Supply of desalinated water	11,634,407.74 m^3 (24.17%)	10,379,780.15 m^3 (10.78%)	9,369,398.66 m^3	8,538,269.61 m^3 (-8.87%)	7,842,586.29 m^3 (-16.30%)
Cost of brine treatment	\$6,606.15 (24.17%)	\$5,893.76 (10.78%)	\$5,320.05	\$4,848.13 (-8.87%)	\$4,453.11 (-16.30%)
Cost of desalination	\$0.5344 (-0.66%)	\$0.5364 (-0.29%)	\$0.538 / m^3	\$0.5393 (0.24%)	\$0.5404 (0.45%)
Cost of natural gas	No change	No change	\$0.0448 / MMBTU	No change	No change

Increasing the unit cost or average total cost of desalinated water seem to decrease the economic surpluses, the supply of desalination, and the cost of brine while the total cost for desalination increases. Decreasing the unit cost of desalinated water seem to increase the economic surpluses, the supply of desalination, and the cost of brine while the total cost for desalination decreases.

The cost of desalination consists of production and conveyance costs to end users as well as the post-treatment cost for the brine discharge. Increasing the supply of desalination would cause the total cost of desalination to increase because of the linear MC structure and the unit cost would increase with increased production. Technology improvements that increase the capacity of water production would lower the unit cost (WateReuse Desalination Committee, 2012).

Table 9: Simulation results with no recycled water in the supply mix and no desalination in the supply mix.

Variables	Baseline Solution	No recycled water	No desalination
Economic surplus with desalination and recycled water	$4,720,840,415	$4,674,857,381 (-0.97%)	4,711,471,016 (-0.20%)
Economic surplus without desalination and recycled water	$4,681,969,357	$4,665,487,983 (-0.35%)	No change
Supply of desalinated water	9,369,398.662 m^3	No change	No change
Cost of brine	$5,320.052308	No change	No change

treatment			
Cost of desalination	$0.538 / m^3	No change	No change
Cost of natural gas	$0.0448 / MMBTU	No change	No change

When the amount of recycled water is set to zero, economic surplus both with and without desalination and recycled water in the supply mix change by less than 1%. When the quantity supplied of desalination is set to zero, the economic surplus with desalination and recycled water decreases by 0.20%. This would be much larger if the capacity of desalination was increased. Currently the capacity is restricted to the amount of water that the Carlsbad facility can desalinate per day.

In regard to the discount factor, the lower the discount factor, the fewer the number of iterations there were in the model. Note that there cannot be a discount factor greater than “1.” And when the standard deviation was changed, nothing else was affected in the model.

The simulation gives us the economic surplus of water supply over demand with and without desalination and recycled water. Recycled water and desalination helps reduce the stress on water in San Diego County. If desalination and recycled water are removed from the equation then aquifer water becomes stressed; this is shown in the results. The results show that including desalination and recycled water gives a larger economic surplus than excluding these two sources. The economic surplus with desalination and recycled water is greater by $38,871,058 in benefits per year. This means that desalination and recycled water diminishes the water scarcity problem in this semi-arid region and thus brings forth a water management issue. This water management question is how much desalination and recycled water should be used and what should be the optimal allocation of water sources. Currently, the answer to this is the capacity constraint of the current wastewater systems and the desalination facility in Carlsbad. The answer also depends on prices. Once climate change creates true water scarcity, we will reach the price ceiling for water, determined by the price of desalination. Once the marginal cost is equal to the price of desalination then as much clean water that is needed can be produced since the ocean has a seemingly endless supply of water. However, the constraints are the capacity of the desalination facility and the price of the water to residents.

As long as the price of imported and underground water is less than the price of desalinated water, San Diego County consumers will not purchase desalinated water. However, there are two ways this problem can be eliminated. One reason is if residents are willing to pay a higher price for water that is a more consistent and reliable source of water than the imported Colorado River supply. Desalination meets these criteria because it produces a cleaner, more secure, reliable and abundant source of water. It helps to ensure a water secure future. However, this solution still has some tradeoffs and negative environmental consequences that were discussed in a previous section. The second reason is if true water scarcity pushes the price of water to the market-clearing price. If this happens then desalinated water can be used to supply almost the entire residential sector with potable water.

Prices determine the allocation of water. For the residential sector, it makes sense to have desalination be the alternative water choice and for the agriculture sector it will be recycled water. This is due to the fact that the water produced from RO is more purified than recycled water. This RO water is better suited for drinking water whereas it would not be good for agriculture because water for agriculture needs more minerals. So if desalination were to be used to provide water to the agriculture sector, minerals would need to be added to it and would, in turn, make desalinated water an even more expensive product. Recycled water is not suited for drinking water because it needs additional purification in order to meet quality standards for direct consumption.

The results of this paper contrast with the results in Mo et al. (2014). Based on the water-energy relationship and the energy intensity of the desalination process, Mo et al. (2014) concludes that reclaimed water is the best choice going forward. However, Mo et al. (2014) ignores the agriculture sector. Including the agriculture sector in our study shows that using both sources of alternative supplies is more beneficial than one or the other. The addition of desalination along with recycled water into the equation does not only increase the supply of water, but it also makes underground sources marginal. Holding the amount of imported and underground water constant, desalination and recycled water together help provide water security.

Chapter 7: Policy Discussion

This thesis differs from the policy implications set forth by Mo et al. (2014) because the authors' conclusion called for use of reclaimed water as the best solution to the water crisis. This thesis is predicated on the use of both desalination and recycled water simultaneously, for different uses. Desalinated water will be used for direct consumption in the residential sector of San Diego County because of its high quality and purification, and recycled water will be used in the agriculture sector because it has more nutrients in the water and is approved for this use.

With recycled water, there is the issue of capacity constraints. Current infrastructure does not support widespread wastewater collection. Discharge pipes would also need to be installed widely across the county for each home so that the wastewater can be brought to a wastewater management facility. These pipes would be separate from the incoming clean water in the residence. This infrastructure should be constructed when the San Diego County districts choose to upgrade their pipe system.

Holding demand constant, the price of water in the residential sector is increased and decreased by 10% and 20% in Table 10. Economic surplus with and without desalination and recycled water in the supply mix does not change too much when price changes, even with a 20% change in price. This is because this is an inelastic good. However, the quantity supplied of desalination is changed. Because of the law of demand, it makes sense that as price increases, the quantity of water demanded decreases. And as the price for water decreases, the quantity of water demanded increases.

Changes in the price of water in the agriculture sector did not have any significant effects on key variables, so there is no need for a sensitivity analysis table. This is probably due to the fact that the agricultural demand for water is significantly less than the residential sector demand for water.

Table 10: Changes in the price of residential water.

Variables	Changes in the price for water in the residential sector				
	-20%	**-10%**	**0%**	**10%**	**20%**
Supply of desalinated water	9,573,464.28m^3 (2.18%)	9,459,003.34m^3 (0.96%)	9,369,398.66 m^3	9,297,346.62 m^3 (-0.77%)	9,238,149.73 m^3 (-1.40%)

Water is a vital part of the economy and managing this resource will become increasingly challenging in the years to come. Water cycles affected by climate change can alter precipitation and water supplies, which is why building the necessary infrastructure to support the increased use of alternative, renewable sources of water will be key going forward. These changes have economic and political implications (Burke, 2017).

Prices are important in this proposed scenario to utilize both desalination and recycled water in the supply mix for San Diego County. If prices for freshwater are lower than prices for desalination, then desalination will not be a viable option as an alternative water use. However, we cannot count out the fact that residents may pay a premium in order to have a reliable, local and abundant source of water (Commission & others, 2004).

The price for water in the residential sector is equal to the MC of water. Climate change scenarios predict less precipitation, which would lead to water scarcity. Drastic price shifts often happen in times of shortages and surplus quantities. So we can conclude that when water scarcity enters the picture and prices for water rise to the market-clearing price, desalination should be increasingly supplied to substitute the existing supply of freshwater. Desalination becomes economically viable under this scenario. Once desalinated water supplies most of the potable water needs of the residential sector, the agriculture sector can use recycled water at capacity (5% of total supply) and then be supplemented by the freshwater that was freed up from the residential sector. Without alternative water sources, San Diego County could enter a water crisis era. Changes in water policy at state and local levels may need to help facilitate this adaptation in the future due to climate change (Davis & Chornesky, 2014).

If these alternative sources are removed from the supply mix, potential benefits of over $38 million will be left on the table in San Diego County. These sources of water, together, will help make a more water secure future for San Diego County residents and agriculture sector. Since San Diego County already has the Carlsbad Desalination facility operating and already uses recycled water for certain uses, the results from this paper imply that these alternative solutions are better used simultaneously, for different purposes. This appears to be the best allocation of the water resources in San Diego County with the given state of the economy, facility capacities, climate change scenarios, and water security goals for the future.

Chapter 8: Conclusion

Water scarcity due to climate change prompts the need for alternative sources of water to supply San Diego County because the current supply is already stressed. As long as the price for imported water from outside of San Diego County, such as the Colorado River or from northern California mountains, is lower than the price for desalinated water, then desalination will not be used. However, as climate change enters the picture, desalination will be a key factor in maintaining water security in San Diego County as underground water sources, including aquifers, will have less and less replenishment. The options for Southern California will be either to increase water imports, look to alternative water sources, or further rationing. With desalination, the scarcity problem is solved because the supply of seawater is seemingly limitless and is replenish-able. Recycled water is not accepted for direct consumption, but it can be used in the agriculture sector. Because of the cost structure in our model, supplying desalination to the agriculture sector would be too expensive due to minerals that would need to be added into the water. Recycled water would be too expensive to use in the residential sector because of the additional purification it would need in order to pass the effluent standards.

This paper concludes that the optimal allocation of desalinated water is to supply the residential sector with potable water, while recycled water is used at capacity to supply the agriculture sector for non-potable use. The desalinated water frees up the freshwater resource, which can then be utilized by the agriculture sector to supplement its water needs. Once desalination and recycled water sources are introduced into the water allocation model, water scarcity is no longer an issue and water management becomes the new focus.

With a water stressed future in mind, the water resources in San Diego County would be stretched thin and eventually underground sources will be depleted. But this can be avoided if desalination becomes a bigger share of the water supply than it is in 2015 (3% of the total water supply). By 2020, the Carlsbad facility is supposed to provide 8% of the supply of water and recycled wastewater is expected to be 7% ("Carlsbad Desalination Plant," 2017). Additional facilities may also need to be built if capacity per plant cannot be increased.

There were some limitations to the approach taken and they will be noted here. The first limitation is in regard to the natural gas component in the desalination process. The opportunity cost of natural gas was not included in this analysis. Because the Encina Power Plant provides the Carlsbad plant with energy, this energy could have been exported for other uses, which were not quantified in this model. The second limitation is that the storage of water was not considered in this analysis. We assume the stock of water to be a constant, for simplicity. The third limitation was that a single price for agricultural water and a single price for residential water were used across districts in each respective sector. A single elasticity of demand for water in the agriculture sector and a single elasticity for the residential sector were also used across districts. One cannot truly expect each district to have the same elasticity of demand and the same price for water. But this was a limitation with the available data because information on taxes and other fees were not available. So, using one price and elasticity to calibrate the demand equations for the agriculture and one price and elasticity to calibrate the demand equations for the residential sectors are possible limitations in the data. This caused the demand equations' intercepts to be the same intercept across districts. But, despite these limitations, the model's results and implications can still be seen as valid and representative of coastal regions.

This thesis is a response to Mo et al. (2014). Mo et al. (2014) analyzed San Diego and Tampa Bay, but this thesis provides a more in depth economic analysis of San Diego County. A better understanding of the implications using alternative water sources in San Diego County helps provide insights for the rest of the coastal communities in the United States. However, an argument could be made that the energy intense process of desalination could cause climate change to progress further; so, finding alternative sources of energy to power desalination facilities are key. Technological advancements could also help reduce the environmental cost of the desalination process and increase the capacity of the desalination facility. For future research, renewable energy could be included in the model so that it makes desalination a less environmentally impactful choice. Research on whether it is economically viable or not to have storage of desalinated water is also an option for further research. Going forward, the future looks promising that water scarcity may not be such an issue along the coastal U.S. as long as alternative sources of water are adopted.

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