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Life Cycle Assessment of Reclaimed Water for Potable and Nonpotable Reuse in California

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This Master's Project

Life Cycle Assessment of Reclaimed Water for Potable and Nonpotable Reuse in California

by

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Abstract

Extreme drought, water scarcity and population growth is forcing California to seek out new water sources. Reclaimed water is considered one of the best alternatives to alleviate water shortages and help meet the water demand sustainably. However, the environmental impacts of reclaimed water have not been fully studied to ensure that the overall benefits of reclaimed water do indeed outweigh the environmental, social, and economic costs. In this study a life cycle assessment (LCA) for potable (direct and indirect) and nonpotable reuse will be conducted to identify and quantify major environmental, social, and economic problems that are attributed to reclaimed water. Additionally, recommendations will be made to achieve optimal benefits for California by suggesting the best type of reuse to help meet water needs of municipalities with minimal impacts.

Acronyms

BG	Billion Gallons
CDF	California Department of Finance
CDPH	California Department of Public Health
CDWR	California Department of Water Resources
CIP	Clean-in-place
CSWRC	California State Water Resources Control Board
DPR	Direct potable reuse
HAA	Haloacetic acids
H_2O_2	Hydrogen peroxide
IPR	Indirect Potable reuse
MAF	Million acre-feet
MGD	Million gallons per day
MG	Million gallons
MF	Microfiltration
RO	Reverse osmosis
RW	Reclaimed water
LCA	Life Cycle Assessment
LCORW	Levelized cost of reclaimed water
NPR	Nonpotable Reuse
THM	Trihalomethanes

1.0 Introduction

Objective

Water scarcity in California is threatening the state's economy, environment and population. This water shortage is attributed to population growth, recent drought conditions and unpredictable climate change. Therefore, the need to increase water reliability and resiliency is essential to maintain the prosperity of the state in the years to come. Water managers have long recognized the importance of protecting water resources, and have long acknowledged that reclaimed water (RW) for potable and nonpotable reuse is necessary to prevent further degradation to water supplies. Reclaimed water is considered one of the best alternatives to help meet water demand sustainably. However, the environmental impacts of reclaimed water have not been fully studied to ensure that the overall benefits of reclaimed water do indeed outweigh the cost that reclaimed water has on the environment. Therefore, in this Masters Project a life cycle assessment (LCA) for potable and nonpotable reuse will be conducted to identify and quantify major environmental, social, and economic problems that are attributed to reclaimed water. Further, recommendations for best applicable reuse will be made reduce impacts for municipalities interested in reclaimed water. For purposes of this analysis, potable reuse will include both indirect and direct systems and nonpotable reuse will include agricultural/landscape irrigation. The common treatment process for each reuse will be analyzed. The assessment will begin at the point where wastewater effluent exits secondary treatment and end where water enters a water treatment plant or water is used for irrigation.

California Water Use

California uses approximately 38 billion gallons (BG) of water per day (USGS, 2010). About 95% of the state's water goes to irrigation, thermoelectric power generation and public supply. Irrigation uses about 23.2 BG per day or 60.7% of state's water, thermoelectric power generation uses approximately 6.6 BG per day or 17.4% of the state's water, and public supply utilizes 6.3 BG per day or 16.6% of the state's water. Only a small portion of water used daily is reclaimed. According to the California

Department of Water Resources, in 2009, roughly 669,000 acre-feet of wastewater was reclaimed (CDWR, 2013), which is equivalent to 0.6 billion gallons per day. The majority of this water is used for landscape and agricultural irrigation and only a small portion of this is used for groundwater replenishment. Furthermore, in 2010 it was estimated that about 1.35 billion gallons of wastewater were treated daily (Hauser, 2010). The majority of the wastewater treated in California is discharged into the Pacific Ocean, losing its value, as this water is not situated for any beneficial use.

Currently, California heavily relies on surface and groundwater supplies, which are under severe stress, resulting in numerous environmental, social and economic problems (Wyman, 2013). In times of drought, California's groundwater reservoirs can supply the state with about 60% of its daily water demand (Croyle et al., 2014). Groundwater basins are overdrafted because there are no regulations that prevent the exploitation of this water supply. This abuse has caused for the water table in nearly all groundwater basins to drop, resulting in land subsidence (land sinking), seawater intrusion, stream depletion, and decrease water quality (Croyle et al., 2014). Furthermore, the use of electricity increases, as more energy is need for pumping. For instance, in the San Joaquin Valley, the groundwater table is 100 feet below historic levels (Croyle et al., 2014) and land subsidence is occurring at a rate of one foot per year in some areas of the valley (Luhdorff and Scalmanini Consulting Engineers, 2014). In 2014, California approved the use of reclaimed water as a strategy to replenish and manage groundwater supplies so that land subsidence and soil issues can be resolved.

In addition, California is on its way toward its fourth consecutive driest year. The year 2013-2014 was declared the driest year on record, having a 34% below average statewide rainfall (Swain et al., 2014). As water shortages continue to stress our water system, increasing reliability of water supplies is necessary if we are to reduce our economic and environmental risks. Reclaimed water will not only reduce the amount of water that needs to be transported but will also increase resiliency against extreme drought. Recent studies conducted by NASA have concluded that 30-year megadroughts have a 12-60% probability of occurring in this century if greenhouse gases (GHG) stop increasing by midcentury. If GHG are not reduced, then the probability of megadrought increases to 80% (Cole et al., 2015). Therefore, the state has to be prepared so it can face these issues with minimal consequences to the economy and environment.

Not only is California facing an extreme drought, but also according to the California Department of Finance (CDF), the state population is expected to increase by 3.8 million and 14 million by 2020 and 2060, respectively. This means that water demand for public supply will increase by 10% by 2020 and 40% by 2060 if the current water consumption per capita is maintained at 181 gallons per day. California is also one of the world's major food producers; hence an increase in world population will result in an increase in water demand for the state. It is imperative for the state government to start managing water resources accordingly. In 2010, California used approximately 23.3 billion gallons per day (BGD) for irrigation purposes, consuming about 74% of all withdrawn freshwater (USGS, 2010). Presently, California produces roughly 400 different farm products, which in 2012 earned the state about $45 billion (Cooley et al., 2014). Therefore, irrigation is important for the state's economy. Historically, the state has reclaimed water for the agricultural sector in effort to reduce the demand of potable water. However, this effort seems to be failing as many farmers see reclaimed water as a cheap water supply to continue irrigating their crops and do nothing to conserve water, as that would be more economically expensive. California has established several regulations that specify how wastewater should be treated if it is going to be used in the agriculture sector. The state concluded that disinfected tertiary recycled water is the minimum treatment for edible crop irrigation. This means that effluent from wastewater needs to be filtered and disinfected before it is reused.

On January 2014, Governor Edmund G. Brown Jr. declared the drought a state of emergency and has authorized several grants and loans to launch recycling water projects throughout California to minimize water use and manage water supplies more efficiently. The state has allocated about $200 million in grants and about $800 million in low interest loans for municipalities interested in reclaimed water (CSWRCB, 2014). Similarly, on October 2013, senate bill SB322 was passed into law. This law requires the State Department of Public Health to analyze the feasibility of developing a uniform standard for direct potable reuse by June 30, 2016. If this new study demonstrates that direct potable reuse (DPR) is safe, then reclaimed water for potable and nonpotable reuse will be allowed in the state. However, before reclaimed water can be implemented in a statewide approach several factors need to be addressed to ensure this new water supply is placed to its best use in the short and long-term. This LCA will be implemented to quantify the environmental impacts and look for mitigation strategies; so reclaimed water can be incorporated into the state with minimal impacts.

Reclaimed Water and It's Benefits

According to the California Water Code 13050, reclaimed water or recycled water is wastewater that has been highly treated for suitable direct beneficial use or controlled use that otherwise would not occur. Reclaimed water (RW) is a valuable resource and is considered by many water managers to be one of the best alternatives to help meet water demand in a sustainable manner. Reclaimed water can help reduce demand of potable use, as RW can be recycled several times before losing its value. Hence, the potable water that was not used can be allocated to a more beneficial use, such as the environment. Many municipalities also see recycled water as a way to diversify their local water portfolios, so they can increase water reliability and resiliency. Reclaimed water reduces stress levels on local surface and groundwater supplies since it is used as an alternative water supply. Water transportation is expensive so reducing water volumes would decrease energy cost. Furthermore, it most cases water quality is improved because it dilutes contaminants. Advanced treated of reclaimed water yields a better water quality than most natural water supplies. In addition, reclaimed water is now used managing strategy for groundwater. Recycled water is used to recharge groundwater reservoirs and sustain the water tables at a certain level to prevent land subsidence. As drought conditions increase throughout the world, many water authorities now consider reclaimed water a viable new drinking water supply. Currently, two cities in Texas (Wichita Falls and New Spring) are reclaiming their wastewater for direct potable reuse. Direct potable reuse is not a new concept. Windhoek the capital of Namibia in Africa has been reclaiming its wastewater for drinking purposes since 1968. Overall, reclaimed water is a viable supply that can help meet California's future water demand, as population and water scarcity increases.

Regulations of Reclaimed Water

California is one of the leaders in reclaimed water, yet only a small percentage of wastewater is reclaimed in the state each year. However, this is changing as the state establishes goals and regulations to increase water recycling for potable and nonpotable reuse. California has established several policies and regulations to encourage an increase in recycled water in order to help mitigate stressors resulting from drought and population growth. Existing policies and regulations are shown in Table 1. The 2013 Recycled Water Policy (CSWRCB, 2013) sets specific goals to increase recycled water in target years 2020 and 2030 by one million acre feet (MAF) and two MAF (from 2002 levels) per year, respectively. The state is also seeking to promote potable reuse to help increase the state's water supply. Key agencies have been identified to regulate reclaimed water. The California State Water Resources Control Board (CSWRC), Regional Water Boards, California Department of Public Health (CDPH), and California Department of Water Resources (CDWR) have been selected to regulate reclaimed water projects. Another current ruling is Title 22 of Code of Regulations, which defines criteria for treatment and usage of reclaimed water for irrigation and groundwater recharge projects. On June 18, 2014 the state implemented rules to regulate indirect potable reuse by setting guidelines for groundwater replenishment projects. In addition, the CDPH is investigating the feasibility and safety of direct potable reuse, so it can be approved. Finally, Title 17 protects drinking water supplies from contaminants and may possibly regulate potable reuse. All of these regulations seek to increase reclaimed water usage to help increase the resiliency and reliability of water.

Table 1: California's policies and regulations for reclaimed water.

Regulations	Description:
Recycled Water Policy, 2013	• Increase recycled water levels of 2002 by at least one MAF by 2020 and two by 2 MAF by 2030 • Encourages potable reuse as way to meet state goals

Title 22 Code of Regulations, Division 4, Chapter 3	• Defines treatment and use criteria for recycled water • Regulates reclaimed water for irrigation and groundwater replenishment projects • Disinfected tertiary treatment is required for water that is for public use and irrigation of edible crops • Gives methods for testing and analysis
Title 17 Codes of Regulations, Division 1, Chapter 5, Group 4	• Regulates drinking water supplies • Protection drinking water supplies from nonpotable reuse water with backflow preventers

Types of Reclaimed Water

Potable

Reclaimed water can be used for potable or nonpotable purposes; treatment is chosen based on its intended use. Potable reuse is not as common due to public opposition, stricter regulations, and high costs (Dahl, 2014). Furthermore, there are two types of potable reuse, which are direct potable reuse (DPR) and indirect potable reuse (IPR). DPR is defined as recycled water that meets or exceeds drinking water standards and is directly injected into a potable distribution system or discharged immediately upstream of a water treatment plant (Tchobanogloues et al., 2011). Usually, the effluent from DPR is blended with local water supplies to reduce risk, improve water quality, and increase public acceptance (Tchobanogloues et al., 2011). DPR does not require a long retention time because it is assumed to be safe for consumption. Municipalities are now considering DPR systems, as a viable water supply to help meet increasing water demands, in part due to their superior water quality. In addition, cities that are trying to diversify their local water supply are pursuing reclaimed water. For instance, San Diego is currently working on a program to diversify its water supplies, so that the area can be resilient against drought, climate change or any political issue that might rise from water scarcity.

Indirect potable reuse is more common, and it may be planned or unplanned. In a planned IPR system wastewater is treated to meet drinking water standards and is discharged into an environmental buffer, where it will be stored for a minimum of six months (CDPH, 2008). A residency time of six months is recommended to gain public acceptance and continue to remove viral contaminants (Tchobanogloues et al., 2011). Also, it will allow for water to mix with other water, hence further reducing health risks, as bacteria would degrade contaminants. IPR treatment process is similar to DPR. However, aesthetics and taste is not a priority since water will not be used immediately. For example, Orange County has an IPR system that was designed to recharge three local basins and prevent seawater intrusion. Unplanned IPR, or *de facto* reuse, is treated wastewater that is released into natural water systems, which is later used unintentionally by other municipalities downstream of the natural system (NAP, 2012). Often this water only receives secondary treatment before it is discharged. Cities along the Mississippi River exemplify *de facto* IPR. Thus far, no human health problems are attributed to *de facto* water reuse (Gerrity et al., 2013). However, the water quality of the Mississippi River has declined as alga booms and anoxic conditions prevail due to the effluent that has been discharged into the river.

Nonpotable

Historically, wastewater has been used in the agricultural sector. However, due to sanitation and environmental problems, this method was discontinued as stricter regulations were adopted to protect public health. Treatment of reclaimed water for nonpotable reuse (NPR) has been practiced in California for about 100 years. In 1932, the city of San Francisco started reusing its wastewater to irrigate Golden Gate Park but discontinued it in 1978 when the plant was shut down because it did not meet new regulations (SFPUC, 2015). This was the first urban water reuse project. Regulations were adopted to encourage water reuse as water scarcity become apparent. Recently, the popularity of reclaimed water for agricultural irrigation has increased; drought conditions and incentives make this supply more appealing to farmers. The treatment of NPR depends on its intended use. For irrigation of public areas and irrigation of edible crops, disinfected tertiary treatment is required. For other uses that do not necessarily come into contact with people, need less treatment.

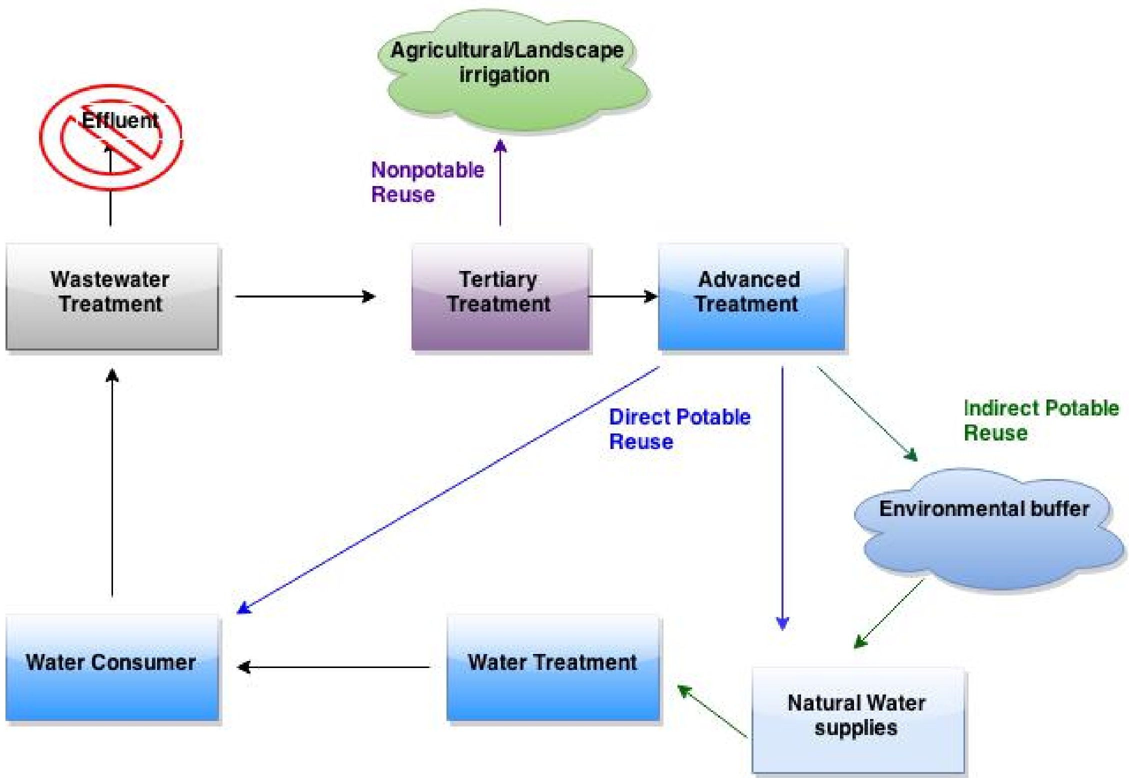

Figure 1: Types of reclaimed water. Wastewater was evolved from wastewater to nonpotable reuse (NPR) to indirect potable reuse (IPR) to direct potable reuse (DPR).

What is a Life Cycle Assessment?

Life cycle assessments (LCAs) were developed to track the flow of resources and account for environmental impacts attributed to the production of goods. The International Organization for Standardization (ISO) is responsible for defining and specifying methods and procedures to conduct LCA (Horne et al., 2009). However, due to the complexity and diversity of projects, ISO does not describe specific techniques or methodologies for the individual phases of LCA (ISO 14040, 2006). The validity of LCA studies depends on the scope established by the analyzer, by the data collected, and by the assumptions that were made. There are specific programs that analyze the life cycle of water. For example, LCAqua software was developed by KIWA Research and Consultancy and assesses the construction and decommissioning phases of potable water treatment plants (Vince et al., 2007).

The implementation of this analysis can be expensive and long, as precise data is needed to account for resources and evaluate impacts. In addition, expensive software programs that have been specifically designed to conduct LCA's are typically used. An

LCA is divided into four phases. Phase one, defines the goals and scope of the project. Phase two, life cycle inventory, is the collection of a detailed inventory to account for all resources used throughout the product's life cycle. Phase three, life cycle impact assessment, quantifies impacts concerning health, environment, social, and economical issues. Finally, stage four, includes a life cycle improvement analysis and interpretation. Recently, this method has been expanded to incorporate and track GHG emissions. The life cycle assessment presented in this Masters Project will evaluate chemical and energy, materials, and land use and waste generated to help assess health and environmental risks and social and economical impacts.

2.0 Methodology and Assumptions

Assumptions and Boundaries

In this Masters Project, it was assumed that the most common treatment process for potable reuse (direct and indirect) was microfiltration, reverse osmosis and advanced oxidation (MF/RO/H2O2-UV). For NPR, it was assumed that the common treatment of use is microfiltration and disinfection using chlorine (Cl_2). This was determined by examining current treatment plants in the United States, specifically California. Data collected were from peer reviews and from future projects. The beginning of each progress was assumed to start once the effluent exists secondary treatment. The end was determined by its intended use. For potable reuse, the life cycle ends once water is delivered to a water treatment facility so it can be treated. For NPR, cycle ends when water is used for irrigation and water percolates soil. Refer to Table 2 for a detailed description of the assumptions made for this LCA.

This study does not include the transportation of chemicals that were used during treatment and sludge generated (dewatered brine) to and out of the treatment plant or the energy required to make these chemicals. However, it accounts for the impacts associated with the amount of chemicals used. For the NPR system, it was also assumed that sprinkles are used during irrigation as a strategy by this sector to increase water conservation. This study will include waste generated, energy consumptions, materials and resources that were depleted by constructing these plants and their social and economic impacts. Due to time constraints and lack of resources, this LCA does not have specific data nor does it use any LCA software. However, based on studies, and this analysis, environmental impacts are analyzed. Data will be quantified using existing methods and literature review.

Table 2: Assumptions and boundaries of LCA.

Systems	Assumptions
Potable reuse (IPR and DPR)	1. Treatment: MF/RO/UV-H_2O_2 2. Starts: effluents exits secondary treatment 3. Ends: reclaimed water enters a treatment plant 4. Does not include the energy used to produce chemicals that are used, but it will account the impacts that are associated with their use 5. Does not include the energy used to transport chemicals or sludge from or to treatment plant
Nonpotable reuse (NPR)	1. Treatment: MF/Cl_2 2. Starts: effluents exits secondary treatment 3. Ends: reclaimed water percolates soil after it was used for irrigation 4. It is assumed sprinkler irrigation was used in the agriculture sector as a strategy to conserve water 5. Steps 4 and 5 are also applicable to nonpotable reuse

Life Cycle of Potable Reuse

The treatment process of reclaimed water depends upon its intended use. For potable reuse a multi-barrier treatment process is required to mitigate risk that can result from treatment failure. The removal of organic compounds, heavy metals, pathogens, viruses, total dissolved solids (TDS), and trace organic compounds is necessary to reduce health risk and to make water aesthetically pleasant. Currently, there are approximately 20 different treatment trains (Gerrity et al., 2013) used worldwide; all such systems will remove most if not all of these contaminants. These multi-barriers systems are designed to be resilient, redundant, and robust to meet all regulatory standards (Gerrity et al., 2013). Multi-barrier treatment is preferred for potable reuse systems because reclaimed water is held to higher standards by the government and public. Therefore, DPR and IPR provide a higher level of protection against pathogens and other contaminants than natural water supplies. Most of the advanced treatment processes incorporate a variation of the following technologies: granular activated carbon, membrane filtration, biological activated carbon, ozonation, advanced oxidation (UV/H_2O_2), and stabilizations. Microfiltration, reverse osmosis, and advanced oxidation (MF/RO/UV-H_2O_2) is often considered the standard treatment process for potable reuse (Gerrity et al., 2013). However, this process is energy intensive and expensive. The life cycle of DPR and IPR using an MF/RO/UV-H_2O_2 treatment process will be analyzed, as it is representative of a standard potable reuse system. See Figure 2 for the life cycle diagram of an MF/RO/UV-H_2O_2 treatment process for both a DPR and IPR system.

The life cycle of both DPR and IPR starts once the effluent exits secondary treatment. Prior to microfiltration, a chemical, such as ferric chloride or alum are added to the effluent to coagulate TDS and increase MF efficiencies. In addition, chlorine is also added to kill any bacteria that might reproduce in the MF system. Water is then pumped through a microfiltration (MF) system, where particles greater than 0.1 microns are rejected (MF filter pores range form 0.1-2 microns, the size depends on the type of water and treatment required). After microfiltration, permeate is pumped and stored until it is fed into the reverse osmosis (RO) system. Before water is passed through RO, sulfuric acid, citric acid, or sodium tripolyphosphate (STTP) are added to help increase the performance of RO. Additionally, water is passed through a cartridge filter system prior to RO. After the RO process, the pH of the effluent is stabilized, since the accumulation of carbon dioxide (CO_2) in water decreases pH. Acidic conditions can erode pipes and equipment if water is not balanced. Therefore, air stripping is needed to remove CO_2 from water. Once water is readjusted, water is then disinfected using hydrogen peroxide and exposing it to high intensity UV light. This process oxidizes (breaks down) any pathogens or chemicals that might have passed through RO.

This treatment system requires maintenance to keep membranes operating at maximum performance. Maintenance such as backwashing is necessary to maintain desired operating pressure, so costs can be minimized. A backwash system removes accumulated solids from membrane by passing back filtrate water every 15 to 60 minutes or when high pressures are present. In this process, membranes are aerated for 30 seconds to 3 minutes (MRWA, No Date). In addition, the MF and RO filters go through a daily chemical cleaning where acids or chlorine are used to clean membranes. This cleaning process increases cleaning periods and prevents early fouling of membranes.

As a final treatment step, water is stabilized and minerals are added to equilibrate filtrate. This is done to protect pipes by adding minerals to reduce the corrosiveness of water. During stabilization pH, alkalinity, and hardness is balanced for taste and to reduce reactiveness. After treatment, water is sent to its respective area of use. Environmental buffers and residency time are the main differences between DPR and IPR. For DPR, water is transported to a water reservoir so it can be treated for drinking purposes. Usually DPR, water is blended with local water supplies to reduce health risks and to improve the water quality of these supplies. The ratios vary with time and water availability. Some municipalities may only blend in 10% of reclaimed water, while other may blend up to 75% (Meehan et al., 2013). However, DPR water can also be sent directly to consumers, without further treatment. This is currently not implemented due to public opposition and concerns about health issues. For an IPR system, the effluent after advanced treatment is sent to an environmental buffer where water is blended and stored for a minimum of six months before it can be used for potable purposes. California is using groundwater recharge as a way to incorporate IPR in the state and to help meet its water reclamation goals. This process is also a strategy to help manage groundwater resources more sustainably. Groundwater recharge using reclaimed water takes longer, and it is more energy intensive as water is pumped into or naturally infiltrated to groundwater basins. Once residency time is over, water is pumped back out so it can be delivered to a water treatment plant, where it is treated to meet drinking water standards.

The Orange County Water District (OCWD), in conjunction with the Orange County Sanitation District (OCSD), just completed expansion of its Groundwater Replenish System (GWRS) project. This project was designed to reclaim water for indirect potable reuse (IPR) to help recharge their local groundwater supplies and serve as seawater intrusion barrier. Approximately, 30 MGD are used as a seawater intrusion barrier in the Huntington Beach and Fountain Valley. The remaining 70 MGD are transported about 13 miles northeast to three local basins (Kraemer, Miller, and Miraloma) where water is used to replenish these basins naturally. This system serves about 600,000 resident daily. By the end of 2015, the project will have a capacity to reclaimed about 100 MGD (GWRS, No Date).

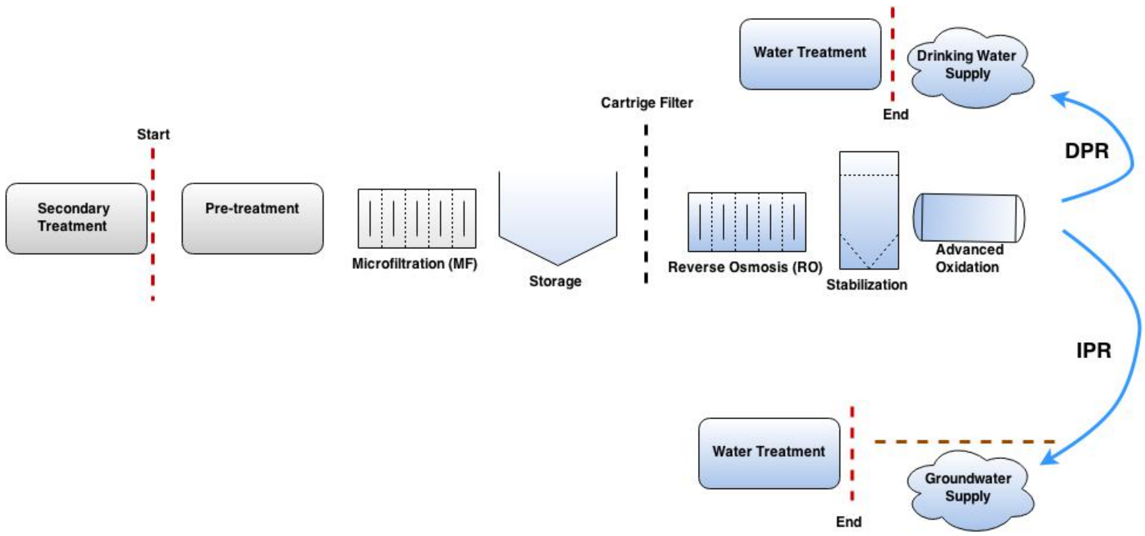

Figure 2: Life cycle of an MF/RO/UV-H2O2 standard process. This treatment train is used or is prosed at the Orange County Groundwater Replenishment System, Wichita Falls and Big Spring Texas, San Diego Purification systems and Westside Reclamation plant (San Francisco).

Life Cycle of Nonpotable Reuse

Title 22 regulates nonpotable reuse (NPR) in California. Water for irrigation that comes into contact with the public or edible crops must receive disinfected tertiary treatment. The State Water Board has identified tertiary treatment as water that is filtered and disinfected. Reclaimed water for irrigation purposes has been used for several decades, since early 1960's, in the state. There are several plants that receive tertiary treatment for agricultural purposes. For example, cities like Monterey Bay, Perris, Los Angeles, and Bakersfield have plants that use reclaimed water for agriculture. Usually, the treatment process is less energy intensive than potable reuse, since it does not required advanced treatment like reverse osmosis (RO). Historically, sand filter, activated carbon and cloth filters are commonly used. These technologies are less energy intensive than microfiltration (MF). However, as microfiltration becomes affordable, new and old treatment plants are now updating to MF. The pore size of membranes will differ depending on the water's intended use. Pore sizes range between 0.1 and 10 micrometers (Fabris et al., 2006). The smaller the size, the more energy the system uses to pass the wastewater through the membrane. Therefore, some municipalities will chose a larger pore size if cost is a priority. For the purpose of this analysis, microfiltration will be used as the preferred filtration process, since most plants are updating to this new filtration technology and it has becomes more economically feasible. Usually, NPR water is transported longer distances because this water has controlled purposes. Additionally, a separate distribution systems is needed to transport water so cross contamination is avoided.

For NPR, the treatment starts when water leaves secondary treatment. Water is then coagulated so microfiltration can be facilitated. Coagulation allows for dissolved solids to be filtered as particles flocculate and makes it easier to settle. Ferric chloride or an aluminum base coagulants (alum) are frequently used as a pretreatment for filtration. The concentrations of these chemicals depend on the water treated. Water then is passed through an MF system, where particles greater than 0.1 microns are filtered out (depending on the pore size of the membrane). Larger pore sizes reduce operation costs. In NPR, a larger pore size is preferred since water is not used for drinking and regulations are not as stringent. Maintenance of an MF system also needs constant backwashing and chemicals to reduce irreversible fouling (Fabris et al., 2006). In addition, a clean in place system is needed to clean membranes every 30 to 60 days.

The permeate is then sent to a storage tank where chlorine is added to disinfect water. The contact time with chlorines is a couple hours, so pathogens that were not filtered out are killed before water is conveyed to consumers, which can include farmers or commercial buildings. Moreover, water storage is necessary as flow is dependent on time. In the past, storage tanks were not built due to the unknown demand of reclaimed water. However, as reclaimed water becomes more popular, water storage will be needed. Water can be stored in storage tanks, ponds or lakes until it is needed.

The distribution of NPR water requires a separate pipe systems so cross-contamination can be prevented. In the case of reclaimed water, purple pipes are installed in areas where reclaimed water is desired. These pipe systems can range in distance from several miles to hundreds of miles. In dense agricultural areas, reclaimed water transportation might be preferable because it requires less piping as a central pipe system can be installed to distribute water. In urban areas, piping system might be more difficult because reclaimed water must be transported to different locations and the pipe system might compete with existing utilities. In addition, cross contamination is more likely to occur, thus needing more maintenance and operation. Personnel have to be trained to mitigate cross contamination of drinking water supplies. The energy used for crop irrigation was included in the LCA because the cycle of reclaimed water ends when water percolates soil and returns to the environment. Refer to Figure 3 for the life cycle of recycled water for nonpotable reuse.

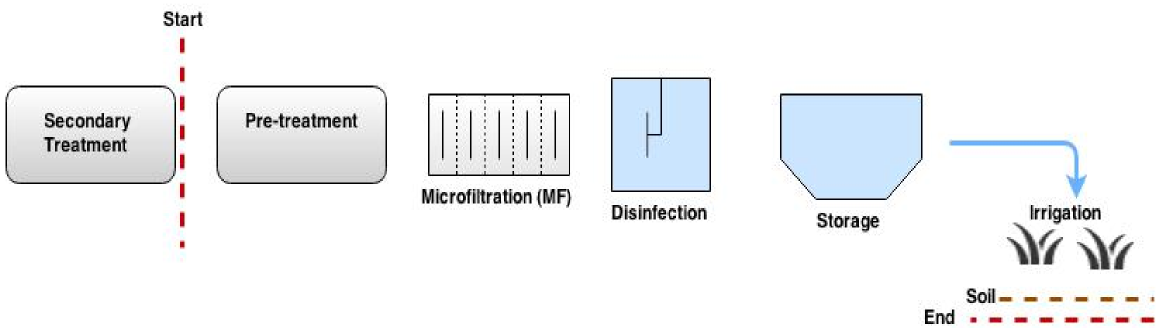

Figure 3: Life cycle of nonpotable reuse (NPR). It was assumed that NPR water is treated using microfiltration and chlorine to disinfect water.

3.0 Life Cycle Inventory

Chemical Inventory

Overall, similar chemicals are used for both potable and nonpotable reuse. It is estimated that potable reuse uses about eight times more chemicals than NPR (Scimmoller et al., 2013). The amount of chemicals used depends on the volume of water that is treated and on the type of treatment. Strong acids and bases are used to clean and maintain membranes. Strong oxidants, such as chlorine and hydroxyl radicals, are used to disinfect water. Detailed inventories of the chemicals used for potable and nonpotable treatment are provided in the following subsections.

Potable Reuse

Several chemicals are used to treat reclaimed water, and the amount of chemicals used is roughly proportional to the volume of water treated (Tong et al., 2013). Chemicals, such a ferric chloride ($FeCl_3$), chlorine (Cl_2), citric acid ($C_6H_8O_7$), sulfuric acid (H_2SO_4), sodium hydroxide (caustic soda, NaOH), and sodium hypochlorite (NaClO), are typically used. See Table 3 for a full list of chemicals used during each treatment process and Figure 4 for an illustration of where chemicals are used. These chemicals are used as a pre-treatment or as a cleaning solution to clean filtration membranes. Chemicals used daily to reduce fouling and clogging are called chemical enhanced backwash (CEB). Usually, these chemicals are added to prevent fouling (Fabris et al., 2006) of membranes and increase in-between cleaning periods. In an MF/RO/H_2O_2-UV system, before effluent enters an MF system, a coagulant is added to precipitate most of the dissolved solids, hence, facilitating the filtration process. Ferric chloride ($FeCl_3$) or aluminum base coagulants, like alum, are used in wastewater treatment to coagulate particles and prevent clogging. Concentrations between 5-15 mg/L are used to coagulate water (Gaulinger, 2007). The amount of coagulant depends on the quality of water that is treated. Additionally, chlorine concentrations below 0.5 mg/L are added to the water prior to MF to form chloramines (MRWA, No Date). This byproduct acts as biocide, which prevents microorganisms from attaching and reproducing in the membranes. Moreover, chlorine is preferred due to its compatibility with RO and MF membranes (Bartels et al., 2004). After permeate exits MF additional chemicals, such as citric acid, sulfuric acid, sodium tripolyphosphate (STTP), and sodium salt of ethylamidiaretetraacetic acid are added to prevent fouling of RO membrane (Bartels et al., 2004 and Rukapan et al., 2015). The amount of these chemicals varies, based on the type of water that has to be treated. These concentrations are also determined based on their economical and chemical feasibility. Following RO, the pH is balanced using air to remove CO_2 and on some occasions, minerals are added to the water to balance it and reduce corrosion hazards.

Supplementary chemicals are used to clean membranes and remove buildup, so pressures can be decreased in the system. Generally, treatment plans have a clean-in-place (CIP) system, where membranes are soaked in acidic solution to remove any buildup. This cleaning procedure is done every 30 to 60 days depending on the permeability of membrane. The chemicals that are typically used are citric acid, sulfuric acid, and sodium hydroxide (Bartels et al., 2004). Acidic conditions are favored to remove inorganic scaling in the membranes and basic conditions are used to remove organic scaling (Warsinger et al., 2015). The waste generated from cleaning is first neutralized and then discharged back into the wastewater treatment plant so it can be treated and be discharged.

Chlorine, ozone (O_3), and advance oxidation (H2O2-UV light) are frequently used for disinfection. However, advanced oxidation is preferred as it breaks down contaminants. Hydrogen peroxide is used as a radical to speed oxidation when water is exposed to UV light. Hydrogen peroxide concentrations of 10-30 mg/L are used to reduce the formation of trihalomethanes (THMs) (Molnar et al., 2015). The oxidation process breaks down contaminants, such as organic compounds and endocrine disruptors that can cause health problems. The breakdown of organic matter occurs when wavelengths between 200-300 nanometers (nm) are absorbed by DNA molecules, resulting in the deactivation of living cells (Schalk et al., 2006). Therefore, advance oxidation with hydrogen peroxide and UV light decreases natural organic matter (Molnar et al., 2015). The efficiency of the oxidation is affected by the turbidity of the water and presence of particulates because these parameters might block UV light from killing organic matter.

Finally, in some cases essential minerals like carbonate and magnesium are added to balance water and minimize water "aggressiveness" and protect soil (Khan, 2013). The addition of minerals increases hardness and alkalinity. Additionally, these minerals are added for taste, as water free of ions (minerals) is said to have a metallic taste. Sodium hydroxide (NaOH) or lime (CaO) is added to adjust pH, alkalinity, hardness, and total dissolved solids (TDS). In some cases, municipalities do not use these chemicals; instead, they just blend reclaimed water with local supplies, as the hardness from these waters adds the necessary ions. This methods balances reclaimed water and improves water quality of natural water bodies. Overall, for both potable and nonpotable reuse, the treatment process uses all the chemicals. It is assumed that no other chemicals are added once treatment is completed.

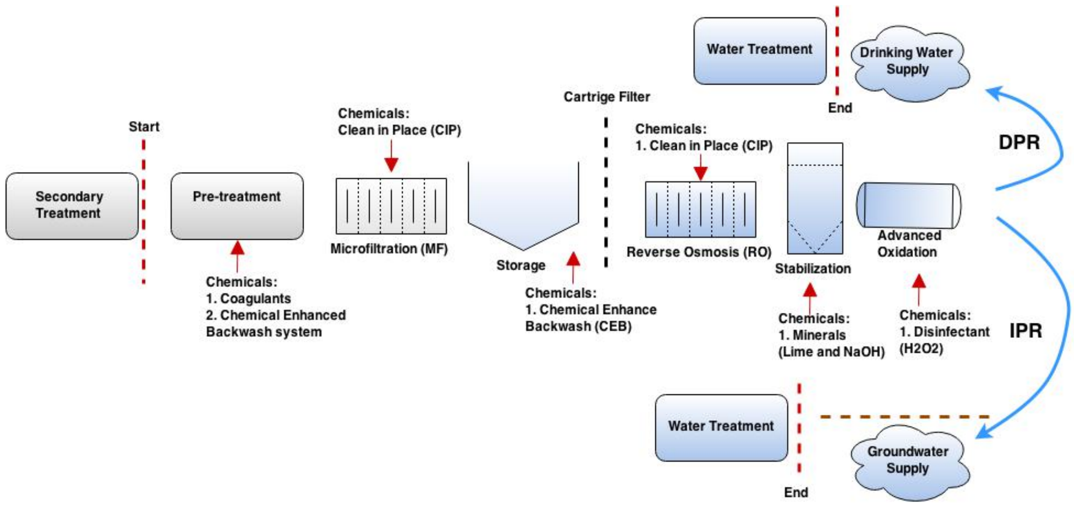

Figure 4: Chemical use through the life cycle of IPR and DPR.

Nonpotable Reuse

The amount of chemicals used for nonpotable reuses is about eight times smaller than potable reuse (Schimmoller et al., 2013), since less treatment is needed. Coagulants, disinfectants, and cleaning solutions will also be needed for this treatment. In NPR systems, water only needs to be filtered and disinfected. Therefore, wastewater needs to be coagulated using ferric chloride of an aluminum-based coagulant. Chlorine is used for both disinfection and maintenance of the MF system. Acidic solutions are also used to clean MF membrane to remove any scaling of the membrane and reduce fouling. The amount of chlorine used is larger, since this chemical is used for two purposes. A small concentration (<0.5 mg/L) of chlorine is added prior to MF, so fouling of the MF can be reduced. For disinfection, a chlorine concentration between 5-20 mg/L is used to kill pathogens and viruses (USEPA, 1999). Unspent chloride provides protection during conveyance (Wu et al., 2009). In industry, the usage of sodium hypochlorite and calcium hypochlorite is used for chlorination. Chlorination requires high dosages and long contact time to be effective. See Table 3 for a list of chemicals used.

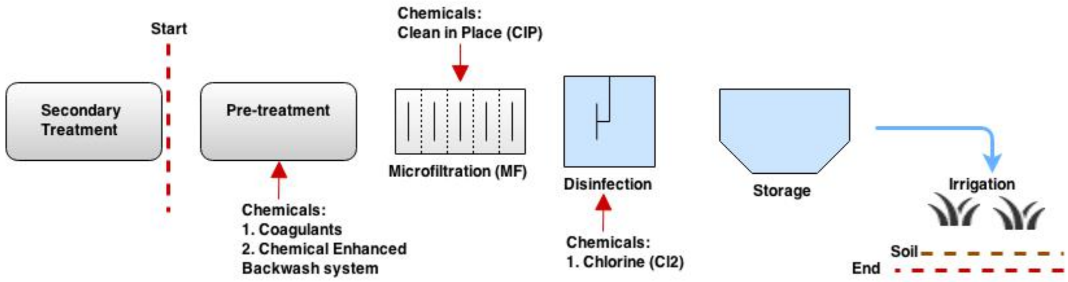

Figure 5: Chemical use through the life cycle NPR.

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Table 3: List of chemicals used in reclaimed water. Exact chemical amount will depend on the water quality and volume of water treated. However, potable reuse uses about eight times more chemicals than NPR (Schimmoller et al., 2013). Data were collected from peer reviews and conceptual engineering reports of San Diego, 2013.

Chemical	Type	Concentration	Nonpotable	Potable
Coagulants (pre-treatment)	Ferric Chloride	5-15 mg/L	MF	MF
	Aluminum based Coagulant (Alum)			
Chemical Enhance Backwash (Pre-treatment)	Chlorine (3ppm)	<0.5 mg/L	MF	MF and RO
	Sulfuric Acid	pH: 2-3		
	Citric Acid			
	Sodium Hypochlorite			
Clean in Place (CIP)	Citric Acid	pH: 2-3	MF	MF and RO
	Sulfuric Acid			
	Sodium Hydroxide	pH: 10-11		
Disinfectant	Hydrogen Peroxide	10-30 mg/L	No	Yes
	UV light	0.5 moles of UV photons/ mole -OH	No	Yes
	Chlorine	5-20 mg/L	Yes	No
Stabilization	Sodium Hydroxide (NaOH)		No	Yes
	Lime (CaO)			
Total			**9**	**11**

Waste Generation

The waste generated depends on the size of the treatment plant. Potable reuse will yield more waste, as more brine is produced (about 25% more) during treatment. Additionally, more equipment needs to be disposed off, like membranes and lamps bulbs that are used, hence, creating more waste. Quantities were not calculated because no real data were obtained. However, assumptions based on the efficiencies of the membrane filtration systems were used to estimate brine volume.

Potable Reuse

The main waste generated in water recycling is sludge, brine, chemicals from backwash, and filtration membranes (MF and RO), and mercury lamps from the UV system. MF systems generally have an efficiency of about 95%. This means that about 5% of the wastewater is rejected and becomes brine. Similarly, an RO system has a 75% recovery rate. Therefore, 25% of the permeate from the MF becomes brine. Therefore, approximately 30% of the wastewater becomes brine in potable reuse. Brine contains high concentration of TDS, organic and inorganics compounds, and pharmaceuticals. Currently, there are no regulations on how to properly dispose of brine. Some utilities chose to discharge their brine without treatment if they have access to the ocean to reduce cost. Additionally, contaminants of emerging concern are not regulated. Hence, health and environmental issues can arise with the disposal of brine. If the brine is not discharged after wastewater treatment, then brine is dewatered. In this process, water is evaporated either mechanically or naturally by evaporation, and the sludge is sent to a landfill. These processes requires chemicals and energy. In addition, water that was used to clean membranes needs to be neutralized before disposal (USDIBR, 2010).

Filter membranes have to be replaced once permeability cannot be restored by CIP process. The life expectancy of a membrane is estimated to be five years (Pinnau, 2008). Once the membrane surpasses its lifespan, waste is generated. Membranes are made of different materials; the most popular membranes are made of polymer, metals, or ceramics (Reif, 2006). Currently, there are no proper disposal methods or recycling procedures to properly dispose of these technologies. Therefore, most of these membranes end up in landfills or are incinerated (Netravali et al., 2003). This waste has the potential to stay in the environment for hundreds of years, as degradation is slow. Finally, the low-pressure mercury lamps that radiate UV light are a hazardous waste, since mercury is used in the light bulb. The state has regulations stating the proper disposal of these lamps. The manufacture lifespan of these lamps is estimated to be about 8,800 hours or one year (USEPA, 1999). Currently, there are proper ways to recycle mercury from lamps, so the environmental impacts can be mitigated. However, the energy used to recycle lamps increases emissions and costs. Waste is also generated from the installation of a pipe network. However, this will not be considered since most waste would be generated every 20-50 years.

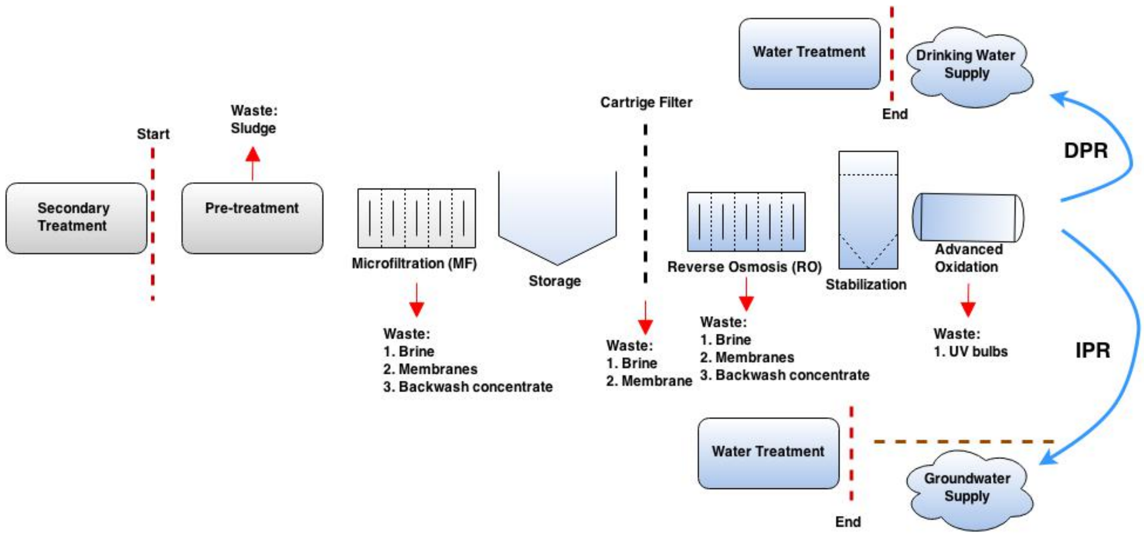


Figure 6: Waste generated during potable reuse for both DPR and IPR.

Nonpotable Reuse

The waste generated from this treatment is sludge, brine, backwash, and microfiltration membranes. The total amount of waste depends on the size of the treatment plant. The higher the capacity of the plant, the more chemical waste and brine generated. The waste disposal is similar to the disposal of potable reuse waste. However, less waste is generated as fewer materials are used for treatment. Similarly, less backwash effluent is generated since backwashing is only done to MF and not RO. Consequently, effluent from backwash is cut down by about half. Sludge production is estimated to be about the same since most of it is produced during coagulation (pre-treatment).

Less brine is produce since only about 5% of water treated is rejected in the microfiltration step. The amount of brines is smaller, which makes it easier to dispose of. There are several ways in which brine can be discharged. One way is by discharging it into the ocean. The second is to dispose of brine by mechanically evaporating excess water. The third method is to evaporate brine by using evaporation ponds. The difference between these disposal processes is the amount of energy, chemicals, and costs that are invested to discharge of brine. Moreover, it is more expensive to install evaporation ponds than to install a mechanical system. However, the most energy intensive and environmentally harmful is mechanical evaporation. The least expensive method would be to discharge brine into the ocean. However, this disposal method does not include the environmental impacts that result as a consequence of discharging into our aquatic systems.

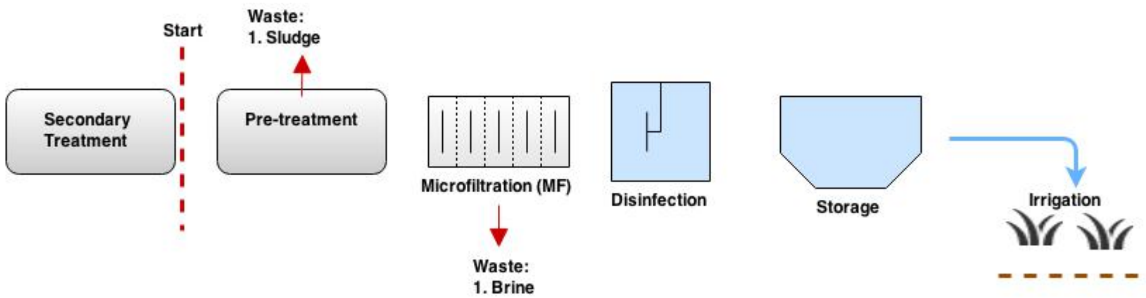


Figure 7: Waste generated during NPR

Energy Consumption

California uses about 30% of its natural gas, 19% of its electricity, and about 88 billion gallons of diesel fuel every year to transport, pump, treat, distribute, and dispose of water that is used by Californians (Copeland, 2013). For most municipalities about 30-40% of their electricity bill is attributed to treatment of both water and wastewater (Copeland, 2013). In addition, during dry years less energy is generated, yet more energy is needed to pump groundwater. For example, in 2004 it was estimated that about 4.4 billion kWh of electricity were used for groundwater pumping (Cohen et al., 2004). The State Water Project (SWP), which transports water from the San Francisco-Delta to Southern California, uses about 2 to 3% of the state's electricity.

Energy use for potable and nonpotable reuse is difficult to calculate because it depends on the treatment process and on the distance and altitude to where water is transported. The implementation of reclaimed water will increase the energy-water, as more energy is used to recycle water. For instance, irrigation systems significantly increase energy usage for nonpotable reuse. For the purpose of this LAC, only direct energy use will be considered. The energy used to transport chemicals from and to the treatment plant will not be accounted for, as will the energy used to dispose of waste outside the facility.

Potable Reuse:

Because potable reuse uses energy for treatment and distribution, energy consumption is a big part of operating pumps, aeration systems, CIP cleaning systems, monitoring, and groundwater injection. A preliminary study by the City of San Diego estimated that to power a 15 MGD reclamation plant, it would cost the city about $4.3 million annually. This cost estimate excludes the cost of conveyance. A high quantity of energy is required to pump water through the small pores of the MF and RO membranes. High pressures are needed so water can be passed through membranes, which increases energy usage. All treatment processes use different amounts of energy. For example, reverse osmosis requires about twice the amount of energy than microfiltration and cartridge filtration, using about 0.0011 to 0.05 kWh per cubic meter (kWh/m^3) (Bahman, 2015 (Tchobanoglous et al., 2014)). During disinfection, the low-pressure mercury lamps use about 0.3 to 0.5 watts per square centimeter (W/cm^2) or about 0.021 to 0.066 kWh/m^3 of treated water. See Table 4 for a list of the energy usage in kWh per meter cube of treated water. Calculating the energy use for conveyance will vary from place to place since it depends on the distance and change in head (elevation). For example, in some areas of California it takes about 2.4 kWh/m^3 to pump water in a tunnel for 16 kilometers and elevate water 600 meters (Matos et al., 2014 and COA, 2010). In potable reuse, water will need to be transported to the designated groundwater basins or to temporary water storage reservoirs.

Typically, wastewater treatment plants are built in locations near sea level and near aquatic systems, like streams or oceans. Low altitudes are desired to facilitate wastewater collection and reduce energy use, since water can flow to these facilities via gravity. Municipalities also save money by building these plants near aquatic systems because disposal cost are reduced, as the effluent can be discharged into nearby aquatic systems. Reclaimed water requires for the filtrate to be transported to areas of use. As a result, energy usage and cost will increase with transportation. The distance that the water needs to be transported will depend both on the location of the treatment plant and the designated storage place. It is estimated that pumping and collecting water consumes about 0.003 to 0.04 kWh/m^3 (Matos et al., 2014). This cost might be higher for certain areas of the state. For instance, a study in 2005 conducted by the California Energy

Commission showed that supply and conveyance of water in northern and southern California varied drastically. Northern California uses about 150 kWh per million gallons for conveyance, while Southern California uses approximately 8,900 kWh per million gallons (CEC, 2005). Therefore, Southern California would benefit the most from reclaimed water for potable reuse than Northern California, because it would be more cost effective.

The energy use for indirect potable reuse is slightly higher than direct potable reuse. This is because water needs to be transported to groundwater basin where water is stored for at least six months and then it is extracted and transported to water treatment facilities. Groundwater pumping is energy intensive. The Environmental Protection Agency (USEPA) estimates that a municipality that uses groundwater as a water supply uses about 1800 kWh per million gallons of water or about 0.4755 kWh/m^3. Of this energy, approximately 90-99 percent is used for groundwater pumping (USEPA, 2013). Assuming that 90% of this energy is used for groundwater pumping, it is estimated that an IPR systems uses about 0.43 kWh/m^3 more than direct potable reuse. In groundwater pumping the energy use depends on the efficiency of the pumps; the vertical elevation that water needs to be lift and the volume of water that is extracted. Surveys indicate that groundwater pumping for industrial and domestic uses cost about $0.07 per cubic meter (Zhu et al., 2007). Groundwater basin are not being replenished at the rate at which water is extracted, thus the price of pumping has increased during the past few years, as the water table is lowered.

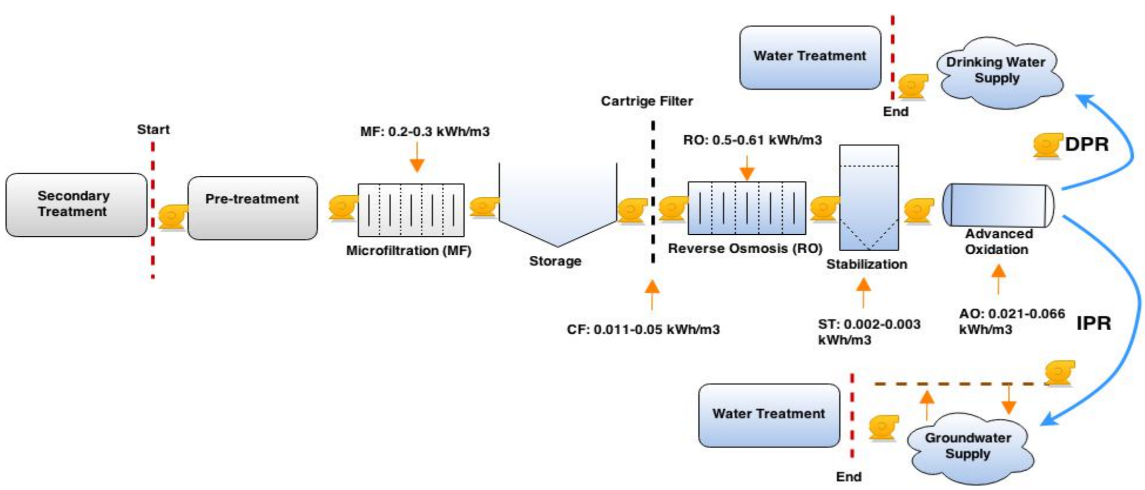


Figure 8: Energy used throughout DPR and IPR. The pumps indicate the energy used to pumped water through each process and transportation.

Nonpotable Reuse

Energy usage in the treatment of nonpotable reuse is lower because reverse osmosis is not used. Energy is still consumed for pumping, cleaning, monitoring, and transporting water to its designated areas. The treatment technologies that are used in this process are less energy intensive. For instance, the overall treatment of nonpotable reuse consumes about 0.2 to 0.37 kWh/m^3 (Bahman, 2015 (Tchobanoglous et al., 2014)), while IPR uses between 0.73 and 1.1 kWh/m^3. The main expenditure of energy in the life cycle is irrigation; irrigating landscapes and crops with sprinklers can use between 0.6 and 1.3 kWh/m^3. The energy used for irrigation is included in this study, since it was assumed they are use to improve water conservation strategies in the agricultural sector. Throughout the life cycle of nonpotable reuse, about 0.2 kWh/m^3 more energy is used in NPR than in both potable reuses. The demand of NPR in urban areas is more spread out, and less quantity is needed. Therefore, pipe networks are smaller in urban areas than in agricultural areas. Networks in urban areas might require more energy because demand is more spread out. This increases the cost of transportation for NPR. See

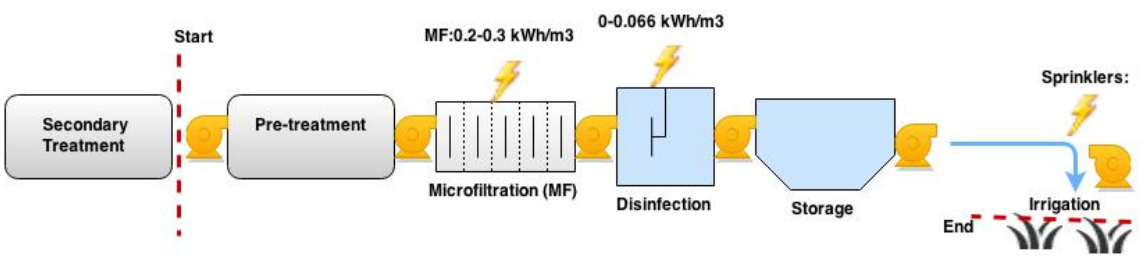


Figure 9: Energy use during NPR.

Table 4: Energy use for potable (IPR and DPR) and nonpotable reuse of water. Data were collected from peer reviews (Matos et al., 2014 and (Bahman, 2015 (Tchobanoglous et al., 2014)).

		Nonpotable	***Potable***	
		Agriculture/Landscape (kwh/m3)	***IPR (kwh/m3)***	***DPR (kwh/m3)***
Wastewater Treatment				
	Microfiltration	0.2-0.3	0.2-0.3	0.2-0.3
	Cartridge filtration	--	0.011-0.05	0.011-0.05
	Reverse Osmosis	--	0.5-0.61	0.5-0.61

Advanced Oxidation (UV/H2O2)	--	.021-.066	.021-.066
UV-B light or chlorination	0-0.066	--	- -
Stabilization	--	0.0016-0.0032	0.0016-0.0032
Subtotal	**0.2-0.37**	**0.73-1.1**	**0.73-1.1**
Transportation	0.002-0.007	0.002-0.007	0.002-0.007
Irrigation Sprinklers	0.6-1.3	--	--
Pumping and collection	0.003-0.04	0.003-0.47	0.003-0.04
Total	**0.805-1.71**	**0.74-1.51**	**0.74-1.08**

Total Cost

Reclaimed water has direct and indirect cost (externalities). The direct cost of reclaimed water includes capital cost and annual operation and maintenance (O&M) cost, energy (power) and chemical cost. Externalities include both environmental and social costs. These externalities are difficult to quantify since it is hard to monetize social and environmental issues such air emissions and resource depletion.

Direct Cost of Potable and Nonpotable Reuse

The capital cost of a reclamation plants is dependent on the capacity to which the plant is designed and the technologies that are used. Operation and maintenance (O&M) depends on the average operational rate at which water is treated. These costs can be in the millions. For example, a preliminary cost estimate of an IPR system in San Diego valued the construction costs of an 18 million gallon per day (MGD) purification plant to be about $369 million with an annual O&M cost of $15.5 million if the plant is operated at 15 MGD (San Diego, 2013). The capital cost of an NPR plant is about 2.5 less than an IPR facility (Schimmoller et al., 2013). In potable reuse, the capital cost is expected to increase depending on brine disposal system, as new infrastructure is needed. Approximately, $52 million is added to the capital cost if a mechanical system is used to evaporate brine and about $180 million is added if evaporations ponds are used for concentrate in a 20 MGD facility (Schimmoller et al., 2013).

The majority of the O&M cost is attributed to power usage for RO and pumping. Staffing cost, power cost, chemical cost, and equipment replacement cost are the major components of the annual expenses. Chemical cost increases with the amount of water that is treated. Potable reuse uses about eight times more chemicals than NPR (Schimmoller et al., 2013). Therefore, the cost will be 8 times higher. The San Diego Water Purification Demonstration Project estimated that the annual chemical cost of a 15 MGD plant is $1.3 million (San Diego, 2013). Based on this estimate, it is assumed that on average a potable reclamation plant will spend about $243 on chemicals per million gallons of water treated. Therefore it is assumed that a NPR plant will spend about $30 per MG for treatment chemicals.

The cost of powering these systems is also a major O&M cost. The energy cost was estimated by taking the average of the total energy used throughout the life cycle (see Table 4). The average was then multiplied by the volume of water treated times the cost of electricity per kilowatt-hour. According to the US Energy Information Administration, the average retail price of electricity in California is 13.50 cents per kWh (EIA, 2014). Based on these assumptions, it was calculated that for a plant operating at 20 MGD NPR plant about $4.7 million are spent on annual electric costs, while IPR and DPR spends about $4.2 and $3.4 million, respectively (see Appendix). During treatment, potable reuse utilizes about seven times more power than NPR. However, throughout the life cycle, NPR consumes more energy because irrigation is very energy intensive. For the purpose of this analysis it was assumed that irrigation with sprinklers was used in the agriculture sector as a strategy to improve water conservation. Overall, through the LCA an IPR system is about $0.5 million cheaper than NPR. New infrastructure would be needed to transport water to its desired destination. For nonpotable reuse, higher O&M is necessary, since more personnel are needed to check systems and prevent cross contamination. Additionally, monitoring systems would be required to minimize contamination issues. See Table 5 for direct cost estimates for reclaimed water.

Table 5: Direct financial cost for a 20 MGD. These numbers were estimated for NPR and potable reuse. Numbers were calculated from preliminary cost estimates from San Diego, 2013 and Scimmoller et al., 2013 study.

Reuse	Capital Cost (million)	Annual O & M Cost (million)	Power Cost (million)	Chemical Cost	Total (million)
NPR	47	2.8	$4.7	$0.22	$55
IPR	120	5.9	$4.2	$1.8	$132
DPR	120	5.9	$3.4	$1.8	$131

Indirect Costs of Potable and Nopotable Reuse

Indirect costs are difficult to quantified. However, Schimmoller et al. estimated that the annual environmental cost of a 20 MGD NPR plant is roughly $0.2 million, while the environmental cost of a similar size potable reuse system would range from $1.6 to $6.3 million. The cost estimates for social and environmental impacts are not going to be measured in this analysis due to the lack of data and expertise. Nevertheless, the social and environmental impacts are going to be noted and analyzed. Refer to sections in Social Cost for more information.

Land Use

Potable and Nonpotable

Since no data was collected, the land used is not estimated for reclaimed water, but it important to note that reclaimed water has a land impact. Land use depends on the size and capacity of the plant, and to some extend on the type of technology used. Land is used for the construction of the facility, storage tanks, pumping stations, and distribution systems. Normally, reclamation plants are built near existing wastewater treatment facilities. The land use for these facilities is relatively small, since MF and RO are compact technologies and do not occupy large spaces. The footprint is relatively small because most of the land is used for the construction of the facility. However, as the capacity (size) of the reclamation plant increase then more land will be disrupted so larger storage tanks can be constructed.

Lager storage tanks are necessary since reclaimed water collects most of its water during the day when water demand is high, but the product is not ready for distribution until later when the water demand is low. Therefore, storage tanks are needed. An example is the Harding Park Recycled Water Project in Daly City. This plant treats about

2.8 million gallons per day (MGD) and has an underground storage tank of 700,000 gallons (about 45x45x45) (SFPUC, 2015). Additionally, the brine disposal also has a high potential of land use, since evaporation ponds require land use.

Furthermore, pumping stations are needed to transport water. These stations depend on the amount of water that is transported. Usually, these stations are relatively small. Distribution systems are necessary to convey the water to its destination. In urban areas, pipe systems will disrupt less land as these distribution systems can be installed in extant areas of use. However, if the water is for nonpotable reuse, then new pipe systems can potentially disrupt new areas. In some cases, CEQA studies might be required before the installation of the pipeline systems. Reclaimed water has a land disturbance, as infrastructure is built to implement water reuse.

Material and Resource Depletion

Potable and Nonpotable reuse

Reclamation projects often require new infrastructure to build facilities, storage tanks, pipeline networks, and pumping stations. This infrastructure requires the usage of material and resources. Materials included plastics (filtration membranes), concrete, chemicals, metals, and water. Some of these materials are energy intensive and have significant environmental impacts. Due to the time constrain, a detailed inventory of these materials was not compiled. However, major materials used in reclaimed water were identified and analyzed to determine the impacts that these materials have on the environment. Refer to

Table 6 for a list of materials/resources used in reclaimed water for potable and nonpotable reuse. In this study it is assumed that the same amount of concrete and metals are used to build the same size reclamation facility for both potable and nonpotable reuse. The amount of chemicals varies by size and treatment process. Ergo, it is assumed that potable reuse uses about eight time the amount of chemicals than NPR. The amount of membranes is also assumed to be twice as high for potable reuse, since both MF and RO are used. Water was included in this list because it differs in each use, and has different impacts. Thus, both reuses use the same volume of water but have different outputs.

Table 6: Materials and resources used for reclaimed water.

Material	Quantity Potable	Quantity NPR
Chemicals	Potable reuse uses about eight times (8x) more chemicals than NPR	NPR uses about 1/8th the amount of chemicals
Metals	Same	Same
Concrete	Same (depends on the size of facilities)	Same
Plastics (filtration membranes)	Potable reuse uses about twice the amount of membranes	½ less the amount of membranes
Water	Same	Same

4.0 Life Cycle assessment

Health Risks

Studies suggest that reclaimed water does not pose a significant threat to human health (Rodrigues-Mozaz et al., 2014 and NAP, 2012), due to its stricter regulations and advanced treatment. The water quality of recycled water is superior, as it contains less nutrients, pathogens, and suspended solids than wastewater effluent and most surface and groundwater supplies. However, these speculations are uncertain, as no long-term risk studies have been conducted to evaluate the health risks of continuous exposure to potable and nonpotable reuse. Additionally, the health impacts associated with the chemicals used during treatment are unknown, as no research has been conducted to assess their impacts on the environment and living organisms. Furthermore, not all contaminants found in reclaimed water have been identified. In recent years, new emerging contaminants from cosmetics, contraceptives and industry are causing concern, as relatively high concentrations of pollutants from these sources have been found in reclaimed water. Thus, emerging contaminants increase uncertainty and health risk because these pollutants can have adverse health effects even at small dosages (Huang et al., 2012). Presently, the state requires reclamation plants to test for 144 target contaminants (OCWD, 2015), as a strategy to reduce health risks. However, this compliance is unreliable, as new emerging contaminants are not monitored properly due to a lack of knowledge or technology.

The likelihood of biological and chemical contamination and formation of harmful byproducts throughout the life cycle of each reuse will be analyzed to determine which reuse has a greater health risk. The risk level is the possibility of an event occurring. If an event is likely or has a chance of occurring, then the risk level will increase. Risk levels are divided into six categories; extremely low risk, low risk, moderate risk, high risk, very high risk, and extreme risk. Extremely low risk is given to events that are unlikely to occur.

Potable reuse

Health Risks from Water Quality

A multi-barrier treatment framework (Gerrity et al., 2013) is used to design potable reuse systems to increase and provide a higher level of protection against mechanical failures, and microbiological and chemical impurities. Ingesting reclaimed water that has been treated for potable reuses has a risk of people being exposured to low concentrations of chemicals and bacteriological pollutants. The water quality of potable reuse is superior to existing drinking water supplies, as advanced treatment kills viruses, pathogens, and bacteria, and breaks down endocrine disrupting compounds that pass through RO membranes. For example, it has been demonstrated that advanced treatment eliminates (below limits) the risk of salmonella and cryptosporidium. Additionally, the relative risk of norovirus and adenovirus is reduced from one to one in a million when wastewater receives advanced treatment (NAP, 2012). Therefore, advanced treatment decreases the likelihood of exposure to viruses and bacteria when reclaimed water is ingested. Since DPR is used almost immediately after treatment, it is safe to assume that DPR has an extremely low risk of bacteriological and viral exposure, since these pathogens are removed during treatment.

In IPR systems, water is injected into groundwater basins or discharged into environmental buffers. This process can facilitate microorganisms found in the soil to degrade endocrine disruptors and other organic matter (Drewes et al., 2003), but studies also show that water injection can degrade the quality of the purified water, as it is exposed to environmental contaminants (Leverenz et al., 2011). Thus, IPR has a moderate risk, as users have a higher exposure to viruses and bacteria. Finally, it is important to note that DPR and IPR are safer than *de facto* reuse because the risk of bacteriological infections is lower.

The presence of organic matter (OM) can also increase health risk, as OM can react with oxidants to form harmful byproducts. For example, in advanced oxidation, when chlorine is exposed to organic matter and UV light, trihalomethanes (THM) and haloacetic acids (HAA) are formed (Kommineni et al., 2000). This are considered carcinogenic and are regulated by the USEPA. These byproducts can also cause spontaneous abortion in women (Swan et al., 1992). Experiments indicate that RO membranes only remove about 40-50% of total organic carbon (Drewes et al., 2003), so about 60-40% of OM is passed through membrane. Nevertheless, studies show that if chlorine concentrations are lower than 5 mg/L, then the formation of these compounds is negligible (Kommineni et al., 2000). Since the concentrations of chlorine used in potable reuse is lower than 5 mg/L, then it is assumed that the formation of these byproducts is minimal and thereby represent extremely low risk. Similar results are assumed for IPR, since similar chlorine concentrations are used during treatment.

Chemical exposures from recycled water are a major obstacle that needs to be resolved, so potable reuse can be accepted and implemented in the state. Chemicals like pesticides, pharmaceuticals, endocrine disrupters, and chemical byproducts have the potential to cause severe health problems if they are not removed from water. Currently, not many studies have been conducted to investigate the long-term effects of ingestion that these contaminants have on people even in small dosages. Furthermore, we lack the knowledge and technology to monitor emerging containments that are found in wastewater. For instance, it was recently discovered that endocrine disruptors increases the probabilities of developing cancer (Lintelmann et al., 2003) and lowers fertility in men (Beck et al., 2006). Other studies suggest that small continuous dosages of endocrine disruptors can result in severe health problems (Huang et al., 2012). Generally, advanced oxidation is used to break down contaminants, like endocrine disrupters, to form less toxic compounds, as they are oxidized with hydroxyl radicals and UV light. Ideally, all endocrine disrupters should be broken down so the feminization of fishes and other aquatic organisms can be prevented, but this does not always occurs. A recent study also suggests that the byproducts generated during treatment can also increase health risk, as some of the byproducts produced are more toxic (Plahuta et al., 2014). In advanced treatment (MF/RO) processes about 98-99% of pesticides, organic compounds, and pharmaceuticals are removed (Rodrigues-Mozaz et al., 2014). However, some pharmaceuticals, such as acetaminophen, and pesticides like diazinon and diuron are not always eliminated. Nevertheless, the concentrations of these contaminants were relatively low as they were found in the low range of nanograms per liter. RO membranes are capable of removing molecules larger than 200 grams per molecule (g/mol) (Rodriguez-Mozaz et al., 2014 and Drewes et al., 2003), yet many of the pollutants discussed above are smaller and thereby present a high risk to human health in both DPR and IPR systems. See Figure 10 for a risk comparison between DPR, IPR, and NPR. Based on this analysis it seems that DPR poses a lesser risk than IPR, as water is less likely to come into contact with pollution.

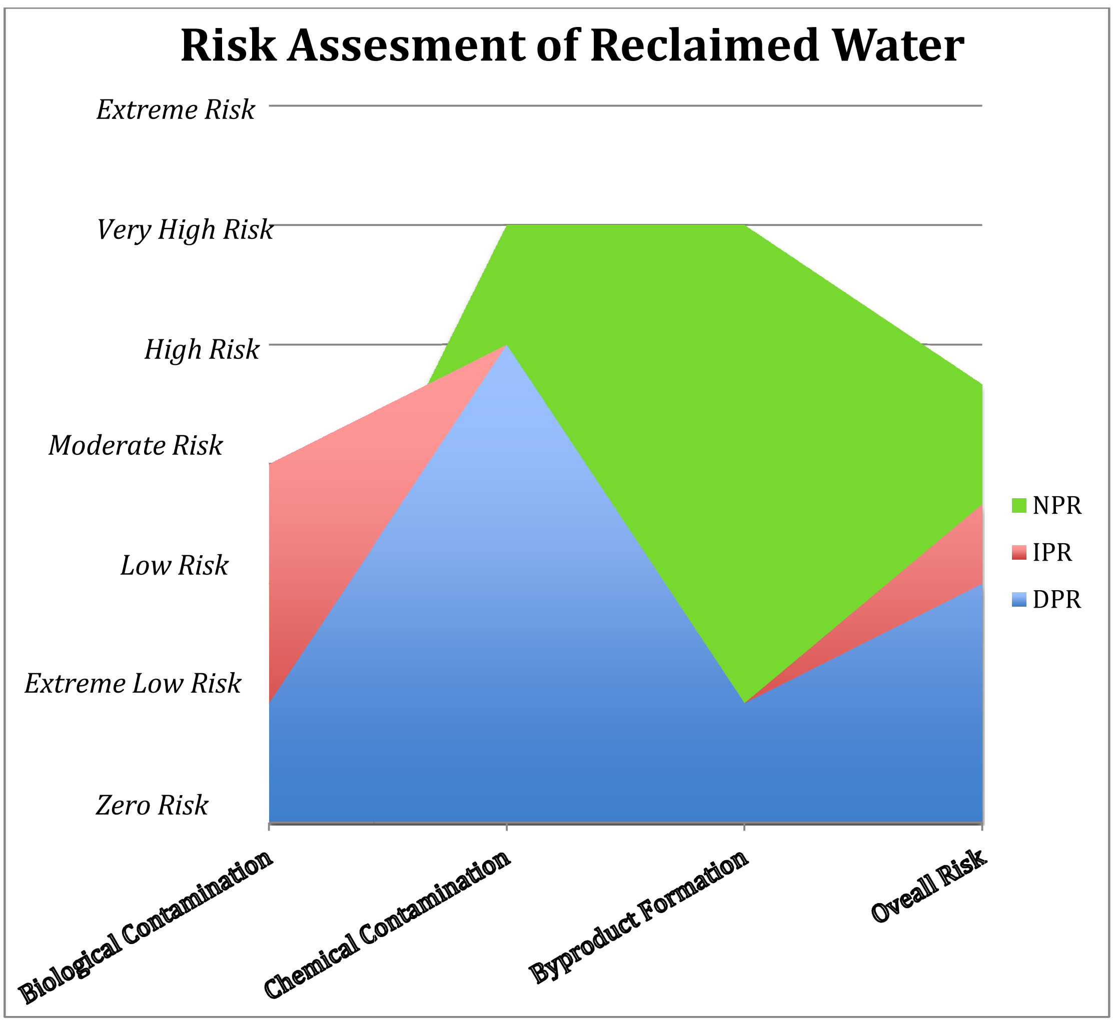


Figure 10: Risk assessment of potable and nonpotable reuse. Risk level was determined based on peer review observations and likelihood of occurrence.

Nonpotable Reuse

Health Risks from Water Quality

The health concerns regarding nonpotable reuse are higher since treatment does not remove all contaminants from wastewater. Therefore, traces of organic matter, antibiotics, pesticides, organophosphates, analgesics and anti-inflammatory are present at low concentrations (Rodriguez-Mozaz, 2014). Microfiltration and disinfection is capable of lessening bacteriological and viral contamination (NAP, 2012). It was discovered that MF removes 99.99% of biological growth (Sadr Ghayeni et al., 1996), but it did not completely remove bacteria, as it only damaged the bacteria thereby preventing growth (Sadr Ghayeni et al., 1999). Hence, the risk of bacteriological infection from NPR is extremely low. Microfiltration process is also not capable of removing all natural organic matter (Fabris et al., 2006), which react with chlorine to form known carcinogenic byproducts like THM and HAAs (Wu et al., 2009 and USEPA 1999). High chlorine concentrations equate to high concentrations of THMs and HAAs (USEPA, 1999). Typically, NPR treatment utilizes chlorine concentrations of up to 20mg/L, which is four times above the recommended concentrations. Therefore, the risk of forming byproducts is very high.

Chemical contamination from chlorine residuals is also highly likely. Chlorine residuals may also damage crops, and consumers of these crops may be indirectly exposed to the disinfection byproducts (DBPs) through the food chain (Wu et al., 2009). It is estimated the there are hundred of DBPs that result from chlorination, but only a few have been identified (Wu, et. al, 2009). Furthermore, contaminants can accumulate in the soil and can cause unknown consequences. For example, endocrine disruptors can cause the feminization of aquatic organisms. Consequently, chemical contamination from NPR is very high. Finally, the water quality of NPR is poorer than potable reuse because treatment is less efficient at removing contaminants. The risk attributed to NPR is higher, just because treatment does not remove contaminants of emerging concern and is more likely to form byproducts.

Health Risks from Cross Contamination

NPR systems have a higher health risk than potable reuses because cross contamination is more likely to occur, especially in urban areas. Normally, nonpotable distribution systems are connected to potable sources. This cross connection can provide a pathway for backflow of nonpotable water into the potable supply, hence contaminating drinking water supplies. Backflows occur because there is a change in pressure. These pressure changes are attributed to breaks, flushing, pumping failure, or emergency firefighting (USEPA, 2001). According to the US Centers of Disease Control and Prevention, cross contamination was responsible for 57 waterborne diseases outbreaks between 1981 and 1998, which resulted in 9,734 illnesses. Of these cases, about 6,330 illnesses were related to microbiological contamination and 680 were caused by chemical contamination. The remaining 2,700 cases were a result of unreported contaminants (USEPA, 2001). Illnesses from microbiological activity were higher than chemical contamination, but, since regulations for NPR have gotten stricter, the risk of contamination will be less as biological risk has decreased to extremely low levels. To mitigate this issue, systems capable of alerting authorities about cross contamination are necessary. Studies conducted by the Australian government have looked into several technologies to minimize contamination. However, such systems will depend on the degree of assurance needed. Additionally, these technologies are expensive.

Health Risks from Waste Generation (Potable and Nonpotable)

Sludge and brine generation has an extremely high health risk if people come in contact with this waste. This is because sludge is highly concentrated with biological and chemical contaminants, so it is highly toxic if it comes into contact with human personnel. Brine also contains high concentrations of contaminants that have been removed from water, such as heavy metals, pesticides, carcinogenic compounds, endocrine disruptors etc. Typically, brine is discharged into oceans, or it can be evaporate mechanically or with evaporation ponds. Evaporation ponds can increase the likelihood of exposure to animals and humans. Thus, sludge and brine needs to be disposed of correctly so these pollutants do not enter our water systems or leak into surrounding ecosystems.

Economic Costs

True Value (Levelized Cost) of Reclaimed Water

Currently, the price of reclaimed water is not reflective of its true cost. This is because reclaimed water is sold at lower rates to increase demand. Therefore, the levelized cost of the three types of water reuses will be performed to determine their true values. Levelized cost is used in the energy sector as a comparison analysis to determine the net present value in per-kilowatt-hour cost (EIA, 2014). This analysis takes into consideration the cost of building and operating the plant throughout its lifespan. Thus, a similar approach is performed to calculate the levelized cost of reclaimed water (LCORW), to compare each reuse and determine which system is more expensive per million gallons (MG) of water and acre-feet treated. LCORW is calculated by dividing the total cost in present value of the plant through its lifespan and then divided by the total amount of water "generated" (recycled) during its service life. For this analysis, it was assumed that each treatment facility has a lifespan (n) of 50 years, and a rate of return (r) of 3% (WHO, 2014). For the purpose of this analysis it was also assumed that the capacity of the plant is 20 MGD and it operates at 15 MGD. Therefore, the capital cost is estimated for a 20 MGD plant, and the power, chemical and operation and maintenance (O&M) costs were derived from a 15 MGD treatment plant. The present value of annuity for power, chemical, and O&M were calculated by using the equation, $PV = Cost * \frac{1-(1+\square)^{-n}}{r}$. These present values were added to the capital cost to find the total present value (PV). The total cost was then divided by the amount of reclaimed water that would be generated in a 15 MGD plant throughout its lifetime. The water quantity was converted to present value, to follow the convectional approximation methodology of levelized cost. Using the same equation that was stated above, the water quantity was calculated. However, the *Cost* was replaced by the amount of water recycled annually (15MG per day*365 day/year). Based on these calculations, it was noted that nonpotable reuse is about $410/AF cheaper than IPR and DPR is about $40/AF cheaper than IPR. Overall, IPR is the most expensive reuse. In general, reclaimed water should not be sold below the LCORW. Otherwise, municipalities will lose money.

Table 7: Levelized costs of three 20MGD reclamation plants, operating at 15 MGD.

Levelized cost	Total Cost (Present Value)	RW Generation (Present Value) (MG)	LCORW ($/MG)	LCORW ($/AF)
NPR	$245,450,363	140,870	$1,740	$570
IPR	$425,431,327	140,870	$3,020	$980
DPR	$404,794,444	140,870	$2,880	$940

Economic Feasibility of Reclaimed Water Based on Location

Cities that are able to purchase their raw water at lower rates than the LCORW (i.e., levelized cost or true cost of reclaimed water) would not financially benefit from the use of reclaimed water, since these cities would lose money by enforcing an alternative that is more costly than their current water sources. Nevertheless, cities that are buying their water at higher rates than the LCORW would greatly benefit from the application of recycled water, as recycled water would be cost effective. For example, Southern cities in California spend millions of dollars to import potable water. In 2013, San Diego paid roughly $1039/AF for untreated imported water (San Diego, 2013). Hence, in San Diego both DPR and IPR are economically feasible since both supplies are below the price of imported potable water by $100/AF and $60/AF, respectively.

Additionally, most cities in California pay about $890/AF for their water supplies (Hanak et al., 2011), making NPR economically feasible for most of the state. Based on the rates provided by Hanak et al., 2011, only certain areas, like the San Francisco Bay Area and Central Coast, would benefit from all three reuses. The South Coast would benefit from both NPR and DPR, as it would save money by purchasing reclaimed water, which is cheaper than their current supplies. See

Table 8 for an overview of the range of water rates throughout the state. It is clear that some areas of California will benefit by recycling water. Other factors, like increasing reliability and water supply, should also be considered when evaluating the total benefits of reclaimed water.

Table 8: Water rates for different regions of the state (Hanak et al., 2011). Green numbers indicate that only NPR is economically feasible. Blue indicates that both NPR and DPR are economically feasible, and red indicates that all three reuses are economically feasible. Black represents no economic feasibility.

Region	Average water price ($/AF)
San Francisco Bay Area	1,190
Central Coast	1,857
South Coast	985
Inland Empire	748
Sacramento Metro Area	789
San Joaquin Valley	545
Rest of state	886

Monetary Losses Due to Artificially Low Rates

A national survey revealed that the majority of existing reclamation plants recover less than 25% of their annual operational costs (Carpenter et al., 2008), because most municipalities have set artificial low prices to encourage the use of reclaimed water. For instance, San Diego sells its NPR water for $0.8 per hundred cubic feet (HCF), while the city charges $4.014/HCF for potable water. The price of NPR has not risen since 2001, when the price was lowered from $1.34 to $0.8 per HCF to promote NPR (City of San Diego, 2015). Based on the LCORW calculated in the section above, reclaimed water for nonpotable reuse should be sold at $570/AF or at $1.31 per HCF, so municipalities do not lose any money. Currently, in San Diego, NPR water is sold at $.50/HCF below its true value. This results in a loss of revenue for the city. Therefore, San Diego is losing about $3.72 million annually. To mitigate such financial losses, reclaimed water needs to be sold at its true value. With regards to DPR and IPR, these supplies need to be sold at their respective LCORW, so no monetary losses will be incurred from the application of these reclamation plants.

Environmental Impacts

Direct Carbon Emissions From Potable and Nonpotable Reuse

Water reclamation increases carbon emissions, as energy is used during its treatment. The size of the plant and type of technologies influence the amount of carbon emissions released. In terms of treatment, potable reuse has higher emissions because reverse osmosis is very energy intensive. It is estimated that a 20 MGD nonpotable reuse treatment plant emits about 1,700 metric tons of CO_2 per year, while a potable reuse plant (MF/RO/UV-H_2O_2) at the same capacity emits about 12,200 metric tons of CO_2 per year (Schimmoller et al., 2013). Therefore, during treatment potable reuse would emit about seven times more CO_2 than NPR. However, when the whole life cycle of each reuse is considered, it was discovered that DPR had the lowest CO_2 emissions, as it uses less energy through its life cycle.

Projections of carbon emissions were based on the average amount of electrical energy used throughout the life cycle (see Table 4). The total average electrical energy use per meter cube of water treated (kWh/m^3) was 1.26, 2.25, and 0.91 for NPR, IPR, and DPR, respectively. Based on these results, it is estimated that IPR emits about 2.5 times more CO_2 than DPR, and about 1.8 times more CO_2 than NPR. Finally, NPR emits about 1.3 times more CO_2 than DPR. As a result, carbon emissions for different size plants would change, since energy use would increase. Similarly, different reuses have different emissions. Furthermore, this analysis excludes the amount of energy used to generate and transport chemicals; therefore, this is not truly representative of these findings, because potable reuse uses eight times more chemicals and it produces more waste that needs to be disposed of.

Land Use

The size of the storage tanks utilized contributes greatly to the magnitude of land used. Land use also depends on the type of reuse. For instance, NPR and DPR reuse requires larger storage tanks than IPR, since their use does not correlate with generation time. The effluent from IPR needs less land, as water is discharged into environmental buffers like surface and groundwater supplies. The land use for water distribution is hard to determine, as it would depend on the volume of water treated, land use regulations, and population size. Furthermore, it is assumed that pumping stations and treatment facilities will be similar within each reuse if they are the same size. Hence, land impacts will mostly depend on the size of storage tanks. It is estimated that for every one MAF of water stored, about 0.30 cubic miles of land will be required.

Material and Resource Depletion

Water Recovery (Multiplier Effect)

Wastewater is a precious resource that, like money, has a multiplier effect if it is recycled. The multiplier effect is use by economists to describe how an injection of money increases economical growth, as spending increases. For this analysis, the multiplier effect will be used to determine how recycling water increases the water supply. For NPR, the multiplier effect would be one because it is assumed that no water can be recovered once it is used for irrigation, as this water would renter the natural water cycle. Potable use allows for water to be recycled multiple times since it is collected after it has been used. Water from DPR can be recovered because, on average, 60 to 90% of potable water is directed to wastewater facilities (Klotz Associates, 2010). Likewise, assuming that the MF system has a 95% recovery rate and the RO has a recovery rate of 75%, the total recovery rate of the wastewater from treatment is about 71%. To calculate the total recovery rate, we will start with one gallon of water that just exited the reclamations plant. Assuming that 10% is lost during conveyance (Hanak et al., 2011), then the total amount of water reaching residents is 90%. Furthermore, assuming that only 75% (average of 60 and 90%) of this reclaimed water is sent back to a wastewater facility after it was used, then approximately 67.5% of reclaimed can be recycled again. Since only 71% of water can be recovered from treatment then about 48% of water can be recovered the second time. The multiplier effect is calculated by diving one over the one minus percent recovery ($\frac{1}{1-\%recovery}$), which is 48%. Hence, DPR has a multiplier effect of 1.92 (See Appendix for work). Thus, for every gallon of water that is reclaimed, about 1.92 gallons are gained just by reclaiming water.

A similar methodology was applied to IPR. A recovery rate from treatment is 71%. Determining the percent of recovery for IPR is difficult, as water would be lost when it enters the environment. This water is lost during evaporation, leaks and infiltration. Making a conservative judgment, I believe approximately 50% of the reclaimed water is lost during this process. About 75% of the water will be recovered after people use it; so only about 26.6% of water is truly recovered from an IPR system. Overall, IPR would have a multiplier effect of 1.36, so the water supply would increase about 1.36 times for every gallon of wastewater treated. Thus, both DRP and IPR will increase drinking water supplies. Furthermore, by expanding the water supply, less water needs to be transported or purchased; thereby reducing costs to municipalities, as less water has to be purchased for potable reuse. In other words, reclaiming water for potable reuse in municipalities has the potential to increase current drinking water supplies.

Soil Quality

Soil contamination can occur when water is injected into groundwater basins and when is used for irrigation. The risk of soil contamination from potable reuse is extremely low as very small concentrations of contaminants are found in the end product, thereby accumulation would be minimal. Nonpotable reuse has a higher risk of soil contamination since the water quality is poorer than potable reuse. Additionally, studies indicate that reclaimed water from nonpotable reuse increases salinity, chlorine and sodium levels. This results in the contamination of agricultural land. However, no observable effects were detected in areas where chlorine levels were high (Platts et al., No Date). NPR has a higher potential of degrading the soil quality, thus causing environmental and health problems as containments accumulate and leach into groundwater supplies.

Impacts of Materials' Depletion

The environmental impacts attributed to the use of materials and resources are substantial, as several of these materials are energy intensive, nonrenewable and nondegradable. For instance, both the chemical and cement industries are large emitters of greenhouse gasses (GHG), as their production processes are energy intensive. It is estimated that approximately 7% of global GHG emissions are emitted from cement plants (Ali et al., 2011), and in 2005 the chemical industry emitted roughly 3.3 gigaton of CO_2 equivalent (gtCO_2e)(ICCA, 2009). The extraction of metal is detrimental to the environment because it causes air and noise pollution, and destroys entire ecosystems as land is disrupted. The production of filtration membranes depletes fossil fuels, metals, and inorganic materials like alumina, titania, and silicates (Reif, 2006). Due to the composite structure of filtration membranes, recycling of these materials is difficult. Filtration membranes are usually sent to landfills where membranes stay for hundreds of years, or are incinerated, which increase air pollution (Netravali et al., 2003). Hence, these materials are lost. Since potable reuse consumes about eight times more chemicals than NPR, the indirect impacts for potable reuse from the chemical sector is eight times greater. It was assumed that the amount of concrete and metals used were similar for both potable and nonpotable reuses, thereby resulting in similar indirect impacts. Potable reuse utilizes about twice the amount of filtration membranes, so it depletes twice the amount of materials than NPR. Finally, water resources are increased with the implementation of recycled water because water is reclaimed. As discussed in the above section, reclaimed water has a multiplier effect (recovery factor); hence, in potable system reclaimed water can be reclaimed multiple times.

Table 9: Impacts of materials. One (1) symbolizes equal magnitudes or similar impacts. Negative numbers implies generation. This is an estimation of how much water is reclaimed.

Material	Description of Possible Environmental Impacts	NPR	IPR	DPR
Chemicals	Chemical production is energy intensive so a higher use of chemicals equals higher GHG emissions	1	8	8
Metals	Mining increase air and noise pollution and disrupts ecosystems	1	1	1
Concrete	Energy intensive so high GHG emissions	1	1	1
Plastics (filtration membranes)	Depletes fossil fuels, metals, and inorganic materials	1	2	2
Water	Water depletion (negatives means that there is a generation)	-1	-1.36	-1.92

Social Impacts

Increase Water Prices and Affordability

California's water systems are under financial stress, as most water systems are old and need to be replaced and upgraded to meet new environmental and safety regulations. Municipalities have been able to fund about 85% of these costs by raising rates for water and wastewater services (Hanak et al., 2014). Therefore, the implementation of reclamation projects will increase water prices in localities where these plants are built. An increase in water prices will heavily impact low-income families, as their cost of living goes up. A higher cost of living can result in new social impacts, like increased poverty and political conflict (Howe, 2005). Thus, mitigating these social impacts is crucial to make reclaimed water suitable and socially just. Currently, California has Proposition 218, which was designed to prevent certain rates and fees from exceeding the cost of providing a service. This proposition harms both water projects and disadvantaged groups, as water agencies are not allowed to generate revenue to fund new projects and lifelines programs for low incomes families (Hanak el at., 2011). Therefore, most municipalities cannot implement reclamation projects or sell water at its true cost because low-income families would not be able to afford these rates. Hence, the funding of recycled water needs to be considered when planning for these projects, and ensure that the most economically feasible reuse is implemented to mitigate monetary losses. In many areas of the state, especially northern California, more than 20% of single-family homes are already paying water bills that exceed 2% of their annual income (Refer to Figure 11), and between 10 and 20% of families in Southern California and Coastal areas are also paying high water bills. However, since the majority of the population lives in coastal area, the cost of implementing reclaimed water projects would have a lesser effect than in areas where populations are smaller. This is because cost can be distributed with more people, thus reducing large spikes in rates.

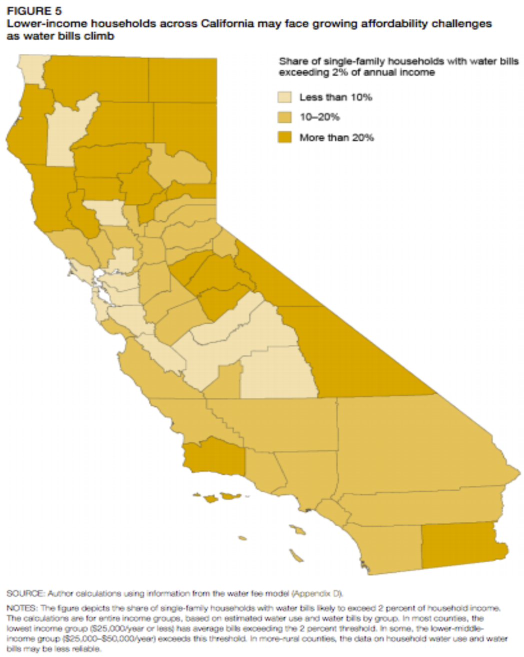


Figure 11: Water bills exceeding 2% of annual income. Darkers areas show areas where more than 20% of population is paying more than 2% of their income on water. The second darkerst color shows 10-20% and lighter color shows less than 10% is population paying more than 2 % on water (hanak et al., 2011)

Social Inequity of Price Discrimination

Currently, the management of reclaimed water is socially unjust, as people benefiting from this resource are not paying its true value. For example, the city of Tucson in Arizona sells its reclaimed water at flat rates instead of block prices. This pricing was implemented to encourage reclaimed water usage, as it can save an owner of an 18-hole golf course up to $150,000 to $200,000 on irrigation annually (Dotson, no date). Likewise, the city of San Diego is losing about $3.72 million annually for adopting similar strategies. Many municipalities are losing money with the implementation of reclaimed water because they have adopted similar pricing strategies. Municipalities are being forced to pass this cost onto wastewater and potable water customers by raising their fees. This strategy is unacceptable as the main users of reclaimed water are agricultural and industrial businesses. These selected groups benefit both monetarily and by having access to cleaner water, while people who do not benefit are paying for it. This social inequity is concerning, as it increases the social gap between the rich (agricultural and business) and everyone else, by increasing water prices. Furthermore, these discriminatory prices are also hindering water conservation efforts as lower prices promote higher consumption.

5.0 Life Cycle Interpretations and Recommendations

Interpretations

The environmental impacts of reclaimed water are substantial as it increases carbon emissions (due to high-energy use), waste generation, and chemical consumption. However, reclaimed water also provides vital benefits, including improvement of water quality and expansion of water supply. Furthermore, the true cost of reclaimed water is competitive with the cost of other water supplies in California. Refer to Figure 12 for a comparison of environmental impacts between the three options.

Overall, indirect potable reuse (IPR) systems have the highest environmental impacts and economic cost, as they use more energy, chemicals and emit more CO_2 than direct potable reuse (DPR) and nonpotable reuse (NPR) systems. Additionally, the water quality of IPR is less because it degrades when mixed with other water supplies during groundwater recharge or surface augmentations.

Direct potable reuse (DPR) systems have the lowest health risk and lowest direct carbon emission and energy use. DPR also has the highest recovery, thus highest potential to increase water supply. Although the true cost of DPR is relatively high, it is about $40/AF cheaper than IPR and thereby is more economically feasible than IPR for a municipality that needs a new potable source.

Nonpotabe reuse (NPR) systems are the most attractive alternative in terms of cost and energy use. These systems use fewer chemicals and generate less waste; however, they provide lower water quality, which can increase health risks. Finally, NPR systems are only capable of expanding water supplies by the amount of water that is recycled, as this water cannot be recovered for further use after it has been utilized. In contrast, both IPR and DPR have higher recycled potential (multiplier effect) because this water can be recovered after residents use it.

One of the social impacts arising from the implementation of reclaimed water is an increase in water prices. High water prices can increase the cost of living, thereby creating social issues, such as social inequality as well as increased poverty and increased political conflict (Howe, 2005). In some areas of the state installing recycled water projects will be difficult, as many cities lack the funds to do so. In many cases municipalities would have to charge less than the true value of reclaimed water to make reclaimed water affordable; thus, municipalities would lose money. These monetary losses would be reflected as cuts to other city expenses. As a consequence, city workers could lose their jobs, which in turn would affect their ability to pay their water bills. It is crucial for a municipality planning on implementing a recycled water project to account for these issues and look for solutions that will have minimal impacts to disadvantaged groups and to the local economy. One solution to this issue, is implementing block pricing, where a certain volume of water is priced at an affordable rate, but the rate increases when higher volumes of water are used. Alternatively, municipalities can incorporate assistance programs for low-income families. It is important that these issues are mitigated during the planning phase so reclaimed water can be socially just.

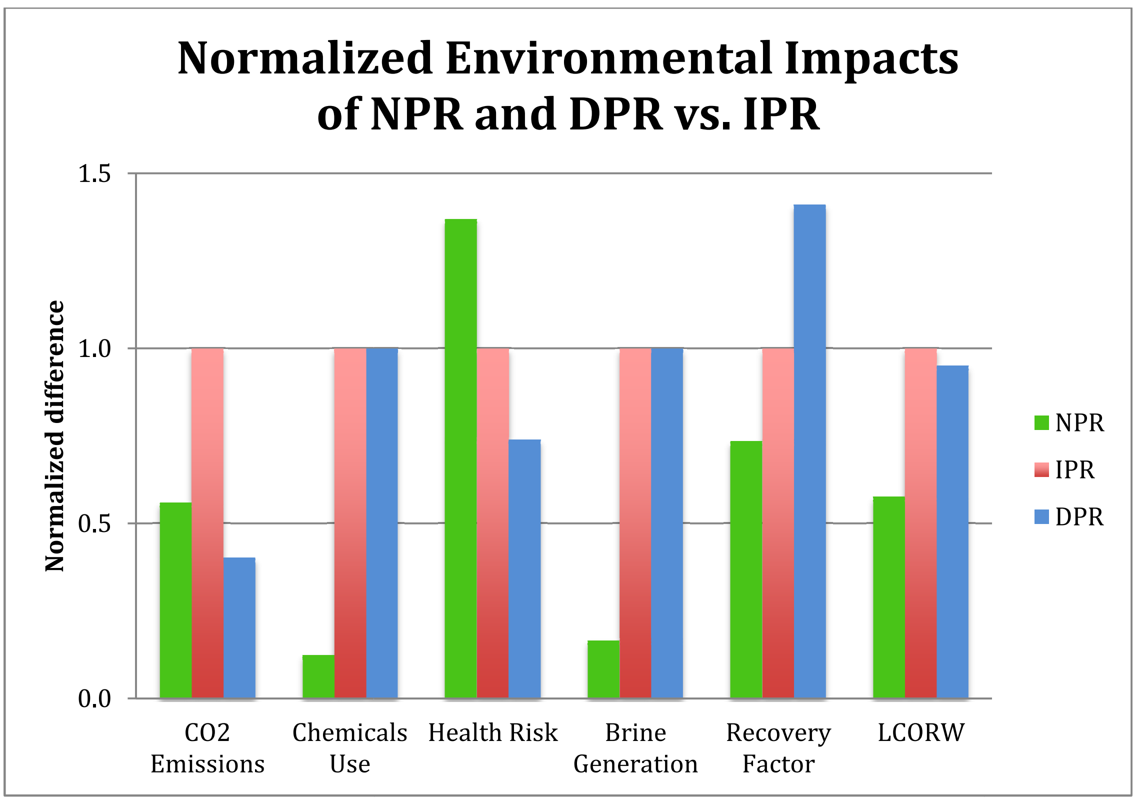


Figure 12: Normalized environmental Impacts of DPR and NPR compared to IPR.

Best Applications of Recycled Water in California

Direct Potable Reuse

Direct potable reuse (DPR) is recommended for areas of the state where potable demand is high and the cost of current water sources are similar or higher than the true cost of reclaimed water (LCORW). For example, cities in the San Francisco Bay Area, and Central and South Coast are paying between $980 and $1,860 per acre-feet for their water. DPR would cost them around $940/AF. For these cities, DPR is economically feasible and beneficial since money would be saved. Other areas that would benefit from the use of DPR are those that import their water from long distances. In these locations, implementing DPR would reduce energy cost and greenhouse gases, as less water would be transported to meet the water demand. For example, on average conveyance in Southern California uses approximately 8,900 kWh per million gallons (CEC, 2005), while DPR (entire life cycle or total energy use) would use approximately 3,400 kWh per million gallons (See Appendix), thereby reducing energy use by about 60%. Furthermore, DPR is appropriate for urban cities, as they already have or are planning to improve their water infrastructure. Additionally, the costs of DPR are lessened as it is distributed on a larger population size; hence, reducing spikes in water prices.

Cities that have poor water quality would also benefit from DPR, as consumers of DPR are less likely to be exposed to biological and chemical contaminants. In theory, DPR systems can be designed to meet or exceed drinking water standards (GWRS, No Date), which would allow these municipalities to save money on water treatment. When DPR is mixed with other supplies the overall water quality increases, which results in a reduction of water treatment for existing potable supplies. Finally, DPR helps municipalities increase local water supplies. This is because for every gallon of water that is recycled, an additional 0.92 gallon of water would be recovered, as this water can be recovered multiple times. Thus, the water supply would increase by about 1.92 times the reclaimed water. As a result, municipalities would save money, as less water needs to be purchased.

Indirect Potable Reuse

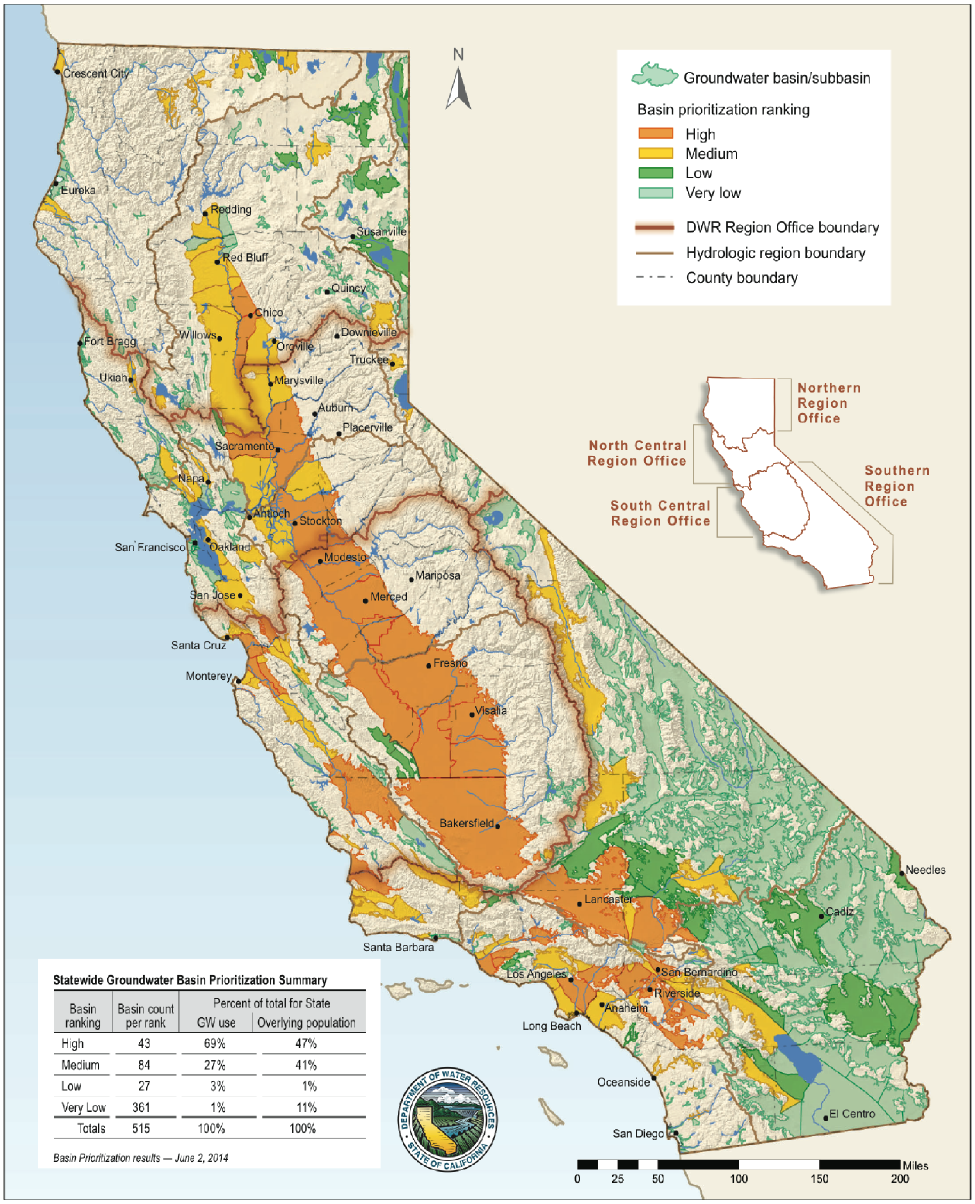
Indirect potable reuse (IPR) is the most expensive reuse system because it requires more electricity for conveyance and pumping. It is estimated that IPR uses about 8,500 kWh per million gallons treated (based on energy use during life cycle). This is similar to what most cities in Southern California are paying for conveyance. Therefore, IPR is economically feasible for areas with high conveyance cost. Although, IPR systems are the most expensive, these systems are recommended for areas with local water supplies, like groundwater aquifers and surface water. In general, the water from IPR improves the water quality of local supplies. Currently, groundwater basins near agricultural areas tend to have higher concentrations of nutrients, pesticides, and chemicals; therefore, IPR is advocated for areas whose water quality is an issue.

Similarly, IPR is encouraged in areas where groundwater is used as the main water supply. In 2009, Senate Bill X7 6 was passed into law, which mandates local agencies with groundwater basins to monitor and report their groundwater elevations (CDWR, 2012). The main goal of this law was to establish a systematic monitoring system to track seasonal and long-term trends in groundwater elevations so groundwater management can be improved. The California Statewide Groundwater Elevation Monitoring (CASGEM) program was created to identify the areas that are mostly threatened by present and future water demand (CDWR, 2014). Refer to Figure 13 for a map of the high and medium priority groundwater basins. IPR systems are recommended for areas that were identified as high and medium priority zones by the CASGEM. Thus, the Central and San Joaquin Valley, Los Angeles Region, and the Sacramento Area are the best places to implement IPR systems. Additionally, in these locations IPR systems can lower pumping cost, as the water table would be raised. Although, IPR systems increase carbon emissions the environmental benefits exceed the consequence, as groundwater aquifers would be recharged and maintained at a constant water table. Furthermore, land subsidence and seawater intrusion would be reduced and energy use for pumping would decrease as the water table is raised. Overall, carbon emissions can be mitigated if the energy used comes from renewable sources. Therefore, IPR systems are ideal for these high and medium priority basins, where large volumes of groundwater are extracted.

Another place where IPR systems are valuable are near coastal areas that are susceptible to seawater intrusion. It has been reported that during drier years and drought, groundwater reservoirs supplied up to 60% of the water demand (Croyle et al., 2014). Thus, coastal areas that depend on groundwater are highly vulnerable to seawater intrusion. Installing IPR systems near these areas, especially the Central Coast (Monterey to Ventura), is recommended to prevent seawater intrusion and its impacts. Seawater intrusion results in the formation of saline water. This water is unsuitable for irrigation or domestic use. The Central Coast, depends on groundwater to irrigate high value crops like strawberries, thus a decrease in water quality would result in great losses for the agricultural sector. It was reported that more than 40% of the Central Coast local groundwater basins were ranked high to medium priority in CASGEM (Martin, 2014). The Central Coast is advised to install IPR systems to prevent seawater intrusion, and protect their water from becoming unsuitable for beneficial use.

Most of the areas where IPR is recommended are located in agriculture zones. It is estimated that approximately 28% of the population in these places is occupied by low-income families (Taylor et al., 2000). Therefore, it is imperative for local agencies to implement equitable prices, so these families are not harmed by these projects. The majority of funding for these projects should come from farmers, as they are responsible for overdrafting and degrading the water quality of these water supplies. Additionally, water sold to groundwater basins should be traded at its true cost; otherwise these costs would be passed to water and wastewater customers.

CASGEM Groundwater Basin Prioritization



Basin ranking	Basin count per rank	Percent of total for State	
		GW use	Overlying population
High	43	69%	47%
Medium	84	27%	41%
Low	27	3%	1%
Very Low	361	1%	11%
Totals	515	100%	100%

Figure 13: Priority areas for groundwater management programs. IPR systems are recommended for areas with high and medium priority rankings (CDWR, 2014).

Nonpotable Reuse

Nonpotable reuse (NPR) is economically feasible in most parts of the state, as reclaimed water is estimated to have a levelized cost of about $570/AF. The majority of the state currently purchases its water at higher prices (except for the San Joaquin Valley), thereby making NPR the most attractive alternative for water reuse (see Table 8). As California enters its fourth consecutive driest year, landscape irrigations needs to be reconsidered, as this water can be allocated for other uses. Therefore, NPR is recommended for agricultural use. Specific areas like the Central Valley and the Central Coast (South Central Region) and parts of the North Central region should implement both NPR and IPR systems to meet their irrigation demand and improve local groundwater management (see Figure 13 for locations). Although, NPR would affect soil quality it would also free up potable water and reduce groundwater extraction. The soil quality in these areas would be affected, as this water contains contaminants that were not removed during treatment, but research shows that they are insignificant. Accumulation of these contaminants can increases salinity and in some cases would contaminate potable groundwater basins. Thus, NPR is not recommended for groundwater recharge because it would diminish water quality, and compromise potable reservoirs. Additionally, NPR is recommended to combat seawater intrusion, as the main goal of this use would be to increase the water table. Injection of NPR near coastal areas would reduce the amount of IPR needed to increase the groundwater table; therefore, IPR can be allocated elsewhere.

NPR is not strongly recommended for landscape irrigation in urban areas, as it would increase the risk of cross contamination, which increases health risks. These systems can be implemented for urban agricultural or industrial areas, but cross connections would need to be eliminated. NPR systems should only be considered in urban areas where there is a low demand for potable reuse. Overall, NPR has the least environmental impacts during the LCA, as less chemicals and energy are used. However, as water scarcity increases, our main focus should be to increase potable supply.

Potential Issues with Reclaimed Water

Currently, reclaimed water has no clear owner. The ambiguity of reclaimed water rights can potentially create social issues, as the industrial and agricultural sectors appropriate of this new source. The Water Code Section 1210 hints that treated wastewater should be owned by the treatment facility (Somach, 1994). Hence, only groups that can afford treatment can technically own this new supply. Furthermore, we have to ask ourselves how reliable is this water supply if it depends on existing sources. Reclaimed water does not generate new supply, and as water continuous to deplete how are we going to adapt to these extreme cases. Finally, how is California preparing to control chemicals from cosmetics, medicines and cleaning supplies to prevent them from entering the water supply?

Table 10: Recommendation for best use of DPR, IPR and NPR

Reuse	Where should these reuses be considered?
NPR	• Agricultural and industrial areas • Coastal areas susceptible to seawater intrusion • Cities with low potable demand
IPR	• Cities with high conveyance cost • Cities with local water supplies, but poor water quality • Cites with high reliance on groundwater supplies • Coastal areas susceptible to seawater intrusion • Cities identified as high and medium priority in the 2014 CAGEM study
DPR	• Cities with high potable demand • Cities purchasing water at a higher cost than levelized cost DPR • Cities that import their water • Urban cities (large populations) • Cities with poor water quality • Cities with no local supplies • Cities that want to increase their water supply

6.0 Conclusion

Reclaimed water is vital for the state, as population grows and water scarcity increases. California will certainly benefit from reclaimed water since it will increase water supply. In addition, the superior water quality that would be supplied to Californians from this source provides a higher level of protections against contaminants. Similarly, it will help alleviate some of the environmental and economic impacts that the state is facing due to the drought. Although, reclaimed water does have social and environmental impacts like carbon emissions, depletion of resources, and waste generation, it will also help the state become more sustainable, as the state government takes this opportunity to improve the state's water management programs. Furthermore, reclaimed water is economically feasible making it a competitive source, so it can be sustained even after the drought is over.

Finally, it is important to recognize that other issues that were not considered in this Masters Project, like water rights can complicate the implementation of these projects. Furthermore, it is imperative to create a study that fully assesses the impacts of reclaimed water, so the necessary precautions are taken. Thus, life cycle assessment methodologies should be conducted for current systems, so impacts can be identified and mitigated before California starts building these new projects in the state.

Appendixes

Levelized (True Cost)

Cost: The capital cost and annual cost were obtained from Schimmoller et al., 2013. These costs were estimated for a 20 MDG plant.

Reuse	Capital Cost (millions)	Annual O & M Cost (millions)	Power Cost (millions)	Chemical Cost	Total (millions)
NPR	47	2.8	$4,691,134	$221,737.50	$55
IPR	120	5.9	$4,196,840	$1,773,900	$132
DPR	120	5.9	$3,394,777	$1,773,900	$131

Annuity costs were converted to present value. It was assumed n=50, r= 3%

$$PV = Cost * \frac{1-(1+r)^{-n}}{r}$$

Levelized cost	Capital cost	PV of O&M	PV of Power	PV of Chemical cost	Total cost
NPR	$47,000,000	$72,043,339	$120,701,771	$5,705,254	$245,450,363
IPR	$120,000,000	$151,805,608	$107,983,691	$45,642,028	$425,431,327
DPR	$120,000,000	$151,805,608	$87,346,808	$45,642,028	$404,794,444

Levelized is calculated by adding the total present value divided by the amount of water generated. Water was discounted because in economic it is assumed that today's resources are more valuable then in the future. $LCORW = \frac{Totalcost}{WaterGenerated}$

Generation (gallons of Water)	PV Gen (MG/Year)	LCORW ($/MG)	LCORW ($/AF)
5475	140870	$1,742.38	$567.76
5475	140870	$3,020.02	$984.08
5475	140870	$2,873.52	$936.34

Multiplier Effect

The multiplier effect is used to see how an injection of money surges the economy as spending increases. For this analysis, this was used to determine how much reclaimed water helps increase the water supply. Therefore, the percent recovery of water for reuse was calculated. The percent recovery was determined how much water is lost during treatment (e.g. brine), conveyance, and use

DPR

So for every gallon that exist the reclaimed facility about 10% of water is loss during conveyance and only about 75% of water used by resident enters a wastewater treatment plant. Once water enter treatment plant 5% is loss during MF and 25% RO.
Water loss during transportation = 10%
Water used by consumer = 1-0.1=0.9
Water entering wastewater treatment plant = .9*0.75= 67.5%
Water recovered during treatment = 95% (MF)*75%(RO) = 71.25%
% Recovered = 71.25% *71.25% = 48.1%
Total amount water recovered (multiplier effect)= 1/(1-% recovered) = 1/(1-.50.8) = 19.2

IPR:

Water loss to environment, = 50%
Water used by consumer = 1-0.1=0.5
Water entering wastewater treatment plant = .5*0.75= 67.5%
Water recovered during treatment = 95% (MF)*75%(RO) = 36.1%
% Recovered = 36.1% *71.25% = 26%
Total amount water recovered (multiplier effect)= 1/(1-% recovered) = 1/(1-.50.8) = 1.36

NPR:

Water can only be recovered 1 time.

Energy

Electricity Cost Estimates for a 20 MGD plant:

Average electricity use during the life cycle of the systems in kWh/m^3

NPR	IPR	DPR
1.259	2.249	0.9075

Cost = average electricity cost * volume of water treated *cost of electricity ($/kWh)
Volume of water treated = 20,000,000 gal/day *365 day/year* 1 m^3/264 gal = 2.76E7 (m3/year)
Cost of electricity = $.135/kWh (EIA)

Power Cost (millions)
=1.2575*20*10^6*0.135*365/264.172
=1.125*20*10^6*0.135*365/264.172
=0.91*20*10^6*0.135*365/264.172

Power Cost (millions per year)
$4,691,134
$4,196,840
$3,394,777

Electricity saved by implementing DPR (See recommendations for DPR)

DPR energy used (kWh/m3) = 0.9075
For 1,000,000 gallons treated about kWh are used.
1,000,000 gal *(1 m^3/264 gal)= 3790 m3
So DPR uses = 0.9075 kWh/m3 * 3790 m3 = 3,440 kWh
So about 3,400 kWh of electricity are used to treat one million gallons
Thus using only 39% (3,440/8,900) of energy compared to conveyance. So by applying DPR Southern California would reduce their energy consumption by 60%

Electricity saved by implementing IPR

IPR energy used (kWh/m3) = 2.249
So IPR = 3790 m3 * 2.249 kWh/m3 =8,523 kWh

Reference:

Ali, M.B., R. Saidur, and M.S. Hossain. 2011. A review on emission analysis in cement industries. Renewable and Sustainable Energy Review 15(5): 2252-61.

Bahman, S. Data was modified from Tchobanoglous et al. 2014. Typical energy requirements for various treatment process technologies used for advanced treatment. See Appendix for data.

Bartels, C., R. Franks, R. Furukawa, P. Murkute, and U. Papukchiev. 2004. Integrated membrane system for of fouling RO desalting of municipal wastewater. Nitto: http://www.membranes.com/docs/papers/New%20Folder/Integrated%20Membrane%20ystem%20for%Low%20Fouling%20RO%20Desalting%20of%20Municipal%20Wastewter.pdf

Beck, I.C., R. Bruhn, J. Gandrass. 2005. Analysis of estrogenic activity in costal surface Waters Of the Baltic Sea using the Yeast estrogen screen. Chemosphere 2006, 63:1870-8.

Carpenter, G.W., G.K. Grinnell, C.M. Haney, G.A. Jacobi, S.W. Koorn, D.M. O'Reilly, C. Pierce, C. Riley, A. Rimer, K.A. Thompson, and D. Vandertulip. 2008. Water Reuse Rates and Chargers 2000 and 2007 survey results. American Water Works Association Water Reuse Committee.

CDPH. 2008. California Department of Public Halth (CDPH). Groundwater Recharge draft regulations. Sacramento, California.

CDWR. 2014. Groundwater Basin Priorization: Final CASGEM basin prioritization Result: http://www.water.ca.gov/groundwater/casgem/basin_prioritization.cfm

CDWR. 2013. California Water Plan: Municipal Recycled Water. California Department of Water Resources (CDWR). Volume 3- Resource Management Strategies Chapter 12:

http://www.waterplan.water.ca.gov/docs/cwpu2013/Final/Vol3_Ch12_Municpal-Recycled-Water.pdf

CDWR. 2012. Senate Bill X7 6, (chapter 1, Statutes of 2009) California Statewide Groundwater Elevation Monitoring (CASGEM) status report. California Department of Warer Resources (CDWR): http://www.water.ca.gov/groundwater/casgem/pdfs/2012%20CASGEM%20Report%20t%20the%20Legilature.pdf

CEC. 2005. California's water-energy relationship. California Energy Commission. http://www.energy.ca.gov/2005publications/CEC-700-2005-011/CEC-700-2005-011 SF.PDF

City of San Diego. 2015. Water Rates. San Diego, California, USA: http://www.sandiego.gov/water/rates/rates/

Cohen, R., B. Nelson, and G. Wolf. 2004. Energy down the drain: The hidden cost of California's Water Supply. Natural Resource Defense Council: https://www.nrdc.org/water/conservation/edrain/edrain.pdf

Cole, S. and L. McCarthy. 2015. NASA study finds carbon emissions could drastically increase risk of U.S. megadrought: http://www.nasa.gov/press/2015/february/nasa-study finds-carbon-emissions-could-dramatically-increase-risk-of-us

Cooley, H., P. Gleick, and R. Wilkinson. 2014. Agricultural Water Conservation and Efficiency Potential in California. Natural Resources Defense Council: Pacific Institute: 1-7.

Croyle, W., D. Gutierrez, J. Ericson, M. Alemi, D. Mathis, and M. Scruggs. 2014. Public update for drought response groundwater basins with potential water shortage and gaps in groundwater monitoring. California Natural Resources Agency, Department of Water

Resources, Sacramento, California:
http://www.water.ca.gov/waterconditions/docs/Drought_Response-Groundwater_Basins_April30_Final_BC.pdf

CSWRCB. 2014. Resolution No. 2014-0015: To provide financial incentive in response to the governor's drought proclamation for near-term recycled water projects funded through the Clean Water State Resolving Fund (CWSRF). California State Water Resources Control Board. Sacramento California:
http://www.swrcb.ca.gov/board_decisions/adopted_orders/resolutions/2014/rs2014_0015.pdf

CSWRCB. 2013. Policy for water quality control for recycled water (recycled water policy). California State Water Resources Control Board. Sacramento California:
http://www.swrcb.ca.gov/water_issues/programs/water_recycling_policy/docs/rwp_revtoc.pdf

Dahl, R. Advanced thinking: potable reuse strategies gain traction. Environmental Health Perspectives, 12: A332-A335.

Dotson, K. No Date. Reclaimed Water Rate help achieve water supply and conservation goals. Tucson Water, Tucson Arizona:
https://www.watereuse.org/files/images/ReclaimedWaterRates.pdf

Drewes, J.E., M. Reinhard, and P. Fox. 2003. Comparing microfiltration-reverse osmosis and soil-aquifer treatment for indirect potable reuse of water. Water Research, 37: 3612-3621.

EIA. 2014. Levelized Cost and Levelized Avoided Cost of New Generation Resources in the Annual Energy Outlook 2014. US Energy Information Administration:
http://www.eia.gov/forecasts/aeo/electricity_generation.cfm

EIA. 2014. State Electricity Profiles. US Energy Information Administration: http://www.eia.gov/electricity/state/

Fabris, R., E.K. Lee, C.W.K. Chow, V. Chen, and M. Drikas. 2006. Pre-treatment to reduce fouling of low pressure micro-filtration (MF) membranes. Journal of Membrane Science, 289: 231-240.

Gaulinger, S. 2007. Coagulation pre-treatment for microfiltration with ceramic membranes. Techneau: https://www.techneau.org/fileadmin/files/Publications/Publications/Deliverables/D2.3.2-1.pdf

Gerrity D., B. Pecson, S.R. Trussell, amd R.R. Trussell. 2013. Potable reuse treatment trains throughout the world. Journal of Water Supply: Research and Technology-AQUA, 62: 321-338.

GWRS. No Date. Groundwater Replenishment System Technical Brochure. Orange County Water District and Orange County Sanitary District: http://www.gwrsystem.com/images/stories/AboutGWRS/GWRS%20Technical%20Brochure.pdf

Hanak, E., B. Gray, J. Lund, D. Mitchell, C. Chappelle, A. Fahlund, K. Jessoe, J. Medellin-Azuara, D. Misczynki, J. Nachbaur, and R. Suddeth. 2014. Paying for Water in California. Public Policy Institute of California: https://watershed.ucdavis.edu/files/biblio/R_314EHR_Paying_for_Water.pdf

Hanak, E., J. Lund, A. Dinar, B. Gray, R. Howitt, J. Mount, P. Moyle, and B. Thompson. 2011. Managing California's Water From Conflict to Reconciliation. Public Policy Institute of California: http://www.ppic.org/content/pubs/report/R_211EHR.pdf

Hauser, H. 2010. California Ocean Wastewater Discharge Report and Inventory. Heal the Ocean. California, USA.

Horne, R., K. Verghese, and T. Grant. 2009. Life Cycle Assessment: Principles, Practice, and Prospects. CSIRO Publishing, Collingwood, Australia.

Howe, C.W. 2005. The functions, impacts and effectiveness of water pricing: Evidence from the United States and Canada. Water Resource Development, 21(1): 43-53.

Huang, Y.Q., C.K.C. Wong, J.S Zheng, H. Bouwman, R. Barra, B. Wahlström, L. Neretin, and M.H. Wong. 2012. Bisphenol A (BPA) in China: A review of sources, environmental levels, and potential human health impacts. Environ Int, 42:91-9.

ICCA. 2009. Innovations for greenhouse gas reductions: A life cycle quantification of carbon abatement solutions enabled by the chemical industry. International Council of Chemical Associations: http://www.americanchemistry.com/Policy/Energy/Climate-Study/Innovations-for-Greenhouse-Gas-Reductions.pdf

Khan, S. 2013. Drinking water through recycling: The benefits and cost of supplying direct to the distribution systems. Australian Academy of Technology Science and Engineering. Melbourne Victoria, Australia.

Klotz Associates. 2010. Caldwell County Regional Water and Wastewater Planning Study. Final Report: http://www.gbra.org/documents/studies/caldwell/09-WastewaterFlows.pdf

Kommineni, S., J. Zoeckler, A. Stocking, S. Liang, A. Flores, and M. Kavanaugh. 2000. Advanced Oxidation Processes Chapter 3.0 Literature Review: http://www.nwri-usa.org/pdfs/TTChapter3AOPs.pdf

Leverenz, H.L., G. Tchobanoglous, and T. Asano. 2011. Direct potable reuse: a future imperative. Journal of Water Reuse and Desalination, 1(1): 2-10.

Lintelmann J., A. Katayama, N. Kurihara, L. Shore, and A. Wenzel. 2003. Endocrine disruptors in the environment (IUPAC Technical Report). Pure Appl Chem,75:631-81.

Luhdorff and Scalmanini Consulting Engineers. 2014. Land Subsidence from groundwater use in the San Joaquin Valley. California Water Foundation: http://www.groundwatervoices.com/wp-content/uploads/2014/07/San-Joaquin-Subsidence-Report-July-24-2014.pdf

Martin, J.N. 2014. Central Coast groundwater: seawater intrusion and other issues. California Water Foundation: http://www.groundwatervoices.com/wp-content/uploads/2014/08/Central-Coast-Groundwater-Report-Aug-2014.pdf

Matos, C., S. Pereira, E.V. Amorin, I. Bentes, and A. Briga-Sa. 2014. Wastewater and greywater reuse on irrigation in centralized and decentralized systems- An integrated approach on water quality, energy consumption and CO2 emissions. Science of the Total Environment, 493: 463-471.

Meehan, K., K.J. Ormerod, and S.A. Moore. 2013. Remaking waste as water: the governance of recycled effluent for potable water supply. Water Alternatives, 6(1): 67-85.

Molnar, J., J. Agbaba, A. Tubic, M. Watson, M. Kragulj, S. Roncevic, and B. Dalmacija. 2015. The effects of ultraviolet/H_2O_2 advanced oxidation on the content and characteristics of groundwater natural organic matter. Water Science & Technology: Water Supply, Volume 15.1: 34-41.

MRWA. No Date. Membrane Filtration. Minnesota Rural Water Association: http://www.mrwa.com/WaterWorksMnl/Chapter%2019%20Membrane%20Filtration.pdf

NAP. 2012. Understanding Water Reuse: Potential for expanding the nation's water supply through reuse of municipal wastewater. National Academies Press, Washington D.C., USA.

Netravali, A.N. and S. Chabba. 2003. Composites get greener. Materialstoday, 6(4): 22-29.

OCWD. 2015. Transparency & public records. Orange County Water District: http://www.ocwd.com/Transparency.aspx

Pinnau, I. 2008. Membranes for water treatment: properties and characterizations. Membrane Technology and Research: http://web.stanford.edu/group/ees/rows/presentations/Pinnau.pdf

Plahuta. M., T. Tisler, M.J. Toman, and A. Pintar. 2014. Efficiency of advanced oxidation processes in lowering bisphenol A toxicity and oestrogenic activity in aqueous samples. Arh Hig Rada Toksikol, 65: 77-87.

Platt, B.E. and M.E. Grismer. Chlorine levels increase after 13 years of recycled water in the Salinas Valley. No Date. California Agriculture, 68(3): 68-74.

Reif, W. Oscar. 2006. Microfiltration membranes: characteristics and manufacturing. Advance Biochem Engin/Biotechnol. 98: 73-103.

Rodriguez-Mozaz, S., M. Ricart, M. Kock-Schulmeyer, H. Guasch, C. Bonnineau, L. Proia, M. Lopez de Alda, S. Sabater, and D. Barcelo. 2014. Pharmaceuticals and pesticides in reclaimed water: efficiency assessment of a microfiltration-reverse osmosis (MF-RO) pilot plant. Journal of Hazardous Materials, 282:165-173.

Rukapan, W., B. Khananthai, T. Srisukphun, W. Chiemchaisri, and C. Chiemchaisri. 2015. Comparison of reverse osmosis membrane fouling characteristics in full-scale leachate treatment systems with chemical coagulation and microfiltration pre-treatments. Water Science And Technology: A Journal Of The International Association On Water Pollution Research, 71(4); 580-587.

Sadr Ghayeni, S.B., P.J. Beatson, A.J Fane, and R.P. Schneider. 1999. Bacterial passage through microfiltration membranes in wastewater application. Journal of Membrane Science 153: 71-82.

Sadr Ghayeni, S.B., S.S. Madaeni, A.G Fane, and R.P. Schneider. 1996. Aspects of microfiltration and reverse osmosis in municipal wastewater reuse. Desalination, 106: 25-29.

San Diego. 2013. Water purification demonstration project. Section F full-scale project considerations. Project report (final draft). San Diego, California, USA.

Schalk, S., V. Adam, E. Arnold, K. Brieden, A. Voronov, and H. Witzke. 2006. UV-Lamps for disinfection and advanced oxidation-Lamp Types, Technologies and Applications. IUVA News, Volume 8:32-37.

SFPUC. 2015. Recycled Water. San Francisco Public Utilities Commission. http://sfwater.org/index.aspx?page=141

SFPUC. 2015. Harding Park Recycled Water Project: San Francisco Public Utilities Commission http://sfwater.org/bids/projectDetail.aspx?prj_id=313

Schimmoller L. and M.J.Kealy. 2013. Fit for purpose water: The cost of overtreating reclaimed water: http://www.watereuse.org/sites/default/files/u18660/WRRF-10-01%20Project%20Synopsis.pdf

Somach, S.L. 1994. Who owns Reclaimed Wastewater. Pacific Law Journal (25): 1087-1096: http://www.heinonline.org/HOL/Page?handle=hein.journals/mcglr25&div=59

Swain D.L., T. Tsiang, M. Haugen, D. Singh, A. Charland, B. Rajaratnam, and N.S. Diffenbaugh. 2014.The extraordinary California drought of 2013/2014: character, context, and the role of climate change. American Meteorological Society: S3-S7.

Taylor, E.J. and P.L. Martin. 2000. The new rural poverty: Central Valley evolving into patchwork of poverty and prosperity. California Agriculture, 54(1): 26-32. http://californiaagriculture.ucanr.edu/landingpage.cfm?article=ca.v054n01p26&fulltext=yes

Tchobanoglous, G., H. Leverenz, M.H. Nellor, and J Crook. 2011. Direct potable reuse a pathway forward. WateReuse Research Foundation and WateReuse California. Alexandria, Virginia, USA.

Tong,L., X.Liu, X. Lui, Z. Yuan, and Q. Zhang. 2013. Life Cycle assessment of water reuse systems in an industrial park. Journal of Environmental Management, 129: 471-478.

USEPA. 2013. Strategies for saving energy at public water systems. United States Environmental Protection Agency: http://water.epa.gov/type/drink/pws/smallsystems/upload/epa816f13004.pdf

USEPA. 2001. Potential Contamination due to cross-connection and backflow and the associated health risk. U.S. Environmental Protection Agency Office of Ground Water and Drinking Water Standards and Risk Management Division. http://www.epa.gov/ogwdw/disinfection/tcr/pdfs/issuepaper_tcr_crossconnection-backflow.pdf

USEPA. 1999. Ultraviolet Radiation. EPA Guidance Manual Alternative Disinfectants and Oxidants. Environmental Protection Agency:

http://water.epa.gov/lawsregs/rulesregs/sdwa/mdbp/upload/2001_01_12_mdbp_alter_chapt_8.pdf

USEPA. 1999. Wastewater Technology Fact Sheet: Chlorine Disinfection. Environmental Protection Agency, Washington, D.C: https://www.cleanwaterservices.org/Content/Documents/About%20Us/Chlorine%20Disinfection%20Fact%20Sheet.pdf

USDIBR. 2010. US Department of the Interior Bureau of Reclamation (USDIBR). Microfiltration (MF) and Untrafiltration (UF). Reclamation Managing Water in the West. http://www.usbr.gov/pmts/water/publications/reportpdfs/Primer%20Files/07%20-%20Micro%20and%20Ultrafiltration.pdf

USGS. 2010. California Water Use Estimates for 2010 Release: http://ca.water.usgs.gov/water_use/2010-california-water-use.html.

Vince, F., E. Aoustin, P. Breant, and F. Marechal. 2008. LCA tool for the environmental evaluation of potable water production. Desalination, 220:37-56.

Warsinger, D.M., J. Swaminathan, E. Guillen-Burrieza, H.A. Arafat, and J.H. Lienhard V. 2015. Desalination 356: 294-313.

WHO. 2015. Costs and benefits of water and sanitation improvements at the global level. World Health Organization. http://www.who.int/water_sanitation_health/wsh0404summary/en/

Wu, L., W. Chen, C. French, and A. Chang. 2009. Safe application of reclaimed water reuse in the southwestern United States. University of California Division of Agriculture and Natural Resources, Publication 8357:1-21. http://anrcatalog.ucdavis.edu/pdf/8357.pdf

Wyman, R.J. 2013. The effects of population on the depletion of fresh water. Population and Development Review, 39:687-704.

Zhu, T., C. Ringler, and X. Cai. 2007. Energy price and groundwater extraction for agriculture: Exploring the energy-water-food nexus at the global and basin level. Working paper.