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Evaluating the Feasibility and Sustainability of Direct Potable Reuse in Las Vegas, NV

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EVALUATING THE FEASIBILITY AND SUSTAINABILITY OF DIRECT POTABLE REUSE IN LAS VEGAS, NV

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ABSTRACT

Community water sources are becoming more and more strained due to several factors including severe drought, population growth, urbanization, and climate change. This has spurred several water agencies to evaluate alternative water supply options to extend their resources. One potential alternative is potable reuse. Potable reuse comes in two forms: indirect potable reuse (IPR) and direct potable reuse (DPR). IPR is the advanced treatment of wastewater effluent before discharging into an environmental buffer that is a drinking water supply such as a lake, river, or groundwater aquifer before extraction and use. DPR is the advanced treatment of wastewater effluent that is directly introduced into a drinking water supply without entering an environmental buffer.

The Southern Nevada Water Authority (SNWA) provides water to the Las Vegas Valley. Ninety percent of the valley's supply comes from the Colorado River in Lake Mead, with an allocation of 300,000 acre-feet per year (ac-ft/y) (SNWA, 2015). All of the water used indoors (approximately 44% of overall use) makes its way to the sewer system and generally flows to one of four wastewater treatment plants (WWTPs). The WWTPs discharge their effluent into the Las Vegas Wash and the water is returned to Lake Mead (i.e., IPR). For every drop of water SNWA returns to the lake, the agency can withdraw an equivalent amount beyond their base allocation. This is referred to as return flow credits (RFCs) and currently provides an additional 200,000 ac-ft/y of supply (approximately). However, the elevation change from Lake Mead to the River Mountain Water Treatment Facility (RMWTF) (one of two major drinking water treatment facilities) is approximately 1,200 feet. Therefore, large amounts of energy and cost are expended to pump water into the Las Vegas Valley, which suggests that this current IPR configuration may not be the most ideal option considering the implications of the energy-water-environment nexus.

This thesis concerns the feasibility of DPR for the Las Vegas water system and provides a sustainability comparison with the current IPR configuration (or status quo) and other supply alternatives. A system dynamics model was developed using Stella 10.1 for the Las Vegas Valley water system. Two DPR treatment trains were evaluated. DPR 1 alternative included microfiltration (MF), reverse osmosis (RO), and ultraviolet light disinfection with advanced oxidation (UV/AOP). DPR 2 alternative included ultrafiltration (UF), ozone (O_3), biological filtration (BAF), and UV/AOP. The status quo, DPR 1, and DPR 2 alternatives were evaluated over a 50-year period from 2016 to 2066 based on metrics of energy to pump and treat the water, energy cost, and greenhouse gas (GHG) emissions. Additionally, water quality metrics of total dissolved solids (TDS) and eutrophication potential were projected. Model simulations for 25%, 50%, 75%, 90%, and 100% of RFCs for DPR were completed. Also, conceptual level capital costs were developed for each flow scenario. DPR 1 had higher costs for every flow alternative due to RO treatment and brine disposal.

The alternatives were screened down to three final alternatives for triple bottom line (TBL) analysis: status quo, DPR 1 with 50% RFCs, and DPR 2 with 50% RFCs. Criteria and sub-criteria were established and weighted for economic, social, and environmental conditions. Status quo was ranked as the highest alternative. It was concluded that the amount of energy and cost

saved from reduced pumping to implement DPR did not outweigh the DPR cost of pumping from the Las Vegas Wash to the RMWTF and additional treatment.

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CHAPTER 1: INTRODUCTION

Research Motivation

Water sources in the United States primarily consist of rivers, lakes, and groundwater basins. Several factors including severe drought, population growth, urbanization, and climate change are continually stressing primary water sources. Several communities have encouraged and succeeded in water conservation efforts to reduce per capita demand, but in many cases the remaining water sources are still not sufficient to meet demands. As a result water resource alternatives must be explored to create additional and more sustainable supplies. One potential alternative is potable water reuse. Potable water reuse is the use of highly treated wastewater for augmenting water supplies. There are two types of potable reuse: indirect potable reuse (IPR) and direct potable reuse (DPR). IPR is the process of sending wastewater effluent (typically at the secondary or tertiary level) to an advanced water treatment facility and then discharging into an environmental buffer such as a river, lake, or groundwater basin. The water is then extracted from the environmental buffer, treated (e.g., at a conventional drinking water treatment facility, and then sent to the consumer. DPR is the process of sending wastewater effluent (also typically at the secondary or tertiary level) to an advanced water treatment facility and then sending the advanced treated water to the influent side of a drinking water treatment plant, blending with finished drinking water from a drinking water treatment plant, or sending the water directly to the consumer. Each scenario bypasses the environmental buffer. IPR and DPR are shown graphically in Figure 1.

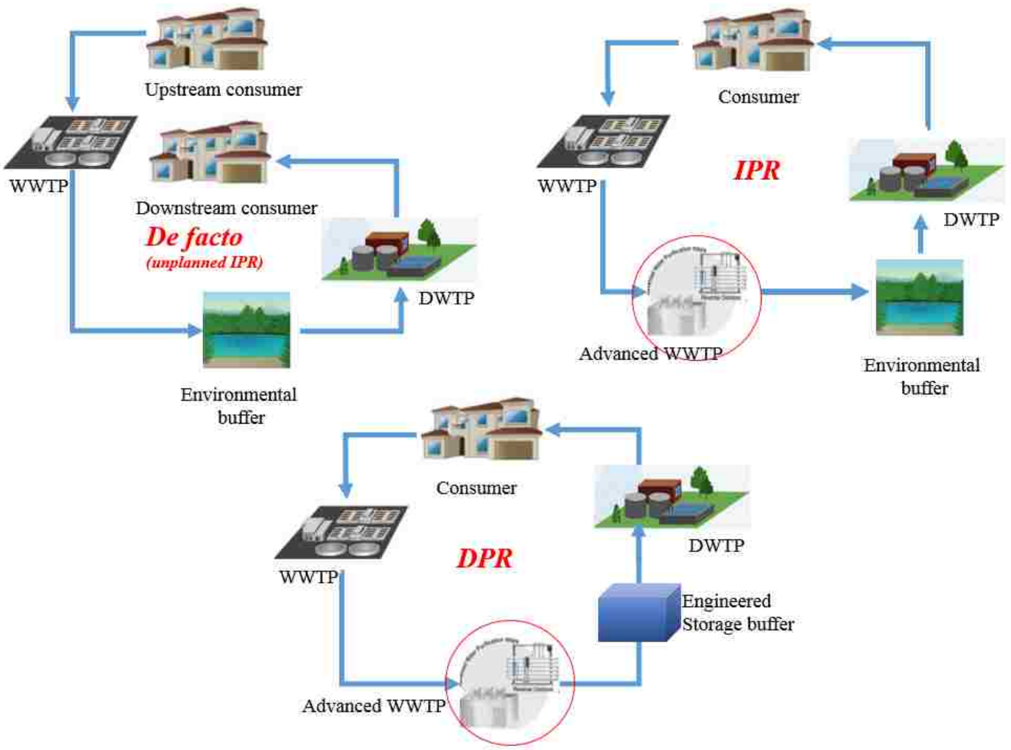

Figure 1: Potable Reuse Diagrams

The City of Las Vegas is located in Clark County in Southern Nevada. The Southern Nevada Water Authority (SNWA) is the water purveyor for Clark County. Clark County relies heavily on the Colorado River for its water supply, with 90 percent of its supply coming from the river and 10 percent coming from various groundwater wells throughout the county. Southern Nevada, along with the entire southwestern United States, has experienced prolonged drought. Water supplies along the Colorado River have been stressed significantly, and in 2007, guidelines were put in place to Colorado River lower basin states because of water shortages (Bureau of Reclamation, 2007). Although SNWA has been successful in promoting conservation throughout the community, conservation alone is not enough to alleviate the effects of prolonged drought and population increase. SNWA is allocated 300,000 acre-ft per year from the Colorado River (SNWA, 2015). This allocation is withdrawn from Lake Mead from one of two water treatment plants: the Alfred Merritt Smith Water Treatment Facility (AMSWTF) and the River Mountains Water Treatment Facility (RMWTF). The treated water is pumped to consumers in the Las Vegas Valley. Approximately 56% of the water withdrawn is used outdoors, and the remaining 44% is used indoors. All water used indoors is discharged into the sewer system and, with the exception of water that travels to several smaller satellite treatment facilities focused on non-potable reuse, makes its way to one of four major wastewater treatment plants in the Las Vegas Valley. Most of the treated wastewater discharges into the Las Vegas Wash and is returned to Lake Mead. The Bureau of Reclamation is the responsible party for tracking Colorado River water, and they deduct any water returned to Lake Mead from Nevada's allocated river withdrawals (www.snwa.com). This return flow credit (RFC) allows SNWA to withdraw flow in addition to their 300,000 acre-ft per year allocation. This process of RFCs is a form of IPR. Whether or not this is labeled as intentional IPR or de facto reuse is debatable. If RFCs were not being credited for SNWA, this would be a normal cycle for wastewater discharge into the environment and labeled de facto reuse. RFCs assist with maintaining Lake Mead levels and not only provide a benefit for SNWA, they also benefit downstream users by replenishing Colorado River supply.

Research Approach

This thesis evaluated the overall feasibility of implementing DPR in the Las Vegas water system. The research aimed to answer the following key questions:

- Is DPR a more efficient water management alternative than the RFC approach?
- Does DPR provide a higher cost to benefit ratio than importing new water supplies?

- Does DPR provide an overall improvement to the environment?

Based on high energy costs for pumping the RFCs from Lake Mead to the Las Vegas Valley, it was hypothesized that DPR can provide a more sustainable and economical water resource for the Las Vegas Valley by substituting more advanced treatment (and any other required infrastructure) for the existing pumping costs associated with the return flows to Lake Mead. Additionally, DPR could actually improve drinking water quality based on the high level of advanced treatment that would be utilized.

The objectives of this research were to 1) develop and calibrate a system dynamics model for the existing Las Vegas Water cycle; 2) expand the system dynamics model to include DPR; 3) compare the DPR model results to a water importation alternative from northern Nevada; 4) compare all the research alternatives based on sustainability metrics such as cost, water quality, and greenhouse gas (GHG) emissions; 5) implement water policy scenarios into the model to see how they affect the overall system.

Research Contribution

This research hopes to provide a baseline for the initial investigation on the feasibility of DPR for communities and agencies looking for alternatives to better use their wastewater effluent. By using the operational metrics evaluated in thesis (i.e. pumping and other energy costs, potential water quality benefits, and GHG emissions) coupled with site specific metrics of concern, communities may be able to answer the initial questions regarding the feasibility of DPR.

Scope of Research

The timeline of the research covers a 50-year time period from the year 2016 to 2066. The purpose of this research was to evaluate the sustainability of DPR and other alternatives. The United States Environmental Protection Agency (EPA) states that sustainability is based on the principle of “everything that we need for our survival and well-being depends, either directly or indirectly, on our natural environment” (www.epa.gov). Sustainability integrates three main facets: economy, environment, and society. The social aspect when dealing with water projects is essentially referring to public health (Schimmoller and Kealy, 2014). Several research papers have been published regarding the public health protection of DPR by the WateReuse Association, the Water Research Foundation, the Water Environment Federation, and others. As such, the social (or public health) aspect of sustainability will not be part of this research and instead the focus is on economic viability and environmental protection.

The following chapters provide a detailed review of the key aspects of water reuse and the water scarcity problem faced in the southwestern United States. Additionally, a description of the system dynamics model development, assumptions, and validation is provided. The model results for the status quo, DPR, and water importation to Las Vegas are summarized based on capital and operational costs, GHG emissions, total dissolved solids (TDS) load, and eutrophication potential. Furthermore, water policy scenarios are introduced to assess how the water system is affected and whether those scenarios positively or negative impact the feasibility and appropriateness of DPR implementation in the Las Vegas water system.

CHAPTER 2: LITERATURE REVIEW

Food-Energy-Water-Environment Nexus

Food, energy, and water are inevitably linked and have a major impact on society. As population continues to increase and climate continues to change, new waves of complications threaten the entirety of the human race. These interconnected challenges have created opportunity for innovative problem solving. Labeling water, energy, and food as a nexus has motivated a global research agenda (Leck et al., 2015). The nexus thought process is focused on addressing complications among multiple sectors, while focusing on the efficiency of the entire system rather than the isolated sector productivity (Hoff, 2011). For example, 90% of global power generation relies on fresh water supplies, and increasing demands on already stressed fresh water resources puts pressure on water-intensive food producers to find alternative sources (Bhaduri et al., 2015). Additionally, river basins where upstream and downstream users are competing for water demands are forced to find trade-offs between cost of water, agriculture, and electricity production (Leck et al., 2015). As shown in Figure 2 from Hoff (2011), using “big picture” analysis and understanding how food, energy, and water are interdependent is essential for developing sustainable solutions for the issues associated with these sectors.

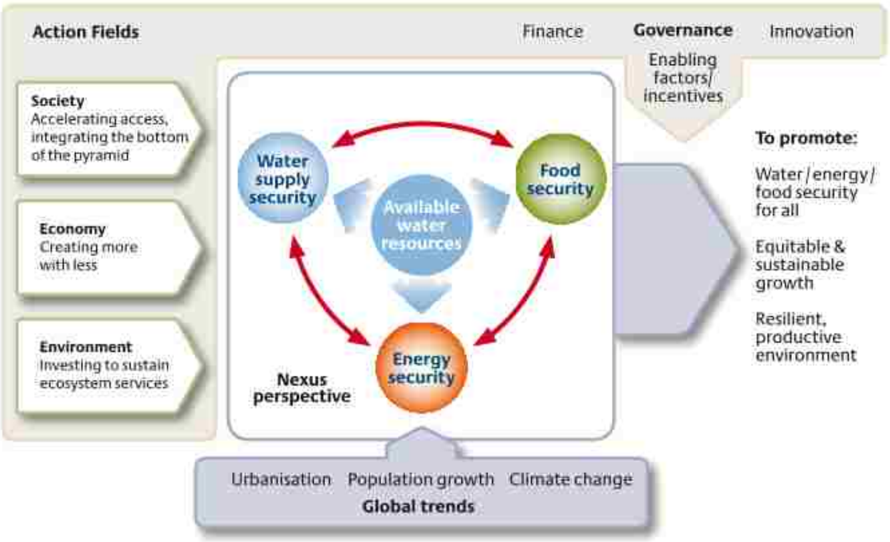

Figure 2: Interdependency of Food, Water, and Energy Nexus (Hoffman 2011)

Embodied Energy

Embodied energy is the energy needed for material production, onsite construction, and demolition and disposal for building and/or products (Dixit et al., 2010). Energy related research has primarily focused on operation and maintenance efficiency and life cycle analysis. However, as structures have become more insulated and mechanical equipment has become more efficient, the energy emphasis has shifted towards embodied energy (Dixit et al., 2010). In fact some suggest that approximately 75% of the total embodied energy in buildings is due to offsite production of materials and components (Ding, 2004). In terms of water industry applications, embodied energy is the inclusive energy needed to produce materials for necessary structures, infrastructure (such as pipelines, fittings, mechanical equipment), and treatment processes (including chemicals and major material components); transportation and fuel for the materials and equipment; transporting the water source to and from a destination; and all necessary construction activities (Mo et al., 2010). With population increases and urbanization, the focus of improving the embodied energy for water importation and treatment will become increasingly more important (Zimmerman et al., 2008).

Embodied Water

Chen et al. (2012) defines embodied water as the total water needed to generate a product or service. Water is linked, both directly and indirectly, to every industry, and as such, it has a significant impact on the economy. As shown by Chen et al. (2012) in Figure 3 with units shown in cubic meters for each million dollars of output generated, embodied water is used highly in the agriculture and food industries.

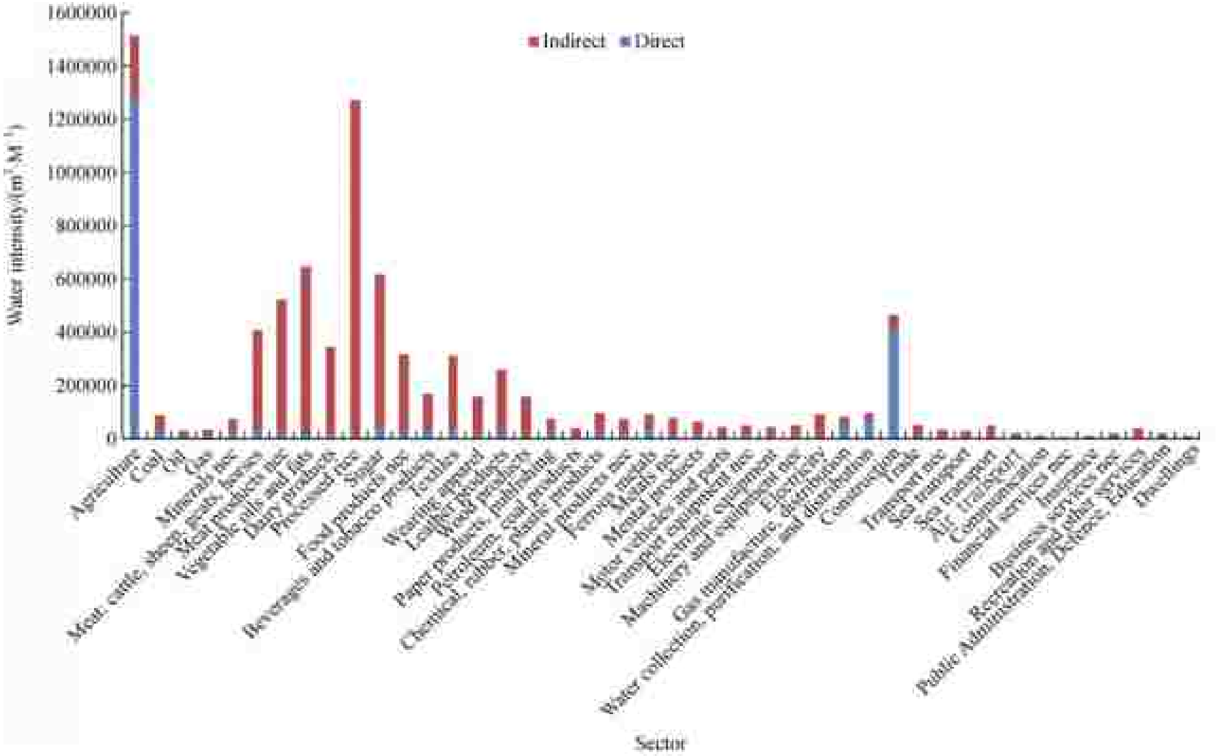

Figure 3: Embodied Water Based on Industry (Chen et al., 2012)

Embodied water within the water sector can be quantified by direct and indirect water use both in construction and operation of facilities (Shao & Chen, 2015). Examples of direct water users are evapotranspiration and aquatic life, and examples of indirect water users are building and infrastructure materials, mechanical equipment, electricity, vegetation and substrate, and tap water. Interestingly, when accounting for embodied water in regards to tap water, it is quantified by the total marginal water cost induced by the tap water supply rather than its direct water content (Shao & Chen, 2015).

Water Reuse

Wastewater effluent has been utilized for several beneficial uses for decades. Recycled water can serve either non-potable or potable purposes. Non-potable water reuse is typically used for landscape irrigation, agricultural irrigation, and industrial uses such as cooling tower water (Schimmoller & Kealy, 2014). Water reuse is practiced the most in the states of California and Florida. However, Texas, Arizona, Nevada, Colorado, and New Mexico are also significant users of recycled water. Various areas in the country have a high demand for reclaimed water depending on major industries. For example, nearly 80 percent of all recycled water in California is used for agricultural irrigation (Schimmoller & Kealy, 2014). Using reclaimed water provides several benefits to communities, including a sustainable alternative supply of water, less energy use than importing water, local control of the reclaimed supply, reduced construction impact of a new imported supply, and reduced quantity of wastewater effluent discharged into the environment (Miller 2006).

Potable Reuse

Potable reuse is the use of a community’s wastewater as a drinking water source (Tchobanoglous et al., 2015). Potable reuse practice is both planned and unplanned in the

United States. Unplanned potable reuse is often referred to as de facto reuse, and occurs when surface waters are subject to upstream wastewater effluent discharges. These effluent discharges fall under the Clean Water Act and are regulated by National Pollutant Discharge Elimination System (NPDES) permits (www.epa.gov). Planned potable reuse can be separated into two categories: indirect potable reuse (IPR) and direct potable reuse (DPR). IPR is the advanced treatment of secondary or tertiary wastewater before being discharged into an environmental buffer such as a lake, river, or groundwater basin, and then is withdrawn as part of the fresh water supply that is sent to the water treatment plant. DPR is the advanced treatment of wastewater effluent, which is then sent to the influent side of a drinking water treatment plant, blended with finished drinking water from a drinking water treatment plant, or sent directly to the consumer. Each scenario bypasses the environmental buffer but often includes an engineered storage buffer (ESB) instead.

Several states including California, Florida, Virginia, Washington, and Nevada have regulations in place for IPR. California has the strictest regulations for IPR, where the California Division of Drink Water (DDW) requires treatment to achieve a minimum 12-log reduction of enteric virus, 10-log reduction of *Giardia* cysts, and 10-log reduction of *Cryptosporidium* oocysts, often referred to as the “12-10-10 Rule” (Tchobanoglous et al., 2015). Technically there are no federal potable reuse regulations, however, certain federal regualtions such as the Clean Water Act and the National Pretreatment Program have a sinificant impact on the source wastewater that is eventualy used for potable reuse (Trussell et al., 2013). In addition to pathogens, there are several other chemical constituents of concern including trace organic compounds (TOrCs), total organic carbon (TOC), and disinfection byproducts (DBPs), some of which are regulated.

Additionally, since IPR is intended to be used for potable purposes, drinking water requirements need to be met, and because of its wastewater origin, recycled water must exceed drinking water quality in some cases (Trussell et al., 2013). Currently, there are no DPR regulations in the United States, and only the state of Texas allows DPR, for which each system is evaluated/regulated on a case-by-case basis (Tchobanoglous et al., 2015). Tchobanoglous et al. (2015) summarized the latest findings for DPR and identified areas needing more information. The document did determine that it is feasible to develop DPR regulations, and as a result, the State of California is in the process of forming said regulations (CA Water Resources Control Board, 2017).

The standard treatment train for IPR (often referred to as full advanced treatment or FAT) is microfiltration (MF), reverse osmosis (RO), and ultraviolet light disinfection and advanced oxidation with hydrogen peroxide (UV/AOP) (Trussell et al., 2013). One of the most common facilities referred to in reference to this treatment train is the Orange County Water District's (OCWD) Groundwater Replenishment System (GWRS). The GWRS is a 100 million gallon per day (mgd) facility that uses the FAT treatment train before discharging into a groundwater basin. The water is then extracted after months of storage/travel time and chlorinated prior to consumption (Tchobanoglous et al., 2015). There are also IPR treatment trains that do not use RO. This can benefit operating costs as well as by not having to dispose of the waste brine associated with RO. Instead unit processes such as ozone (O_3) and biological activated carbon are used, as shown in Figure 4 (Trussell et al., 2013).

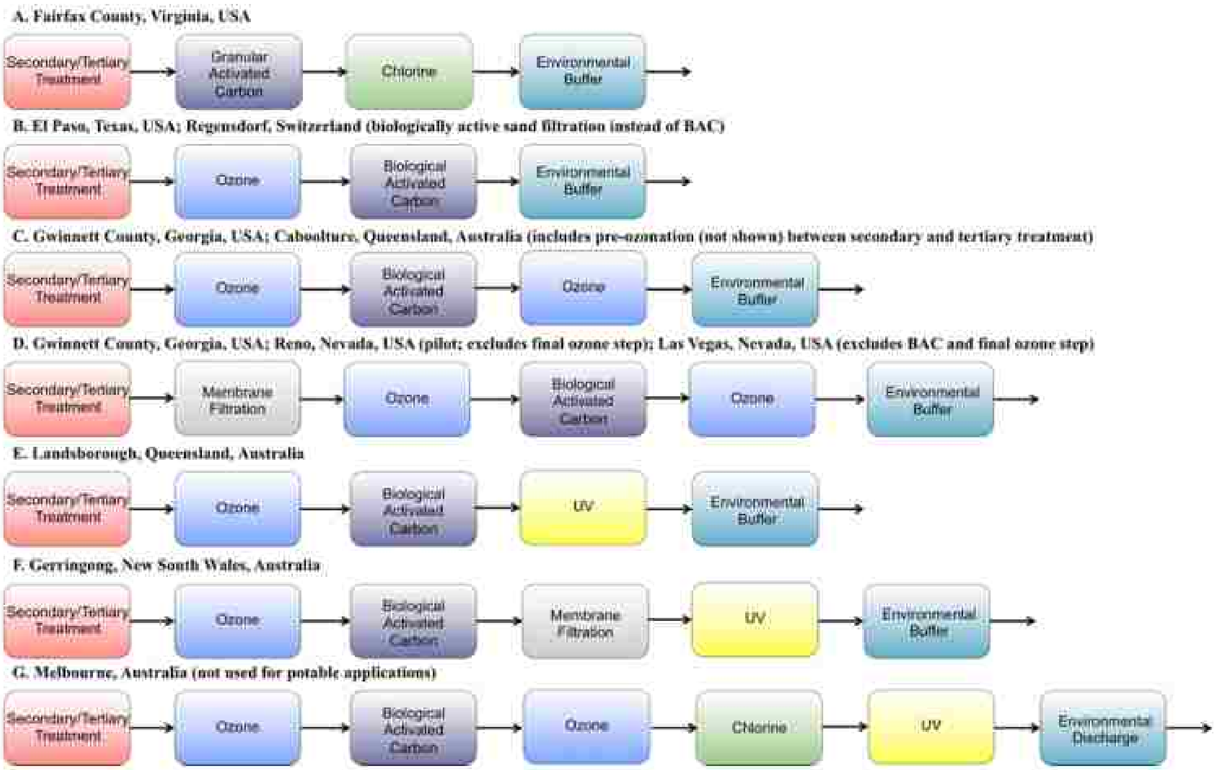

Figure 4: Water Reuse Treatment Trains without Reverse Osmosis (Trussell et al., 2013)

DPR treatment train requirements are not expected to be much different than IPR treatment trains. The key differences would be the use of an ESB rather than an environmental buffer and/or the use of a more robust monitoring system (Tchobanoglous et al., 2015). By removing the environmental buffer, the time and distance traveled by the treated water decreases dramatically, which reduces energy and cost for distribtuion. However, this also dramatically reduces the time to detect and respond to potential failures, such as when unit processes do not meet established public health criteria. This drives the need for redundant treatment and robust monitoring (Pecson et al., 2015). The only DPR facility in the United States is in Big Spring, Texas at the Colorado Municipal Water District's Raw Water Production Facility (RWPF). The RWPF uses MF, RO, UV/AOP, and then the product water is blended with raw surface water in a transmission line prior to treatment at a drinking water treatment facility (Tchobanoglous et al., 2015). The two most common treatment trains proposed for DPR are 1) MF, RO, UV/AOP, ESB and 2) ultrafiltration (UF), O_3, BAC, UV/AOP (Tchobanoglous et. al, 2015). These treatment trains may or may not include an ESB and have been shown to exceed the 12-10-10 rule as shown in Tables 1 & 2 (Tchobanoglous et al., 2015).

Table 1: Log Reduction Credits for DPR Train 1 (Tchobanoglous et al., 2015)

Process	**Log Reduction Credits**		
	V[1]	**G[2]**	**C[3]**
MF		4	4
RO	1.5	1.5	1.5
UV/AOP	6	6	6
ESB w/ Free Chlorine[4]	6	3	0
Total for Treatment Train	**13.5**	**14.5**	**11.5**

1. Virus
2. Giardia
3. Cryptosporidium
4. Contact Time= 900 mg-min/L

Table 2: Log Reduction Credits for DPR Train 2 (Tchobanoglous et al., 2015)

Process	**Log Reduction Credits**		
	V[1]	**G[2]**	**C[3]**
O_3[4]	5	3	0
BAF	0	0	0
UF	1	4	4
UV/AOP	6	6	6
ESB w/ Free Chlorine[5]	6	3	0
Total for Treatment Train	**18**	**16**	**10**

1. Virus
2. Giardia
3. Cryptosporidium
4. Contact Time= 1 mg-min/L
5. Contact Time= 900 mg-min/L

Salveson et al. (2016) provides examples of ESBs for DPR scenarios. Scenarios ranged from simple to complex tank schemes with intricate online monitoring technology, to residence time in the AWTF discharge pipeline. One DPR example was in Lubbock, TX which had a discharge pipeline approximately six miles long and would have a residence time of one hour and fifteen minutes, assuming 7 feet per second (Salveson et al., 2016). This research will follow a similar approach with the DPR pipeline from the proposed AWTF to the RMWTF as a sufficient ESB.

Several research projects have been performed by the Water Environment and Reuse Foundation (WE&RF) (formerly known as the WateReuse Research Foundation and the Water Environment Research Foundation), the Water Research Foundation (WRF), and various academic research groups. The results from this research suggest that potable reuse is adequately protective of public health and capable of producing a water quality that meets or exceeds drinking water standards (Tchobanoglous et al., 2015). However, public perception continues to be a major hurdle in potable reuse projects. The public generally understands the water cycle in terms of evaporation and circulation, but they are still disconnected and misunderstand the water cycle when it comes to human use (Macpherson & Snyder, 2013). Macpherson & Snyder (2013) refer to this as the "The Big Picture Gap." For the past century wastewater treatment plants have been treating water to allow for safe discharge to the environment. However, wastewater treatment plants have been doing so "out of sight and out of mind," with minimal observation from society (Macpherson & Snyder, 2013). The public has historically perceived sewage as a waste needed to be disposed of, so the idea of returning it to a drinking water source is often controversial (Macpherson & Snyder, 2013).

Water in Southern Nevada

Nevada is one of seven states that withdraw from the Colorado River (www.usbr.gov). Ninety percent of the Las Vegas water supply comes from Colorado River water via Lake Mead, with an allocation of 300,000 acre-feet per year plus return flow credits (RFCs) from treated wastewater from the Las Vegas Wash (www.snwa.com). Figure 5 shows the water use cycle for the Las Vegas Valley.

Figure 5: Water Use Cycle for the Las Vegas Valley

Concerns for Colorado River supplies being strained or reduced due to population increases in the southwestern United States, climate change, and reduced precipitation due to prolonged drought have been ongoing for the better part of the past three decades (Barnett & Oierce, 2008). From the year 2000 to the year 2014, both snowfall and runoff into the Colorado River Basin were below normal conditions (SNWA, 2015). This resulted in the storage of the two primary reservoirs of the basin, Lake Powell and Lake Mead, to be only 44% (SNWA, 2015). Additionally, Las Vegas experienced one of the biggest population booms from the 1950s to present day, increasing from approximately 44,000 to over 2 million people (SNWA, 2015). With Lake Mead levels starting to decline, the Secretary of Interior issued a Record of Decision for new guidelines on how to operate the lower Colorado River Basin reservoirs (Secretary of Interior, 2007). The interim guidelines dictated Colorado River allocation reductions for lower basin states based on Lake Mead elevations. SNWA’s reduction limits are summarized in Table 3.

Table 3: SNWA's Allocation Reduction Based on Lake Mead Elevation

Lake Mead Water Elevation	**Allocation[1] (ac-ft/y)**	**Allocation Reduction (ac-ft/y)**
1,075 – 1,050 ft	287,000	13,000
1,050 – 1,025 ft	283,000	17,000
Below 1,025 ft[2]	280,000	20,000
1. Original Allocation is 300,000 ac-ft/y 2. Re-consultation is required when the elevation drops below 1,025 ft.		

Figure 6 was taken from SNWA (2015) and shows the historical elevation of Lake Mead in relation to the existing intakes.

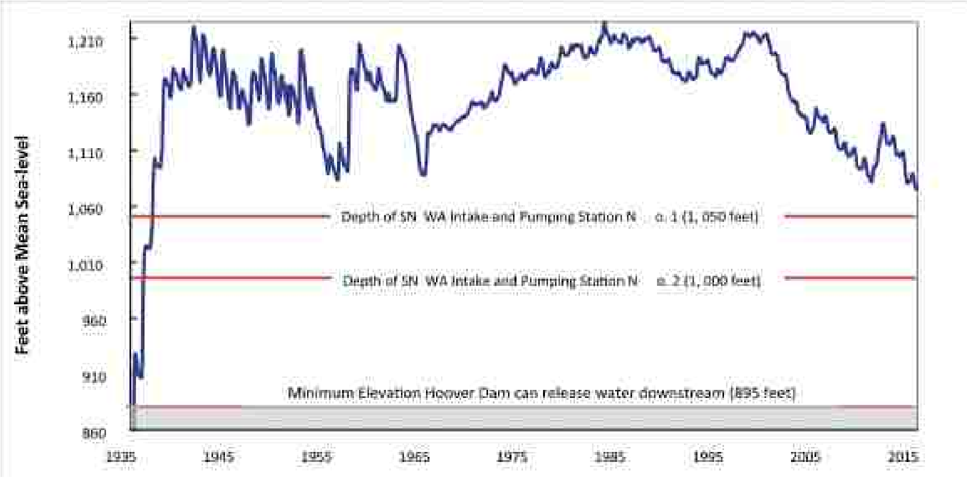

Figure 6: Historical Elevation of Lake Mead (SNWA, 2015)

In order to secure their supply, SNWA constructed a new third intake to withdraw water from Lake Mead. Intake No. 1 is capable of withdrawing water down to an elevation of 1,050 ft, and Intake No. 2 can withdraw water down to an elevation of 1,000 ft. With the completion of Intake No. 3, SNWA is now able to withdraw water down to an elevation of 895 ft, which is the elevation when Hoover Dam can no longer release water downstream (SNWA, 2015).

Water Quality

In addition to supply concerns, water quality for Lake Mead increasingly has been brought to the forefront of water related issues. Specific constituents of concern are the loadings of total dissolved solids (TDS) and nutrients such as nitrogen (N) and total phosphorous (TP). The EPA has set a secondary maximum contaminant level (MCL) for TDS at 500 milligrams per liter (mg/L) (www.epa.gov). The TDS concentrations at both the AMSWTF and the RMWTF already exceed the secondary MCL at 643 mg/L and 656 mg/L, respectively (SNWA, 2016). There are many factors contributing to the high TDS concentrations in Lake Mead. One factor is that Lake Mead is at the low end of the Colorado River, and as the river flows from the State of Colorado down to Mexico minerals dissolve along the way, increasing the concentration as the river runs south (www.lvvwd.com). Another factor contributing to TDS concentration in Lake Mead is the RFCs from the Las Vegas Wash. The Las Vegas Wash flow is mostly highly treated wastewater but also consists of urban runoff, shallow groundwater runoff, and storm water. Additionally, approximately 30 percent of the Las Vegas Valley population uses a water softening system for their residential supply (Venkatesan et al., 2011). The concentrated brine as a result of the water softening systems is discharged to the sewer collection system and enters the WWTPs. TDS is not removed in the wastewater treatment process, and as a result the TDS load increase from the water softening systems, as well as the other runoff sources enters Lake Mead via RFCs. High TDS can make water sources unpalatable and removing TDS can improve overall water quality. However, quantifying the economic benefits of removing TDS is difficult. TDS can cause damage to infrastructure and certain agricultural crops (Borda, 2004). A summary of the potential economic impacts from TDS found in the literature are listed in Table 4 below.

Table 4: Economic Impacts from TDS

Description	**Economic Impact**	**Source**
Cost to Colorado River users from salinity	$306 to 312 million in damages per year	Venkatesan et al. (2011)
Projected cost to Colorado River users from salinity in 2025	$471 million per year	Venkatesan et al., 2011
Damage from TDS concentrations of 900 mg/L to 1,400 mg/L at Imperial Dam, AZ	$33,100 per mg/L annually (1978 dollars	Anderson & Kleinman, 1978

TDS damage in Los Angeles for municipal and industrial use	$880 to $1.44 billion (1978 dollars)	Anderson & Kleinman, 1978
Cost saving from a 10 mg/L reduction in salinity for municipal and industrial users	$1.12 million per year or $112,000 per mg/L	Anderson & Kleinman, 1978
Damages from salinity for concentrations from 800 mg/L to 1,400 mg/L	$244,300 per mg/L to $326,100 mg/L or $24.43 to $32.1 per ton of salt, assuming 1 mg/L equals 10,000 tons of salt (1976 dollars)	Kleinman & Brown, 1980
TDS damage for ten year annual average of 767 mg/L	$310.8 million (1986 dollars), average of $1.2 million per mg/L or $116 per ton of salt	Lohman et al., 1988
Lower Colorado benefit from removing salt	$116 per ton of salt removed (1998 dollars)	Borda, 2004
Model developed to estimate cost and benefits of removing 67 mg/L of salt	$75 million in benefits (2000 dollars); $112 per ton in benefit and $63 per ton to implement salinity control measures	Borda, 2004

The algal bloom of 2001 in Lake Mead let to the formation of the Algal Task Force (Bureau of Water Quality Planning, 2003). It was determined that one of the major contributing factors for the algal bloom was an excess of nutrients, specifically phosphorous. As a result total maximum daily loads (TMDLs) were developed for the wastewater dischargers for the months of March through October, for a total waste load allocation of 333 pounds per day (lbs/day)of TP, and a combined concentration of 0.21 mg/L (Bureau of Water Quality Planning, 2003). The WWTPs for the City of North Las Vegas (CNLV), the City of Las Vegas (CLV), Clark County Water

Reclamation District (CCWRD), and the City of Henderson (COH) all focus on phosphorous removal to prevent eutrophication of Lake Mead.

Future Water Supply Alternatives for Southern Nevada

Continuing with the status quo approach of relying on SNWA's Colorado River allocation in conjunction with RFCs has its advantages and disadvantages. For example, using RFCs allows SNWA expand their withdrawals from Lake Mead to meet their demand needs, and the RFCs aid in sustaining the ecosystem along the Las Vegas Wash. However, even with successful conservation efforts and reducing per capita demand, SNWA's supply from Lake Mead is not enough to meet future demands (SNWA, 2015). Additionally, the difference in elevation from Lake Mead to the Las Vegas Valley is approximately 1200 ft. This requires an enormous amount of energy to pump water from Lake Mead and produces an excessive amount of carbon dioxide (CO_2) that is ultimately released into the atmosphere (Shrestha, 2010).

Another alternative for SNWA water supplies is bringing water from northern Nevada via the Clark, Lincoln, and White Pine Counties Groundwater Development Project (GDP). The GDP is a $3.22 billion project consisting of several wells, 263 miles of pipeline and laterals, pump stations, a water treatment facility, and power facilities (SNWA, 2012). The GDP would add 134,434 ac-ft/y to SNWA's supply. Not only would this project increase supply but would create additional RFCs to Lake Mead, further extending the amount of water that can be withdrawn (SNWA, 2015). However, this project comes at a large expense and it may be advantageous to evaluate lower cost alternatives. The proposed alignment for the GDP is shown in Figure 7 and was taken from SNWA (2012).

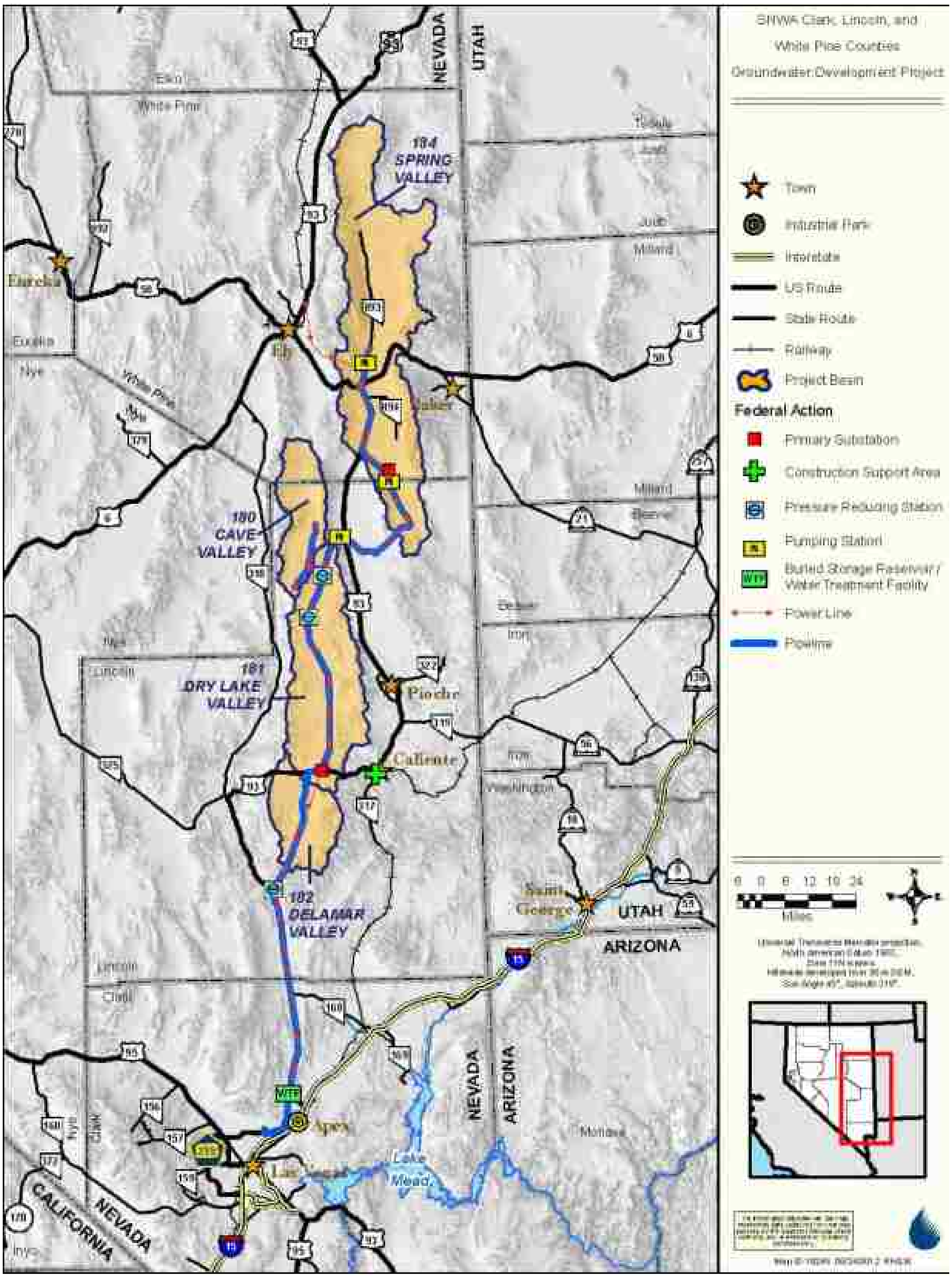

Figure 7: Anticipated Alignment for GDP (SNWA, 2012)

Expanding water reuse in the Las Vegas Valley could be used as another water supply alternative. In addition to meeting TP requirements for discharge into the Las Vegas Wash, all four WWTPs in Las Vegas are capable of producing tertiary quality effluent. Approximately 22,000 ac-ft/y is used for non-potable reuse purposes such as irrigation (SNWA, 2015). Expanding non-potable reuse capabilities would require less Colorado River water needed for outdoor use. However, this would also reduce the amount of RFCs to Lake Mead. Another potential for maximizing water reuse would be to implement DPR. All or a portion of the flow being used as RFCs to Lake Mead could be used for DPR. Essentially the same amount of water could be used by SNWA (i.e., Colorado River Allocation plus DPR water which once was RFC water), only the water would be pumped a shorter linear distance as well as a reduced change in elevation. However, an additional advanced water treatment facility would need to be constructed in order to meet potable water standards. Although this scenario considers discharging into what could be considered an environmental buffer (i.e. the Las Vegas Wash), this is still considered DPR. Over 90% of the flow in the Las Vegas Wash is treated wastewater. Further, Olivieri et al. (2016) evaluated the feasibility of uniform DPR regulations for the State of California and considered IPR scenarios for short retention times in the environment. There was an identified regulatory gap between IPR projects with shorter retention times in the environmental buffer and DPR projects with no buffer. The study concluded that any potable reuse project that discharges into the environment with a retention time of less than two months it is considered DPR (Oivieri et al., 2016). Therefore, because of the high percentage of wastewater within the wash and the short retention time (which would be less than two months), using flow from the Las Vegas Wash for potable reuse can be considered DPR.

System Dynamics Concepts

System dynamics models help explain the change of a system over time and allow for multiple interconnected variables to be evaluated simultaneously (Sterman, 2000). Stocks and flows are used to track accumulations of materials and how they move through a system. Flows are the rates of change over time into the stocks, and stocks depict the state of the system and are used to make decisions. Connectors are used to establish relationships between stocks and flows in a system (Sterman, 2000).

Over the years, several System Dynamics has been developed for various water (Tamaddun et al., 2018; Chen et al., 2017; Ahmad 2016; Mirchi et al., 2012) and environmental management (Amoueyan et al., 2017; Venkatesan et al., 2011a,b; Rusuli et al., 2015) applications. System dynamics has been used for flood management (Ahmad and Simonovic 2000; 2001; 2004; 2006), water allocations (Wu et al., 2015; Qaiser et al., 2011, 2013), climate change impact on water resources (Dawadi et al., 2012, 2013; Zhang et al., 2016), carbon footprint of water projects (Shrestha et al., 2011, 2012; Bukhary et al., 2017), water conservation (Ahmad and Prashar 2010) and energy planning (Moumoni et al. 2014). Models have also been developed (Stave 2003; Nussbaum et al., 2015) for Lake Mead and the Las Vegas water supply system to educate public about water conservation. Stave (2003) modeled the Las Vegas water system to evaluate different water policies and their effect on local water supplies. A key focus of the paper was to increase stakeholder and public understanding of water management issues. Stave (2003) cited Ford (1999) as well as Richardson and Pugh (1989) for major steps that should take place when developing a system dynamics model. The steps are as follows:

1. Define the problem
2. Describe the system
3. Develop the model
4. Build confidence in the model
5. Use the model for policy analysis
6. Use the model for public outreach

As with any problem solving process, steps are iterative, and results can provide feedback to previous steps in order to fine-tune the process (Stave, 2003). The paper evaluated several policies which included increasing water supply, decreasing hotel use, decreasing indoor residential use, decreasing residential outdoor use, decreasing population growth, and combinations of policies. Reducing population growth and decreasing outdoor residential use extended the amount of time that supply exceeded water demand for the valley. For this research, the two policies of reducing outdoor use and introducing a new water supply were implemented to see how they would affect a potential DPR system, the status quo, and other water supply alternatives for the Las Vegas Valley.

In addition, Venkatesan et al. (2011) evaluated how the Las Vegas water system impacted the salt loading to Lake Mead using a system dynamics model. Salt loading, or TDS, is added to Lake Mead (and subsequently the lower Colorado River Basin) from the Las Vegas Valley via the Las Vegas Wash. In 2005, approximately 1,373,946 kilograms per day (1,106 million pounds per year) of TDS was added to Lake Mead via the Las Vegas Wash (Venkatesan et. al, 2011). The loading consisted of the following sources:

- runoff and seepage, 38.2%
- TDS supplied from Lake Mead to indoor use, 33.7%
- human wastes, 18.7%
- water softeners, 8.6%
- other sources, 0.7%

In addition to TDS evaluation, the study evaluated different water policies including conservation measures and increasing the amount of non-potable reuse to see their effects on water demand (Venkatesan et al., 2011). Regardless of the water policy, the water demand was not able to be met for future population projections based on the per capita goal of 199 gpcd set by SNWA. Additional water sources were deemed necessary to meet future demands. However, policies did affect the TDS loading. Conservation measures, both for indoor and outdoor use, yielded higher TDS loads in the Las Vegas Wash. Higher TDS loading was also observed when increasing the amount on non-potable water reuse (Venkatesan et. al, 2011).

In a separate study, Venkatesan et al. (2011) used a similar model to evaluate TDS and energy when implementing IPR and DPR scenarios in the Las Vegas Valley. The model assumed a reverse osmosis (RO) installation at every wastewater treatment plant with a capacity increase every four years over the study period. Although the results showed a water quality improvement from TDS removal with the RO systems, available water was decreased due to the water loss from the membrane systems. However, when DPR was implemented, the results showed a 53% energy decrease when compared to the status quo scenario of RFCs flowing to Lake Mead and then pumping them back up to the Las Vegas Valley.

CHAPTER 3: MODEL DEVELOPMENT

General Model Framework

The system dynamics model was developed using Stella 10.1 to simulate the water cycle for Las Vegas, NV and to introduce DPR scenarios as well as other water policies to observe how they affect the system and future water use. The baseline model simulated the current conditions for the Las Vegas Valley, and once validated, DPR alternatives were introduced and evaluated. The baseline model tracks flow in units of ac-ft/y from Lake Mead to the water treatment plants, to water use within the valley (both indoor and outdoor use), through the wastewater treatment plants (WWTP) for the water used indoors, and water being returned to the lake via the Las Vegas Wash (i.e. RFCs). Figure 8 shows a basic diagram of the baseline model and how DPR will be introduced.

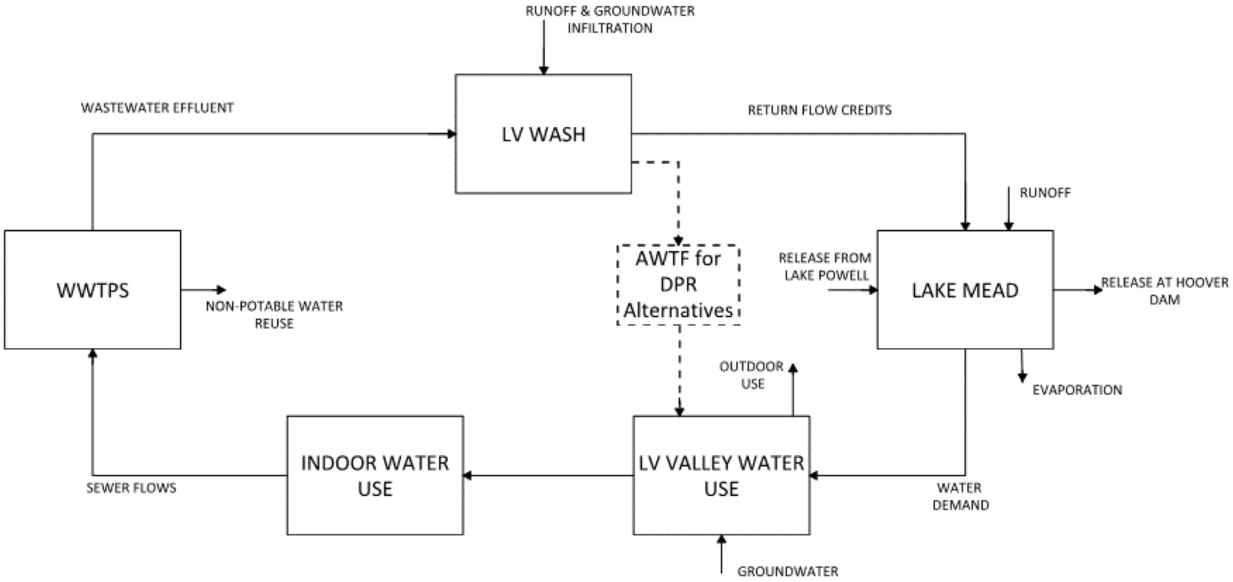

Figure 8: Water Diagram for Model Base Condition

Tra (2015) provided a long-term population projection through the year 2050, and values were interpolated to project population through 2066. This projection is shown in Figure 9 below.

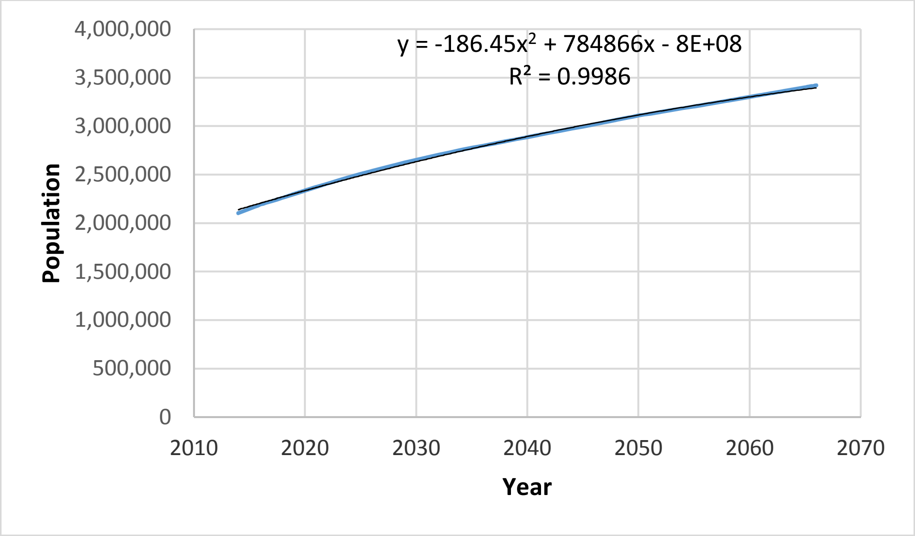

Figure 9: Population Projection Using Data from Tra (2015)

The 2016 water demand was 205 gallon per capita per day (gpcpd), or 0.229 ac-ft/y per person (www.snwa.com). SNWA has a conservation goal of lowering the overall per capita water demand to 199 gpcpd, or 0.223 ac-ft/y per year, by the year 2035 (www.snwa.com). The model assumed a constant per capita demand of 205 gpcpd until 2035, and then used a constant value of 199 gpcpd through the rest of the study period. The per capita demand was coupled with the population projection to estimate the water demand for the Las Vegas Valley every year for 50 years (from 2016 through 2066). Limits were included in the model to not exceed SNWA's allocation of the Colorado River, which is 300,000 ac-ft/y. In addition to the Colorado River allocation, the model accounts for SNWA's groundwater rights, which are 40,629 ac-ft/y (SNWA, 2015).

The overall water use for the Las Vegas Valley was separated between outdoor and indoor use. Outdoor use accounts for approximately 56% of the total water demand and is considered lost (i.e., consumed), meaning water used outdoors can only be used once and then is evaporated into the atmosphere. Indoor use is approximately 44% of the total water demand, and most water used indoors eventually makes its way to the WWTPs (www.snwa.com). All water conveyed through the WWTPs is considered a water resource and is reused. Approximately 22,000 ac-ft/y is reused for non-potable purposes such as irrigation for parks or golf courses (SNWA, 2015). Non-potable reuse was assumed constant throughout the study period. All other wastewater effluent is discharged to the Las Vegas Wash and considered RFCs to Lake Mead.

The baseline model also tracks the energy, cost, and GHG emissions associated with pumping the RFCs from Lake Mead up over to the RMWTF. The RFCs are converted from ac-ft/y to gallons per minute (gpm) in order to calculate the electrical horsepower (EHP) using the following equation:

$$EHP = \frac{FH}{3957E_pE_m}$$

Where:

- F = flow (gpm)
- H = elevation (ft)
- 3957 = conversion factor for EHP (33,000 ft-lb per minute divided by 8.34 lbs per gallon of water)
- E_p = pump efficiency (assumed 0.8.)
- E_m = motor efficiency (assumed 0.9)

EHP is converted to kilowatt hours (kWh) per year and multiplied by a cost per kWh based on current local rates for NV Energy. Energy use for the State of Nevada was taken from the United States Energy Information Administration (USEIA). Nearly 88% of the energy consumed in Nevada comes from outside the state and mostly comes from natural gas. Nevada is also the state with the highest geothermal energy generation with a net generation of 10%. Other renewable energy sources Nevada include solar with a net generation of approximately 6.2%. Nevada's energy portfolio standard requires that by 2025 25% of energy sales come from renewable energy sources. In 2016, Nevada's utility-scale net electricity generation was 21.6% renewable energy sources (www.eia.gov). The USEIA summarized energy use for the state from all available energy sources, as well as the GHG emissions since the year 1980 (www.eia.gov). This information was used to calculate a ratio of 3.4 lbs CO_2 per kWh, and this ratio was used in the model to determine the GHG emissions for energy use.

In addition to flow, the model tracks TDS throughout the Las Vegas Valley water system. TDS load in million pounds per year (M lbs/y) is accounted for as water is withdrawn from Lake Mead and used indoors. TDS loads into the system from Lake Mead, human wastes, water softeners, and runoff and seepage into the Las Vegas Wash were considered as stated in Chapter 2 from Venkatesan et al. (2011). TDS concentration values were known entering the WTFs, entering the WWTPs, and in the Las Vegas Wash. TDS concentration was calculated using load and flow and compared to the known values.

Model Alternatives

Three baseline scenarios were modeled: status quo, DPR alternative 1 (DPR 1), and DPR alternative 2 (DPR 2). The status quo scenario modeled the current conditions of the Las Vegas Valley, specifically showing that RFCs are making their way to Lake Mead. Population projection and per capita water demand values (as previously stated in this chapter) were used to estimate overall water demand for the Las Vegas Valley from 2016 to 2066. DPR 1 uses the same baseline conditions as status quo for population projection and water demand. However, instead of RFCs flowing to Lake Mead, flow in the Las Vegas Wash is diverted to an advanced water treatment facility (AWTF) and then sent directly to the RMWTF. DPR 1 modeled 25%, 50%, 75%, 90%, and 100% of the RFCs bypassing the lake and being sent to the AWTF and then to RMWTF. DPR 1 represents a treatment train of MF, RO, UV/AOP, and the water is blended with raw surface water from Lake Mead prior to entering the RMWTF. DPR 2 was modeled similarly to DPR 1, but the treatment train included UF, O_3, BAF, and UV/AOP prior to blending with Lake Mead water prior to entering the RMWTF.

This study also considered the GDP from northern Nevada, but this scenario was not modeled because the pertinent information was already provided in a 2012 report from SNWA. Information from this report will be summarized in the following chapter.

General Variables for Evaluation

Several variables were used to evaluate and compare each model scenario. The general variables that affect the specific outcomes for the model are population projection, per capita water demand, and RFCs. Population projection and per capita water demand directly impact the overall water demand for the Las Vegas Valley. However, RFCs are the single most important variable in the model. RFCs were used to directly compare each scenario. Capital costs for each DPR scenario were based on percentages of the RFCs. Additionally, all of the specific variables used for evaluation were based as on the amount of RFCs and how they were used.

Specific Variables for Evaluation

The specific variables used to evaluate the model scenarios are all related to the RFCs. Energy use and cost compared pumping RFCs from Lake Mead to the RMWTF to the DPR scenarios of pumping from the Las Vegas Wash at a point down stream of all the WWTPs to RMWTF (see Figure 10). All costs associated with pumping are only related to water that is considered RFCs. pumping of the original allocation water from the lake are not included to focus on the costs associated with RFCs only.

Figure 10: Proposed Bypass Location for DPR Scenarios

Additionally, energy use and cost were determined and compared for the additional treatment needed for DPR 1 and DPR 2. Energy use was based on typical values for each unit process per amount of flow per values found in the literature, and energy cost was $0.11 per kWh based on current NV Energy rates. Typical values and assumptions for energy use for the DPR treatment scenarios are shown in Table 5.

Table 5: Typical Energy Values for Treatment Processes

Technology	**Typical Values (kWh/AF)**	**Value used (kWh/AF)**	**Applicable DPR Scenario**		**Source**
			DPR 1	**DPR 2**	
MF/UF	240 to 360	300	✓	✓	Raucher & Tchobanoglous (2014)
RO	550 to 700	625	✓		Raucher & Tchobanoglous (2014)
UV/Peroxide	98 to 326	196	✓	✓	Chang et al. (2008)
O_3	128	128		✓	Gerrity et al. (2014)
BAF	31	31		✓	Gerrity et al. (2014)

Furthermore, TDS load was tracked from the initial withdrawal of water from Lake Mead to its discharge back into Lake Mead via the Las Vegas Wash. The water withdrawn from Lake Mead for use is taken from a deeper elevation and is less affected by evaporation and, therefore, has a lower TDS concentration (LaBounty & Burns 2005). The TDS concentration at the water treatment facilities is known to be approximately 656 mg/L, which was used as a starting point to calculate load in the model.

Major Assumptions and Limitations

There were several assumptions made in the system dynamics model. First, the model was not meant to be an accurate hydrological model of Lake Mead. This affects the model in several ways. For example, the model assumed Southern Nevada's full allocation of 300,000 acre-ft/y was always available throughout the study period and that the lake elevation was constant at 1075 ft. Elevation change depends highly on the operational inflows from the upstream reservoir and releases at Hoover Dam. Lake volume and elevation cannot be modeled after an observed pattern. Instead, they are manually adjusted by the United States Bureau of Reclamation (USBR) based on the conditions of the entire Colorado River. Additionally, evaporation in the Las Vegas Wash was not considered. This type of model would take extensive data gathering coordination with the USBR to understand the conditions and scenarios needed to form an accurate model. Additionally, constant values for dry weather runoff and groundwater seepage were assumed for the duration of the study period. Further, because of these major assumptions for how the system interacts with Lake Mead, TDS concentration cannot accurately be projected. For example, the overall TDS concentration for

Boulder Basin was 1,021 mg/L in 2004, but the TDS entering the WTF was only 635 mg/L due to the elevation where the water was withdrawn (Roefer et al., 2005). One reason for this is lower water elevations are less susceptible to effects of evaporation (Roefer et al., 2005). Therefore, the TDS portion of the model was not a closed loop, meaning that the model flow begins at the WTF and ends at the Las Vegas Wash and does not include Lake Mead. The increases in TDS were approximated based on published values for TDS concentration from the literature and existing water quality reports. For example, from the year 2000 to 2004 the TDS concentrations entering the WTFs increased 11% (Roefer et al., 2005). Based on 2016 water quality reports the increase from 2004 to 2016 TDS was 3%. Overall, from 2000 to 2016 TDS increased approximately 12 percent, with an average increase of 0.75% per year. This 0.75% increase per year in TDS concentration was assumed for the 50-year study.

For other assumptions, TP loads entering Lake Mead via the Las Vegas Wash were calculated based on the total waste load allocations (WLA) permitted to all four WWTPS by the Nevada Department of Environmental Protection (Bureau of Water Quality Planning, 2003). The WWTPS are limited to a discharge a combined concentration of TP to the Las Vegas Wash of 0.21 mg/L for the months of March through October. To approximate eutrophication potential, the limiting concentration for TP was used to calculate the TP load for the entire year based on flow. It was assumed that as more flow is diverted from the Las Vega Wash for DPR alternatives less TP load is entering the lake, and therefore, reducing the lake’s eutrophication potential.

Further, the model evaluates all wastewater flow as a whole and does not separate it into the four different WWTPs in the Las Vegas Valley. A location was arbitrarily selected in the Las Vegas Wash for the diversion point where flow was diverted for the DPR scenarios.

Capital costs for the DPR scenarios were developed based on flow and treatment technology. Conceptual level cost curves were used from Snyder et al. (2014) and are summarized in Table 6 below.

Table 6: Capital Cost Curve Equations from Snyder et al. (2014)

Process	**Capital Cost**[a] **($M/MGD)**
Ozone	1.51 × (Plant Capacity, in MGD)$^{-0.47}$
UV/H_2O_2	0.25 × (Plant Capacity, in MGD)$^{-0.056}$
MF or UF	1.89 × (Plant Capacity, in MGD)$^{-0.22}$
NF or RO	7.14 × (Plant Capacity, in MGD)$^{-0.22}$
BAC	1.05 × (Plant Capacity, in MGD)$^{-0.15}$

Additional capital costs for the pipeline needed to divert flow from the Las Vegas Wash to the proposed AWTF and then on to the RMWTF were developed using Carollo Engineers, Inc. Cost Estimating System (CCES). The CCES uses Carollo's large database for cost of material, equipment, and labor. The database is frequently updated based on market conditions.

CHAPTER 4: MODEL RESULTS

Model Calibration and Validation

The model was calibrated in several different steps as the model progressed in development. First, certain key inputs were tested to confirm the model was operating as intended. For example, population, water demand, and water supply from Lake Mead were set at zero simultaneously to confirm the various model stocks and flows were interconnected properly. Sterman 2010 refers to this as the behavior anomaly test. The model responded appropriately with no water supply flowing through the different stages. Next, the model was validated by comparing with existing data projections for the Las Vegas Valley. SNWA projected the available water versus demand through 2065 in the 2015 Water Resources Plan as shown in Figure 11 below (SNWA, 2015).

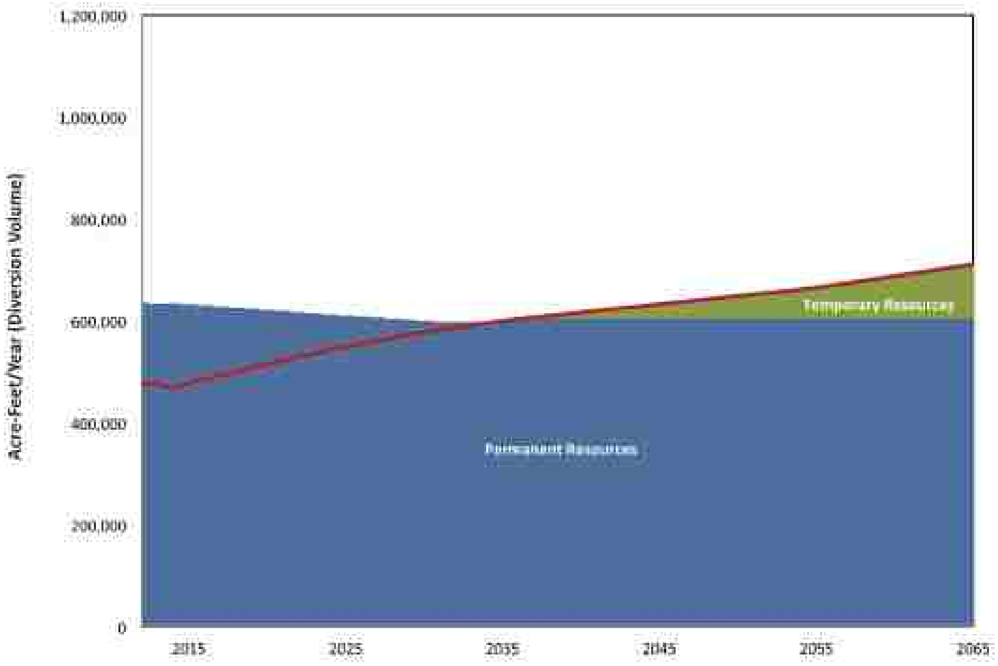

Figure 11: SNWA's Supply & Demand Projection Under Normal Conditions (SNWA 2015)

The red line in Figure 11 represents the projected water demand, and it shows supply outlasting demand until approximately the year 2035. Permanent resources represent water from the Colorado River and local groundwater rights within the valley. The temporary resources represent water banking that has taken place based on agreements with Arizona and California.

A similar graph was created to compare the supply verse demand output from the model and is shown in Figure 12 below.

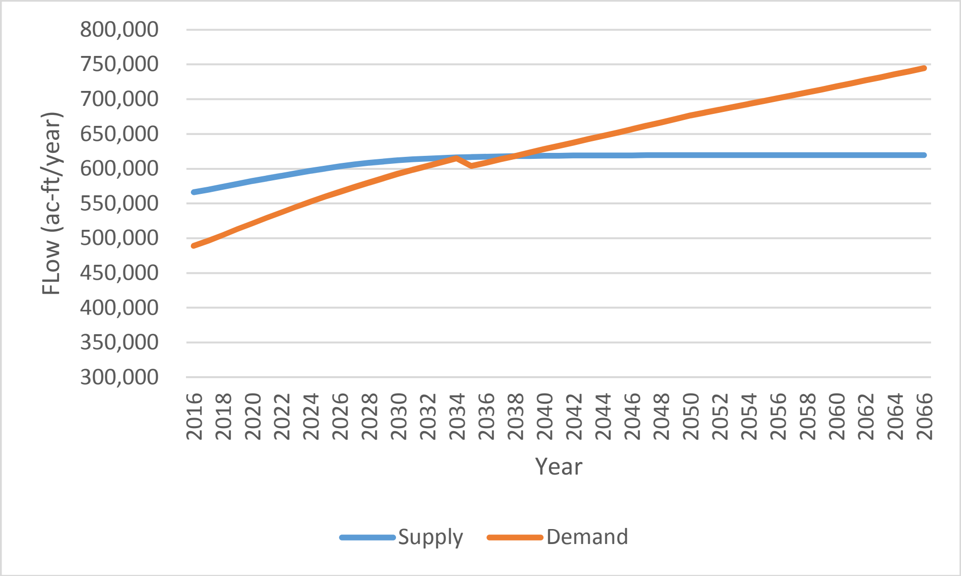

Figure 12: Model Results for Supply vs Demand

Compared to Figure 11, the model yielded similar results with supply meeting demands until the year 2037 at an available flow of 617,884 ac-ft/y. The decrease in per capita demand from 205 gpcpd to 199 gpcpd in 2035 extended the time that supply outlasted demand approximately 3 years. The model was able to yield results of supply lasting within 3 year of the published report by SNWA, and the water flow portion of the model was deemed acceptable.

TDS concentrations entering the RMWTF, entering the WWTPs, and in the Las Vegas Wash have been reported at 656 mg/L, 1,100 mg/L, and 1,650 mg/L, respectively (SNWA, 2016). The initial concentration entering RMWTF was used to start the load simulation of the model, with a constant increase in concentration of 0.75% per year. TDS loads were added for water softener users and human waste for indoor use based on population, as well as for runoff into the Las Vegas Wash as mentioned in Chapter 3. Concentrations were checked at the RMWTF, WWTPs, and the Las Vegas Wash to determine the variance and are shown in Figure 13.

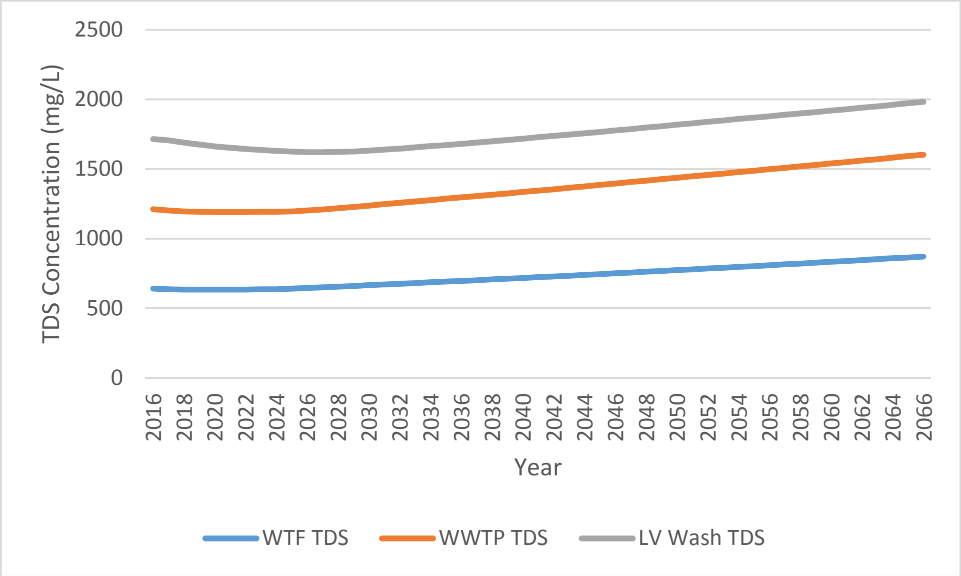

Figure 13: Model Results for TDS Concentration Entering the WTFs, WWTPs, and the LV Wash

The initial results in Figure 13 fall within 2%, 10%, and 7% of the reported values for WTF, WWTP, and LV Wash concentration, respectively. Because the variance is within 10% or less of the reported values, the TDS portion of the model was deemed acceptable.

It should be noted that he rise in TDS concentration at RMWTF approaches 9000 mg/L. This equates to approximately $1.5x10^9$ lbs of TDS entering the Las Vegas Valley per year. If the status quo alternative continues for the foreseeable future, TDS will inevitably become more of a concern.

Results

Status Quo Alternative

The status quo alternative projects the current operation for the next 50 years. That is, all treated wastewater is sent back to Lake Mead via the Las Vegas Wash as RFCs. The model results for the amount of RFCs, the cost to pump the RFCs from Lake Mead to the RMWTF, and the GHG emissions associated with pumping the RFCs from Lake Mead for the study period are shown in Figures 14, 15, and 186 respectively.

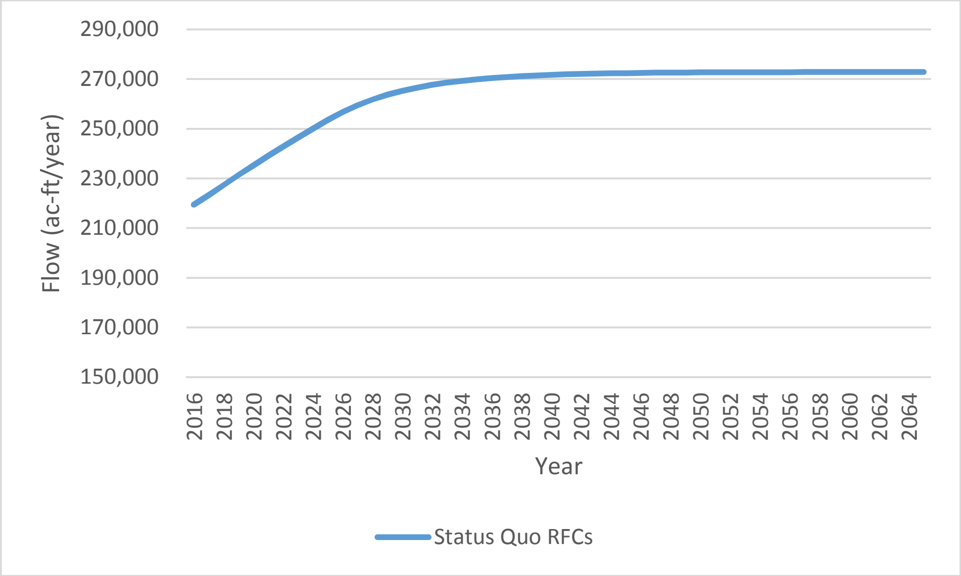

Figure 14: Annual RFCs for Status Quo Alternative

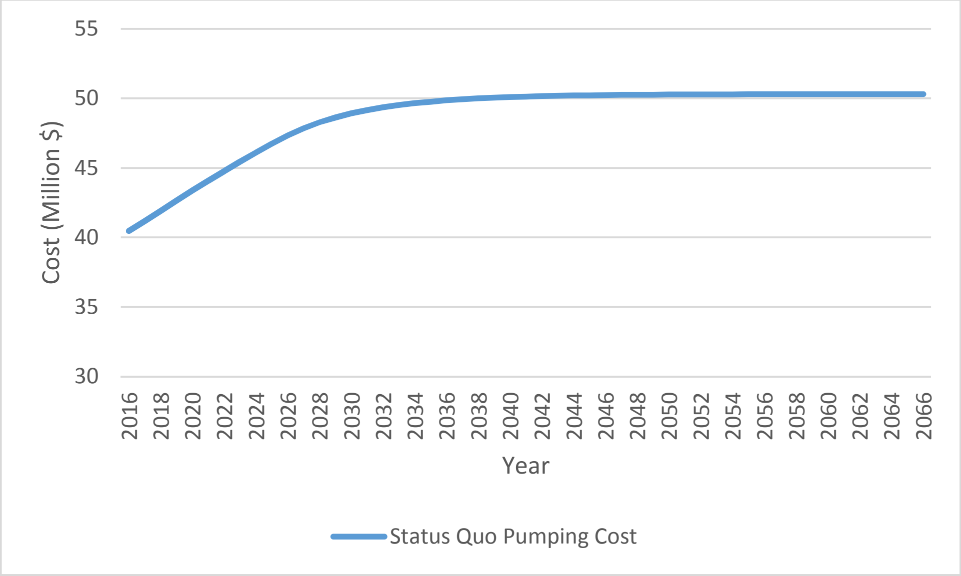

Figure 15: Annual RFCs Pumping Costs from Lake Mead

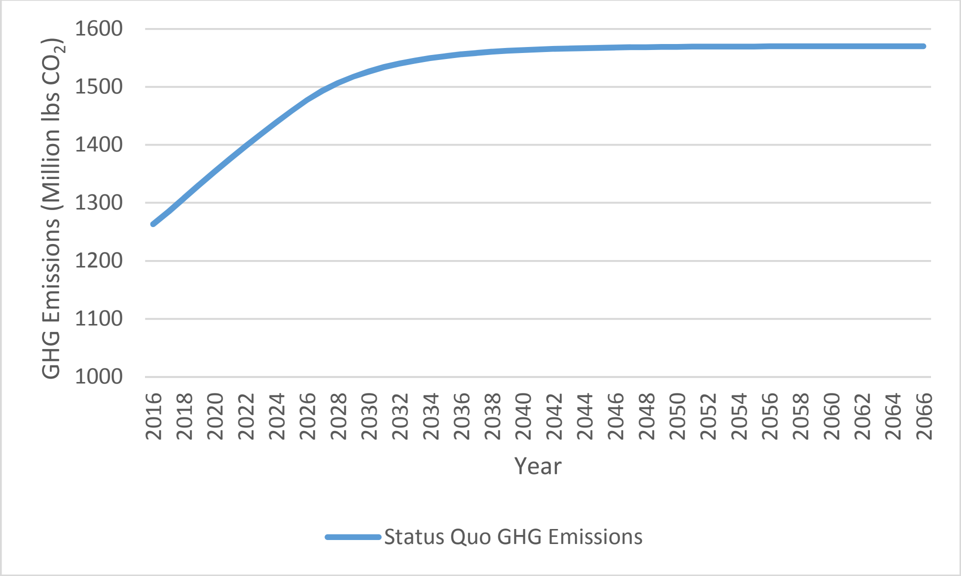

Figure 16: Annual GHG Emissions from Pumping RFCs from Lake Mead

The maximum value over the study period for RFCs, pumping costs for RFCs from the lake, and GHG emission for pumping RFCs from the lake were 272,840 ac-ft/y, $50.3M/y, and 1.6x$10^9$ lbs CO_2/y, respectfully. 272,840 ac-ft/y is the maximum amount of RFCs that occur based on the full allocation always being available, 44% of overall use continually being used indoors, and a fixed amount of non-potable water reuse every year (22,000 ac-ft/y) over the study period.

Figure 17 shows the TP entering Lake Mead assuming the permitted concentration of 0.21 mg/L is met year round over the study period.

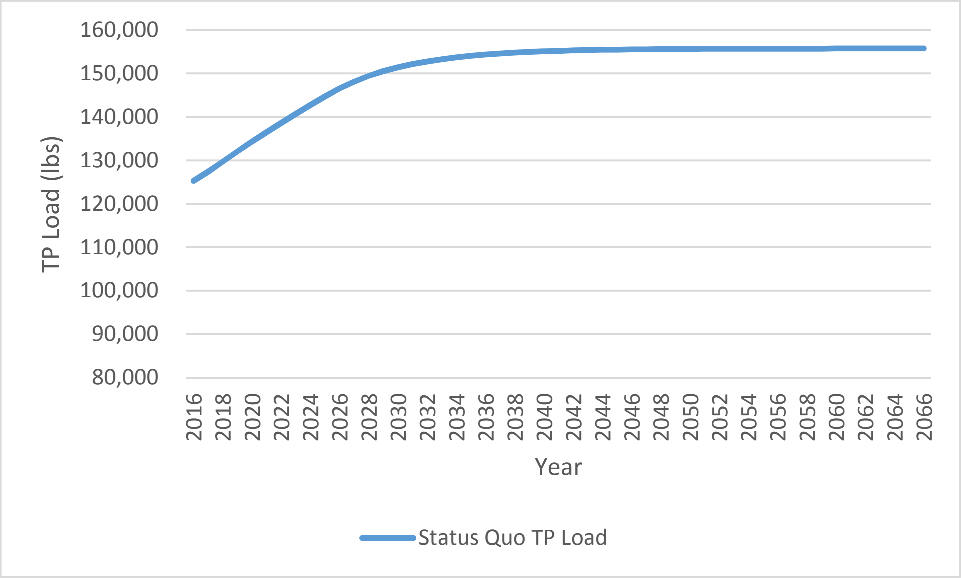

Figure 17: TP Load Entering the Lake

The maximum TP load over the study period was 155,702 lbs. The TP entering the lake is limited by the amount of RFCs flowing to the lake and assuming the total TP concentration is fixed at 0.21 mg/L over the study period.

Sensitivity Analysis

Sensitivity analyses were done for key inputs of the model to test their impact on the results. Key parameters effecting pumping energy (other than flow) are pump and motor efficiencies and lake elevation. Pump efficiencies were tested from 70% through 95% in 5% increments, while keeping motor efficiency constant at 90%. The results for pump efficiency impact on pumping energy are shown in Figure 18.

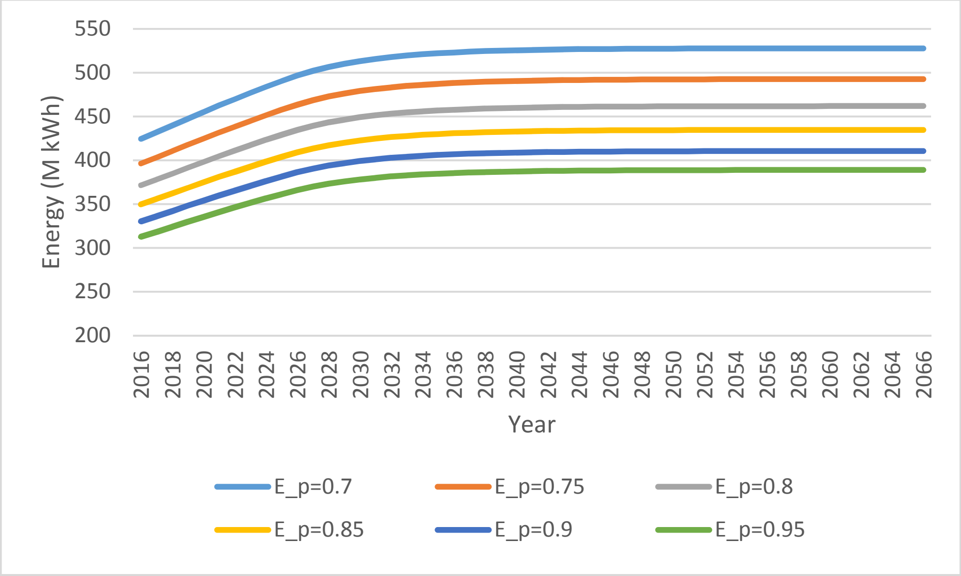

Figure 18: Sensitivity Analysis for Pump Efficiency

The sensitivity analysis for pump efficiency resulted in an energy variance of approximately 135 M kWh/year. Similarly, the sensitivity of motor efficiency was tested using the same range of efficiencies, and assuming a constant pump efficiency of 80%. The results for motor efficiency impact on pumping energy are shown in Figure 19.

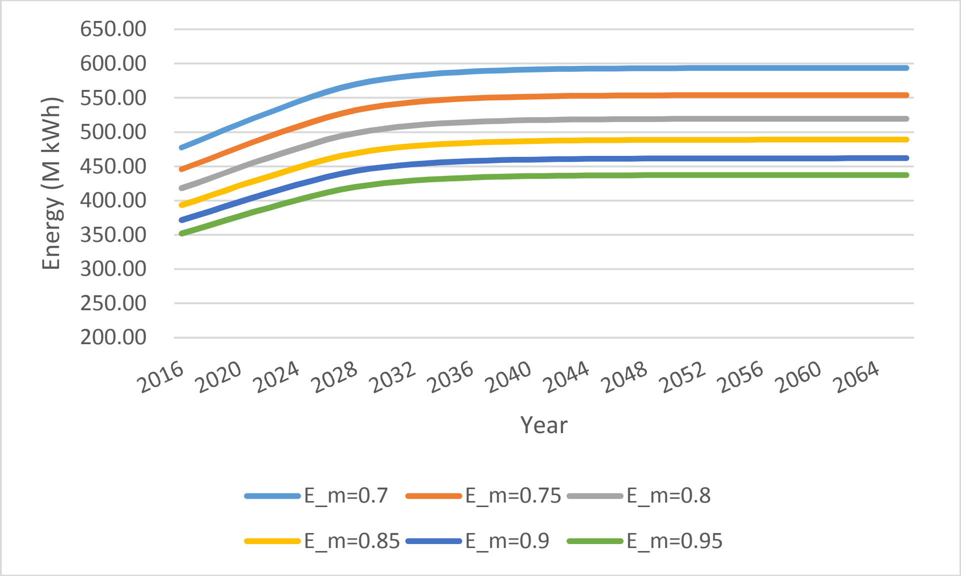

Figure 19: Sensitivity Analysis for Motor Efficiency

The sensitivity analysis for motor efficiency resulted in an energy variance of approximately 113 M kWh/year. Further, lake level sensitivity was tested for pumping energy impact with elevations ranging from 1035 feet through 1115 feet in 20 foot increments, and is shown in Figure 20.

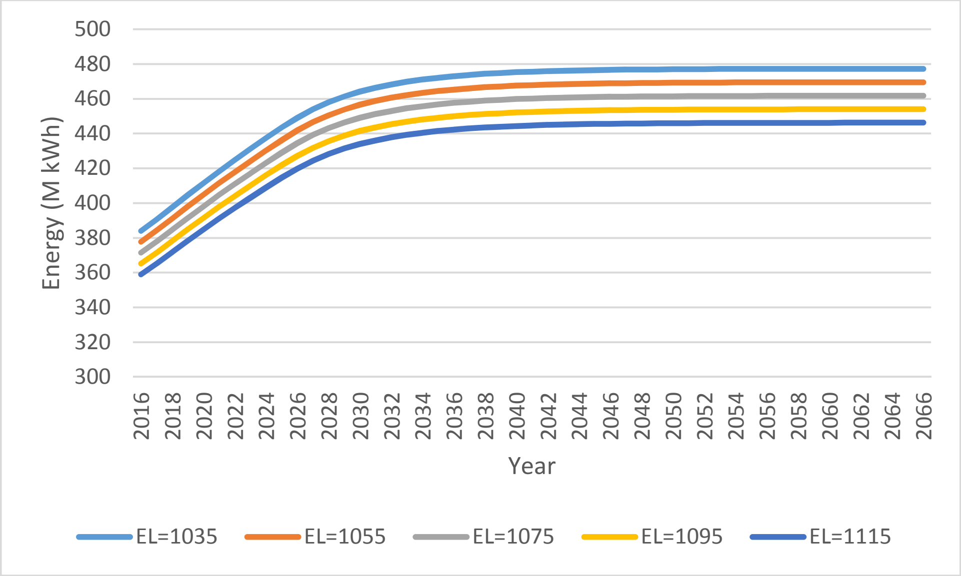

Figure 20: Sensitivity Analysis for Lake Elevation

Although lake elevation has a lesser impact on pumping energy and pump and motor efficiencies, the impact is still worth mentioning with an energy variance of approximately 30 M kWh/year. The impacts on energy from pumping and motor efficiencies, as well as lake elevation will directly impact the pumping cost and the GHG emissions from pumping. It should be noted that as technology improves over time and pumping equipment becomes more efficient operational benefits will be seen in energy, cost, and environmental impacts (from a decrease in GHG emissions). Additionally, as Lake Mead elevation declines, operational costs and emissions will continue to increase over time. The sensitivity analysis for efficiencies and lake elevation are applicable to status quo and both DPR alternatives.

DPR 1 Alternative

DPR 1 simulated 25%, 50%, 75%, 90%, and 100% of the RFCs bypassing Lake Mead and being sent to an AWTF prior to being sent directly to the RMWTF. The DPR 1 represents a treatment train of MF, RO, and UV/AOP. To achieve acceptable TDS levels, it was assumed that 100% of the flow was sent through RO. The supply demand projections for the different flow scenarios are shown in Figure 21.

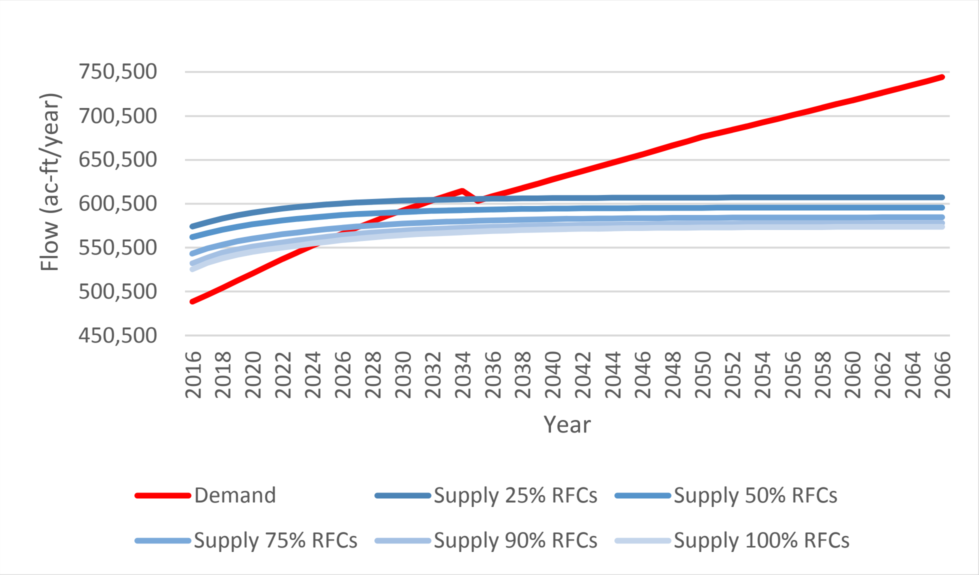

Figure 21: Supply vs Demand for Alternative DPR 1 Flow Scenarios

The supply decreases for each flow scenario compared to the status quo alternative due to the 10% water loss from the RO treatment. Therefore, the greater the flow scenario sent through the RO process the greater amount of water loss will occur. The supply outlasts demand until 2032, 2029, 2027, 2025, and 2024, for flow scenarios 25%, 50%, 75%, 90%, and 100%, respectively.

A sensitivity analysis was done to see the impact of RO water loss on the supply-demand projections. For the flow scenario of 100% of RFCs being bypassed for DPR, water loss percentages from RO were tested from 10% down to 0% in 2% increments and are shown in Figure 22.

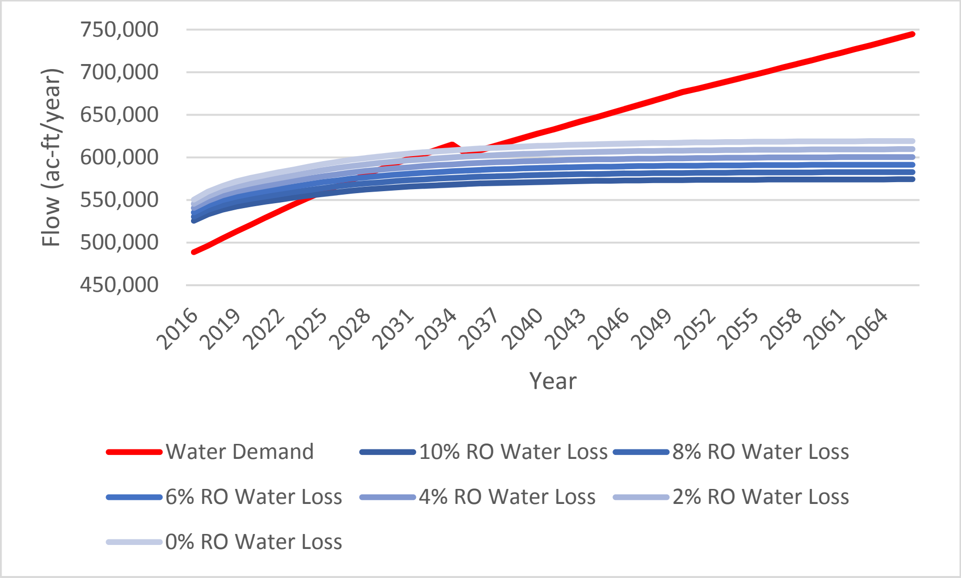

Figure 22: Sensitivity Analysis for RO Water Loss

The change in the amount of supply base on the range of water losses tested was approximately 40,000 acre-ft/year. As the loss decreases the supply-demand projections get closer to the status quo projections. As RO technology improves to operate with lower loss percentages while remaining economical, concerns regarding reduced supply will continually decrease.

The operational costs were calculated for following operational elements:

- treatment costs for DPR 1
- pumping from the Las Vegas Wash to the proposed AWTF
- pumping from the AWTF to the RMWTF
- pumping the remaining RFCs from Lake Mead

The operational costs were calculated for 25%, 50%, 75%, 90%, and 100% of the RFCs and are in Figures 23 through 27 respectively.

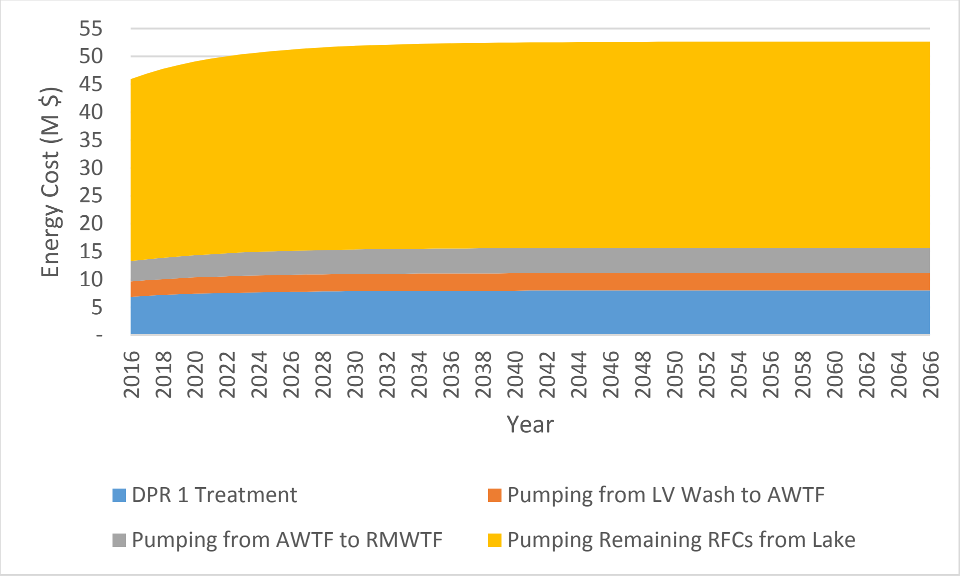

Figure 23: Energy Costs for DPR 1 - 25% RFCs

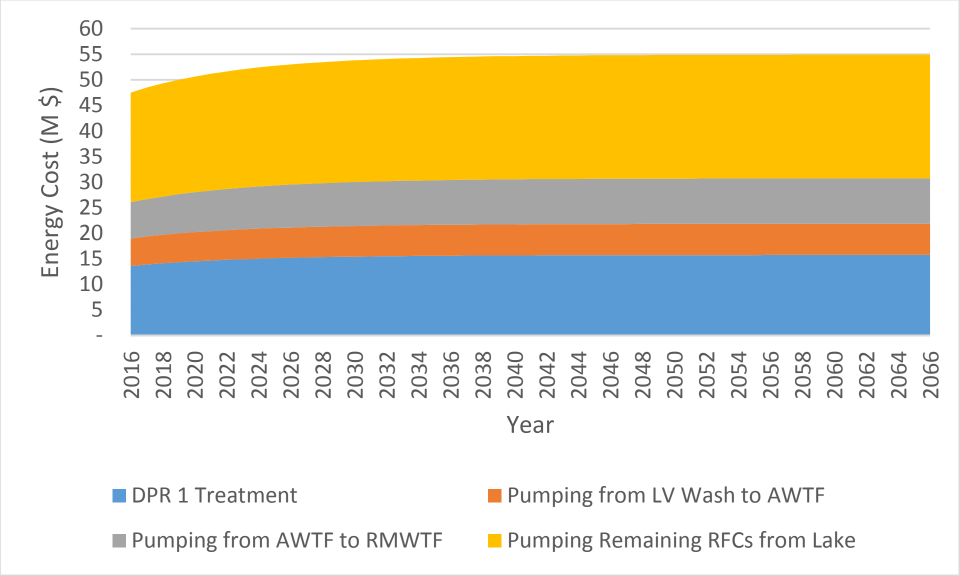

Figure 24: Energy Costs for DPR 1 - 50% RFCs

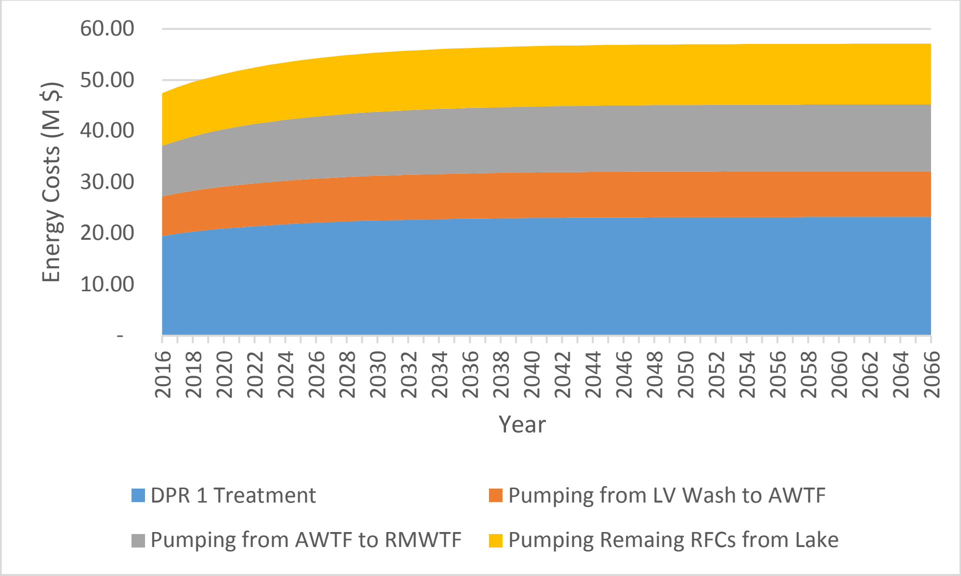

Figure 25: Energy Costs for DPR 1 - 75% RFCs

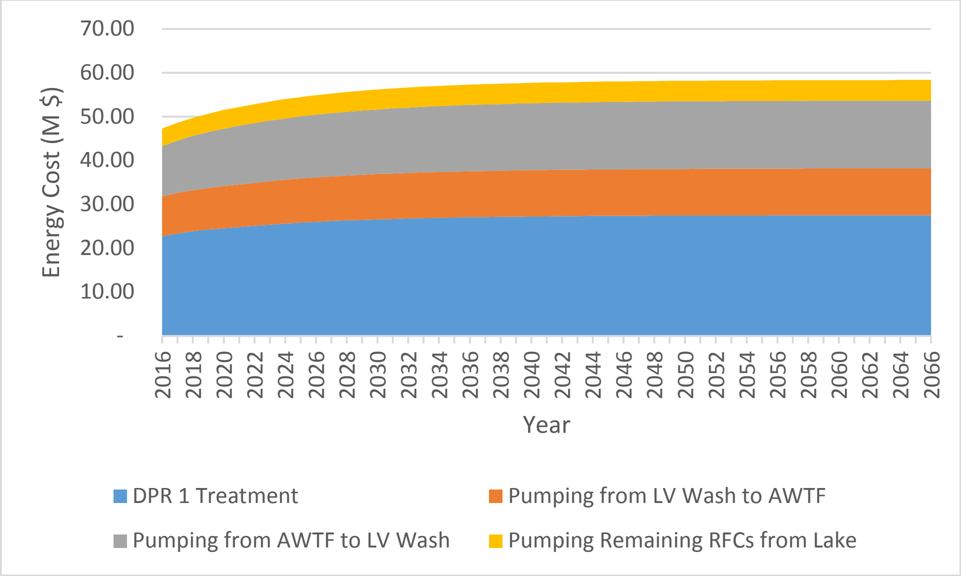

Figure 26: Energy Costs for DPR 1 - 90% RFCs

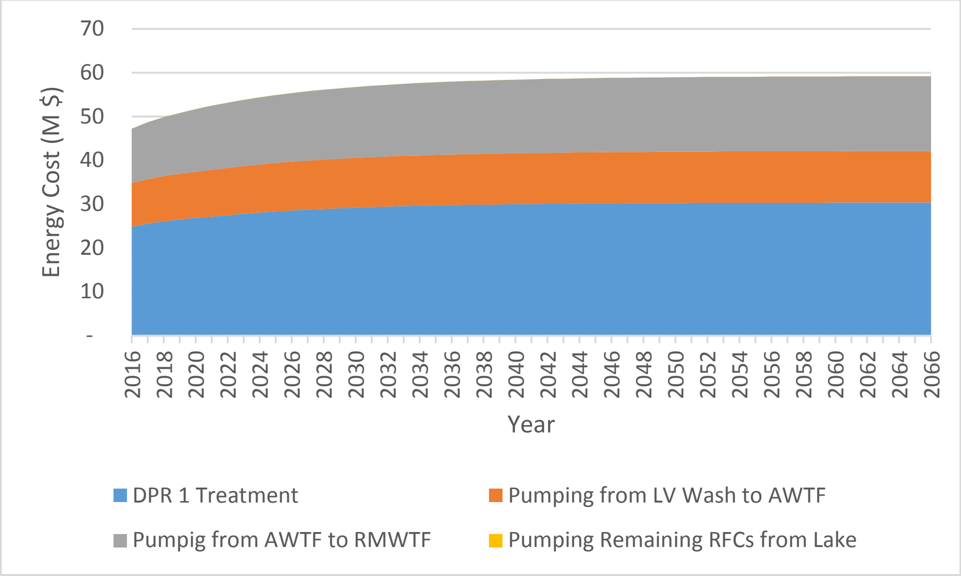

Figure 27: Energy Costs for DPR 1 - 100% RFCs

Although the elevation that needs to be pumped is reduced from bypassing the lake, pumping costs contribute a significant portion of the energy costs. Pumping from the Las Vegas Wash to the AWTF and then to the RMWTF account for 14%, 27%, 39%, 45%, and 49% of the overall energy costs for bypassing 25%, 50%, 75%, 90%, and 100% of RFCs, respectively.

Similarly, GHG emissions are shown for the operational elements for all flow scenarios in Figures 28 through 33.

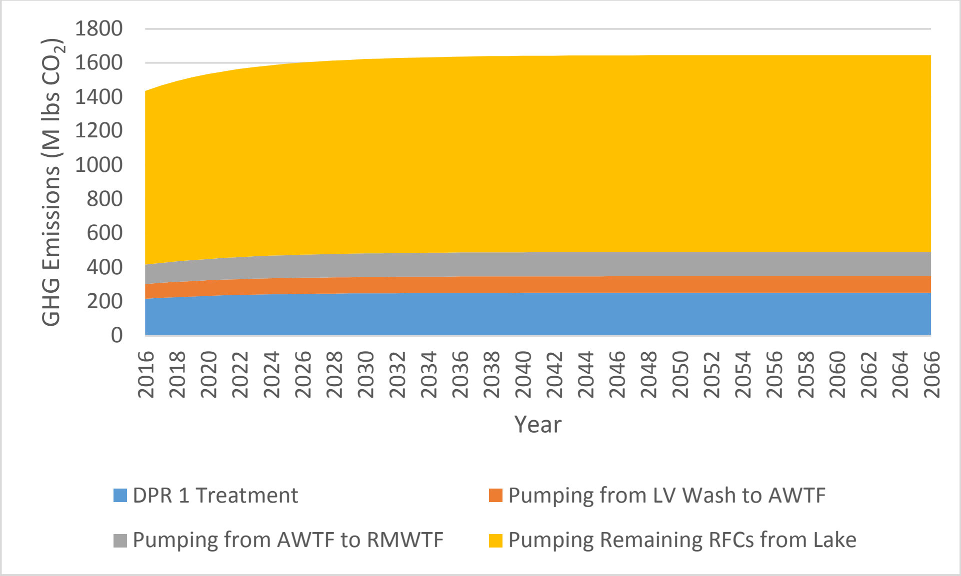

Figure 28: GHG Emissions for DPR 1 - 25% RFCs

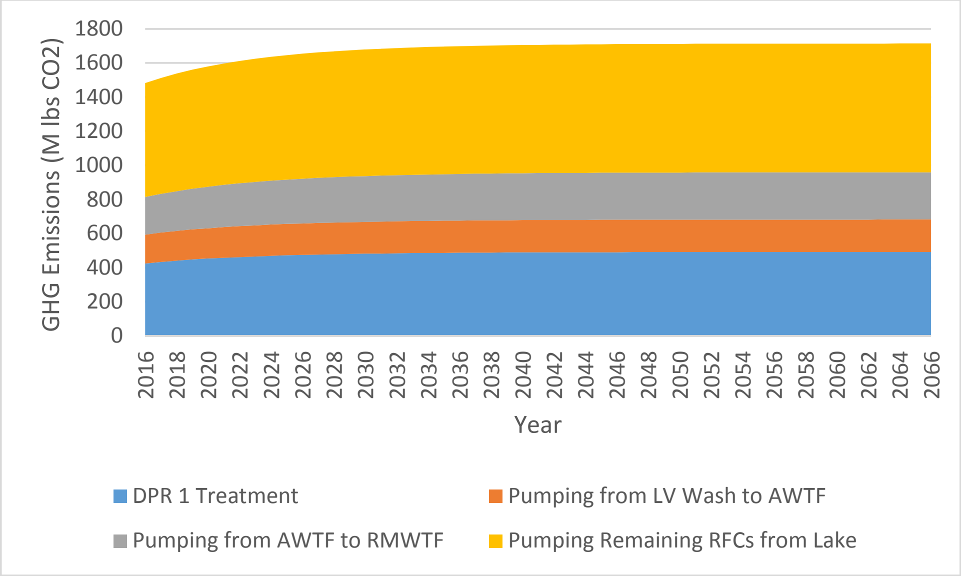

Figure 29: GHG Emissions for DPR 1 - 50% RFCs

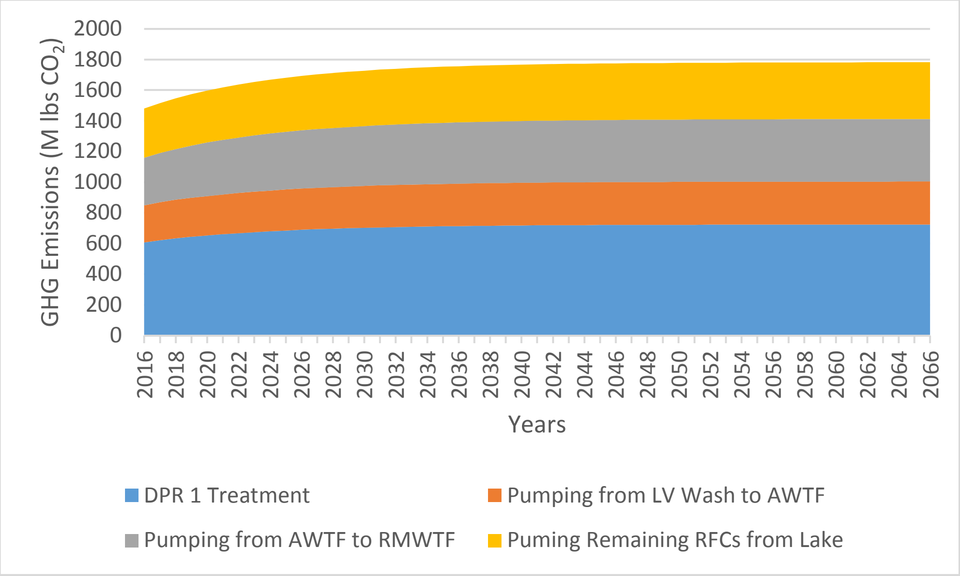

Figure 30: GHG Emissions for DPR 1 - 75% RFCs

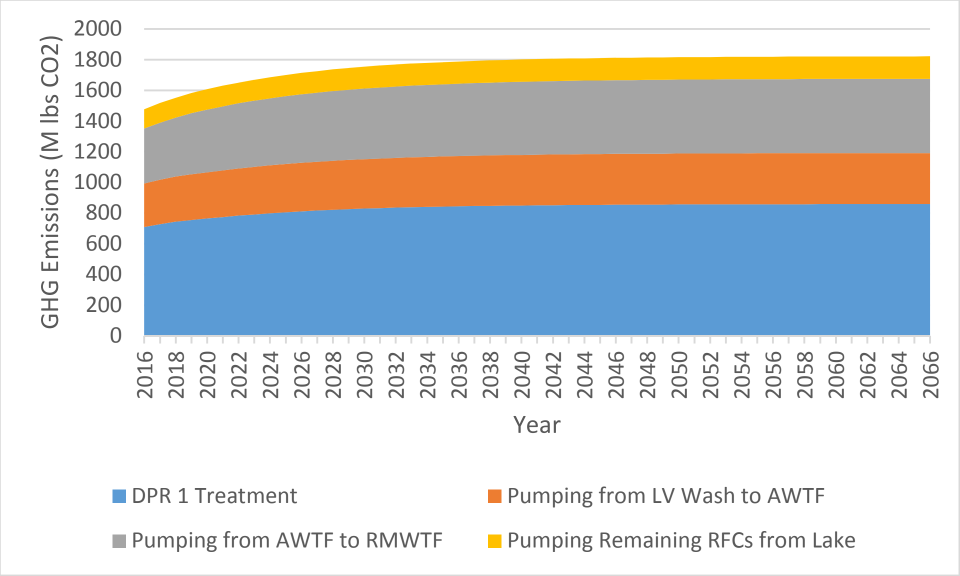

Figure 31: GHG Emissions for DPR 1 - 90% RFCs

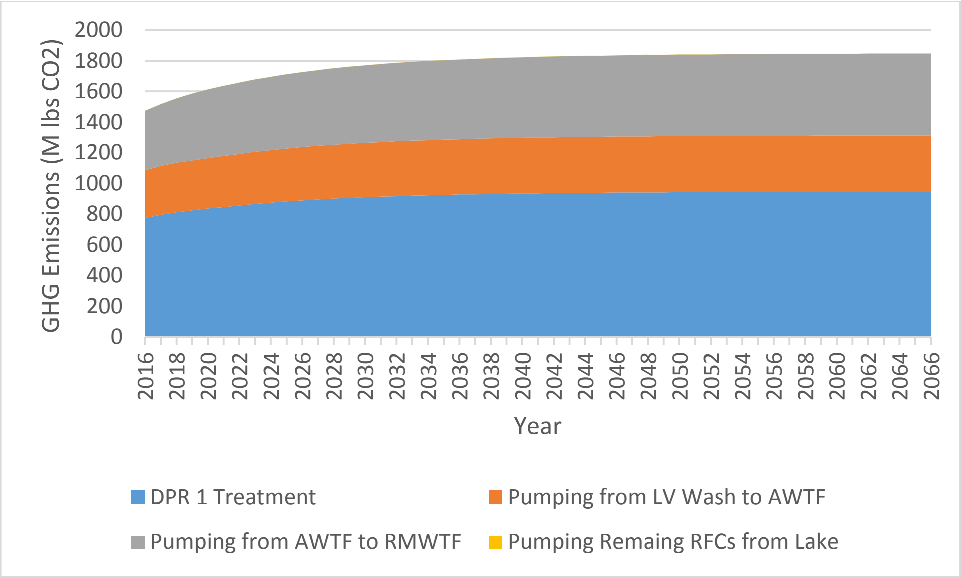

Figure 32: GHG Emissions for DPR 1 - 100% RFCs

Similar to energy costs, GHG emissions from pumping from the Las Vegas Wash to the AWTF, and then to the RMWTF account for 15%, 27%, 39%, 45%, and 49% of the total GHG emissions for the flow scenarios 25%, 50%, 75%, 90%, and 100% RFCs.

The amount of TDS removed for each flow scenario and the corresponding concentration entering the RMWTF are shown Figures 33 and 34, respectively.

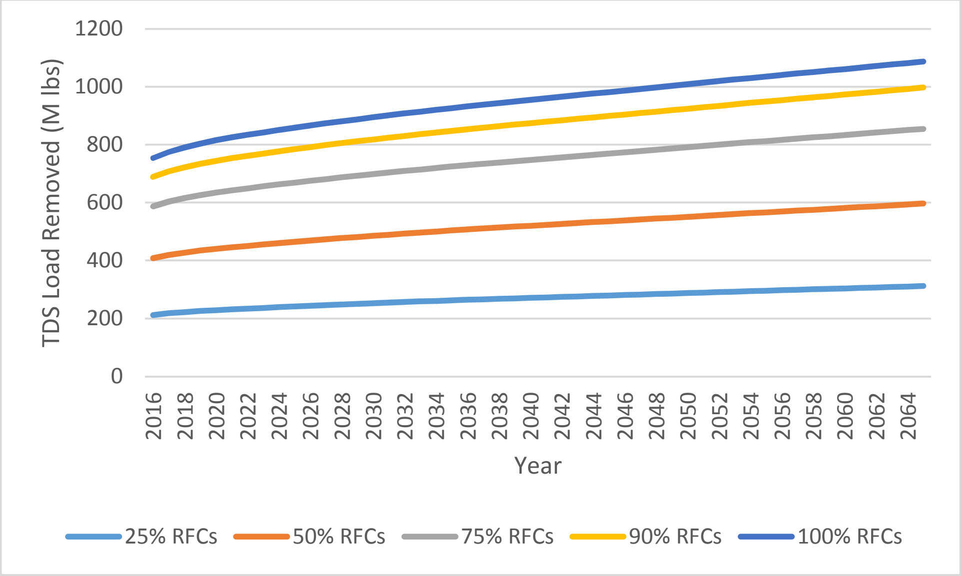

Figure 33: TDS Load Removed for DPR 1

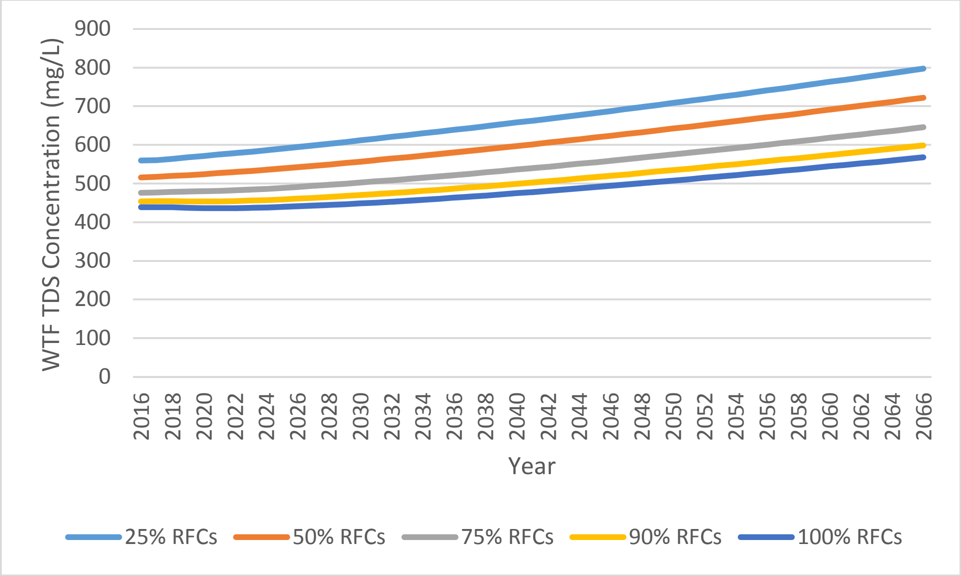

Figure 34: RMWTF TDS Concentration for DPR 1

As expected the more RFCs bypassing the lake and sent through the DPR 1 AWTF (which included RO), the more TDS is removed and the lower the concentration is entering the RMWTF.

The amounts of TP entering the lake are shown in Figure 35 and are common for both DPR 1 and DPR 2 alternatives.

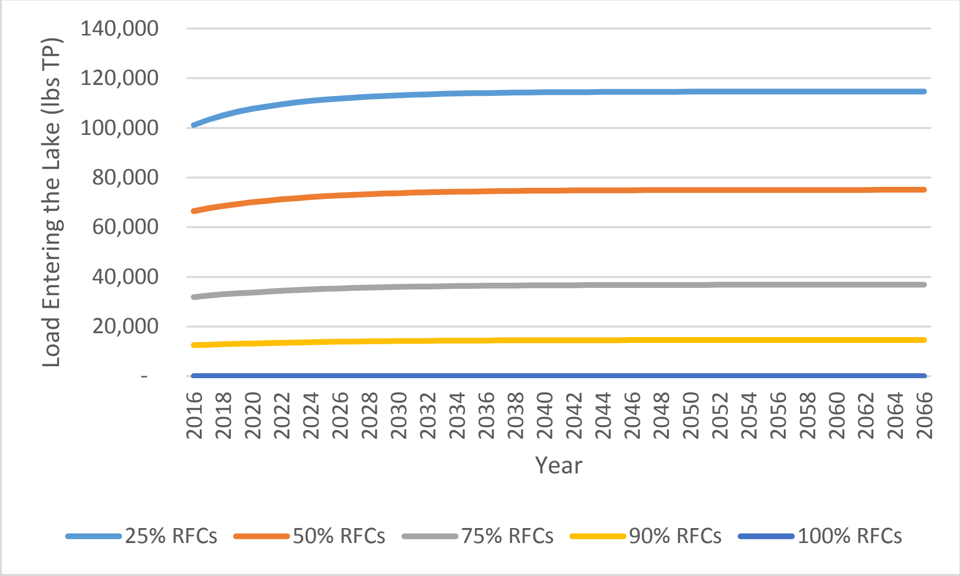

Figure 35: TP Load Entering the Lake for DPR Alternatives

DPR 2 Alternative

Similar to the DPR 1, DPR 2 simulates the flow scenarios as RFCs bypassing Lake Mead and sent to a new AWTF prior to being sent directly to the RMWTF. The DPR 2 alternative represents a treatment train of UF, O_3, BAF, and UV/AOP. The supply demand projections for the different flow scenarios are shown in Figure 36.

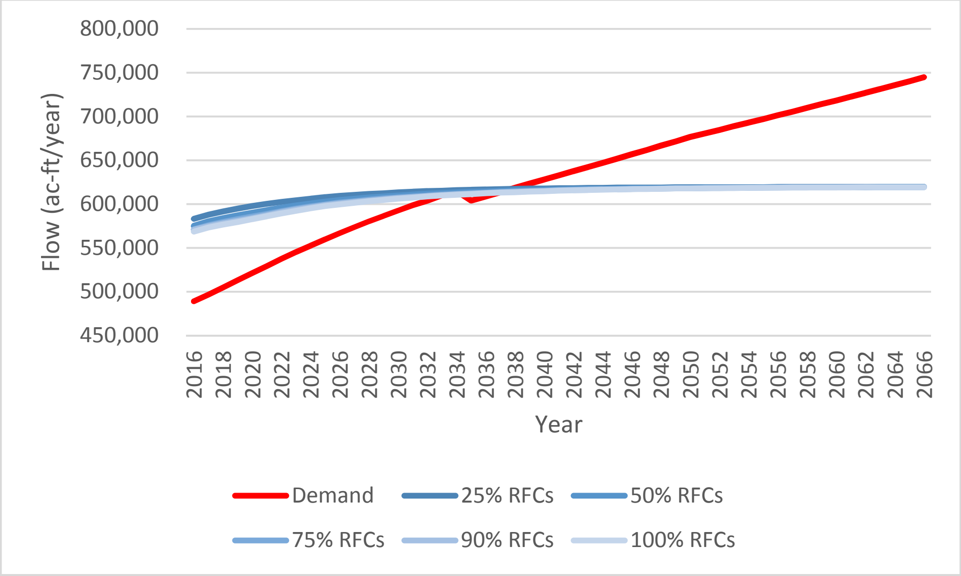

Figure 36: Supply vs Demand for DPR 2

The results show a slight decrease in supply as more RFCs bypass the lake. The decrease was due to the structure of the model and how flow is bypassed from the lake. The minor supply decrease resulted in a 1 year decrease of supply outlasting demand. It was assumed that the 1 year decrease in supply could be neglected, and all flow scenarios match the status quo alternative of meeting demands until the year 2037.

The energy costs were determined similar to DPR 1 for the same flow scenarios of RFCs bypassing the lake. The energy cost results are shown in Figures 37 through 42 for the various flow scenarios.

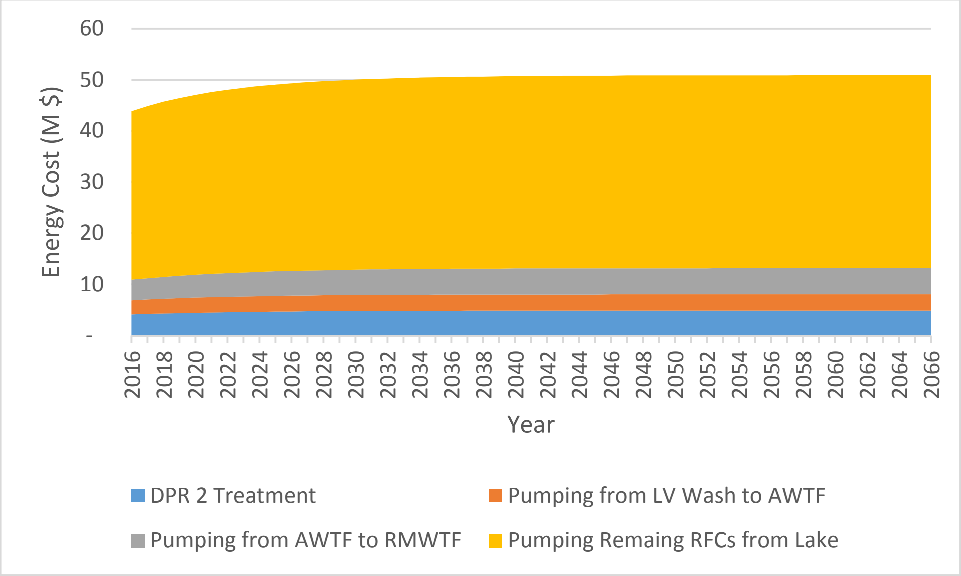

Figure 37: Energy Costs for DPR 2 - 25% RFCs

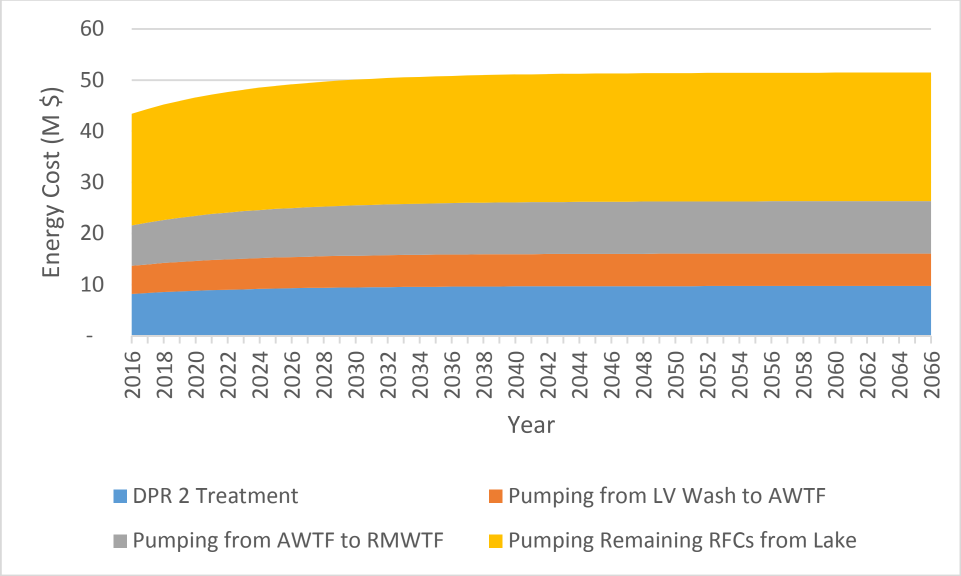

Figure 38: Energy Costs for DPR 2 - 50% RFCs

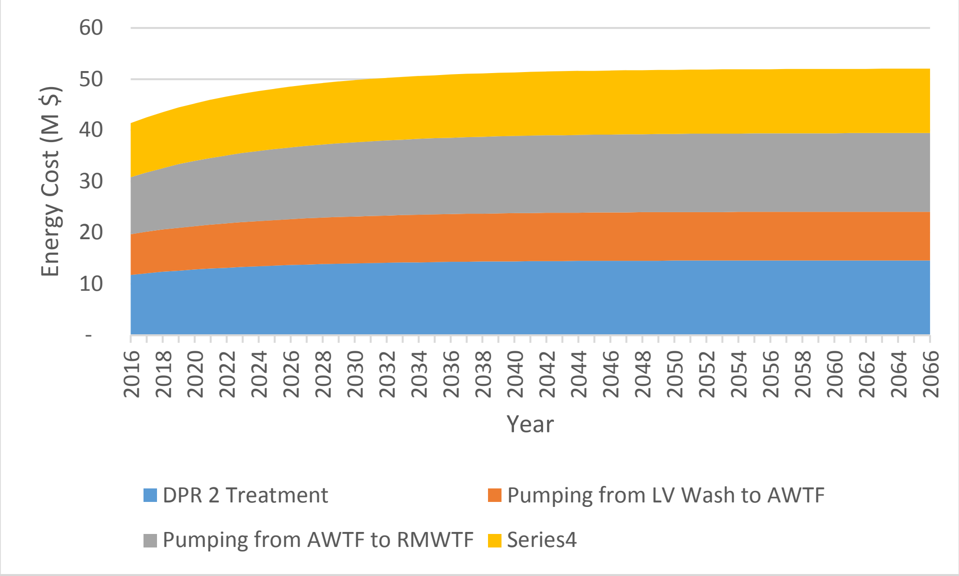

Figure 39: Energy Costs for DPR 2 - 75% RFCs

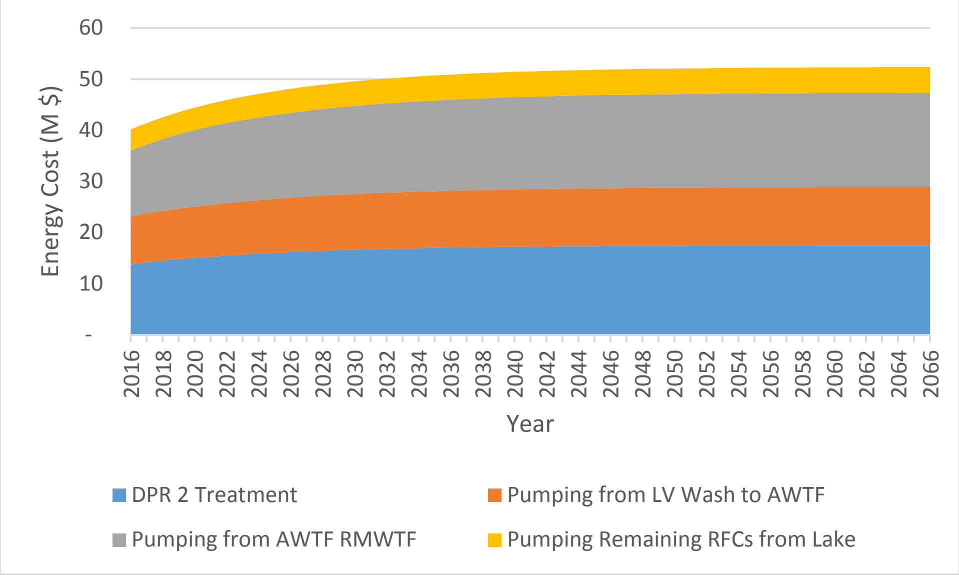

Figure 40: Energy Costs for DPR 2 - 90% RFCs

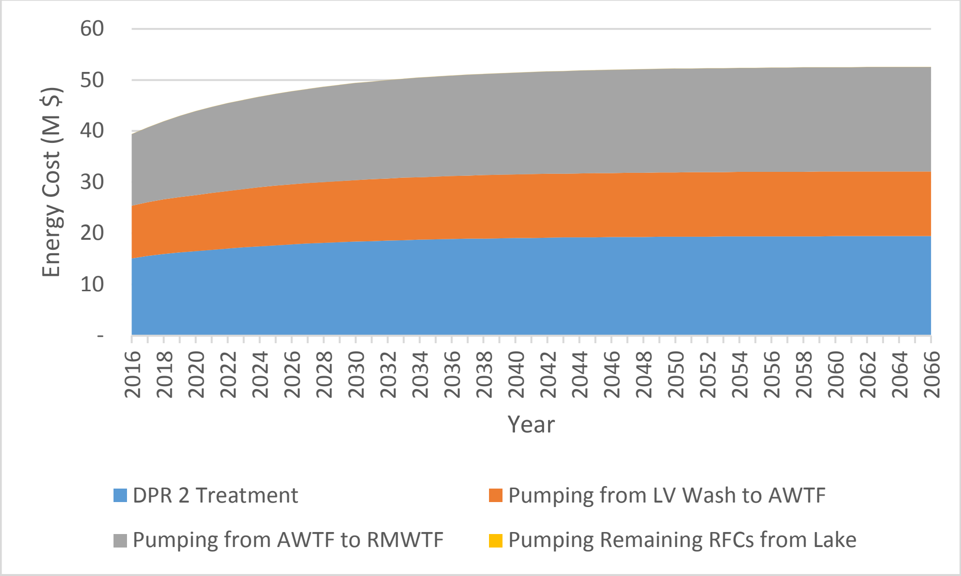

Figure 41: Energy Costs for DPR 2 - 100% RFCs

Similar to DPR 1, a large portion of energy costs for DPR 2 were from pumping from the Las Vegas Wash to the AWTF and then to the RMWTF.. The pumping energy costs for bypassing the lake accounted for 16%, 32%, 48%, 57%, and 63% of the overall energy costs for flow scenarios 25%, 50%, 75%, 90%, 100% RFCs.

GHG emissions were calculated for DPR 2 similarly as was done for DPR 1 and are shown in Figures 42 through 46.

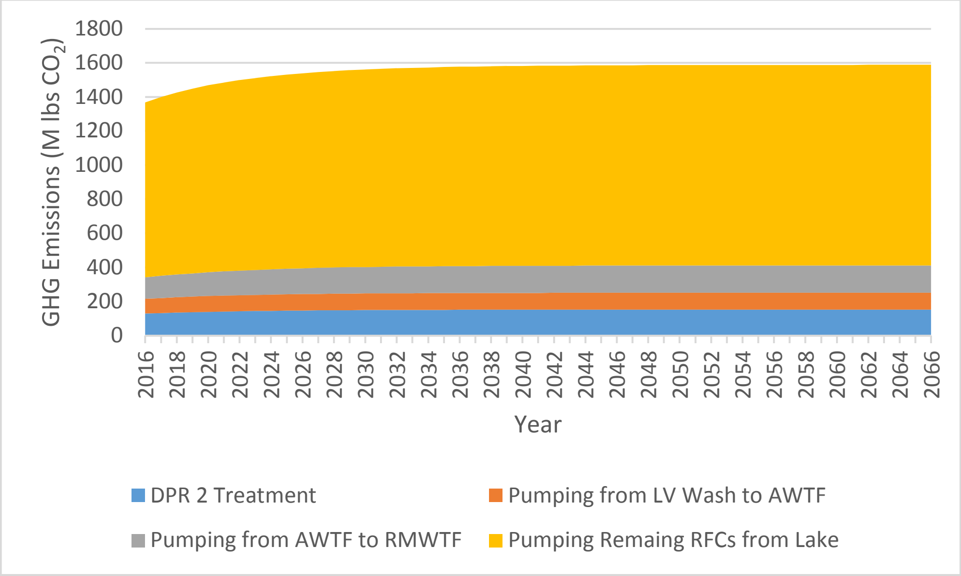

Figure 42: GHG Emissions for DPR 2 - 25% RFCs

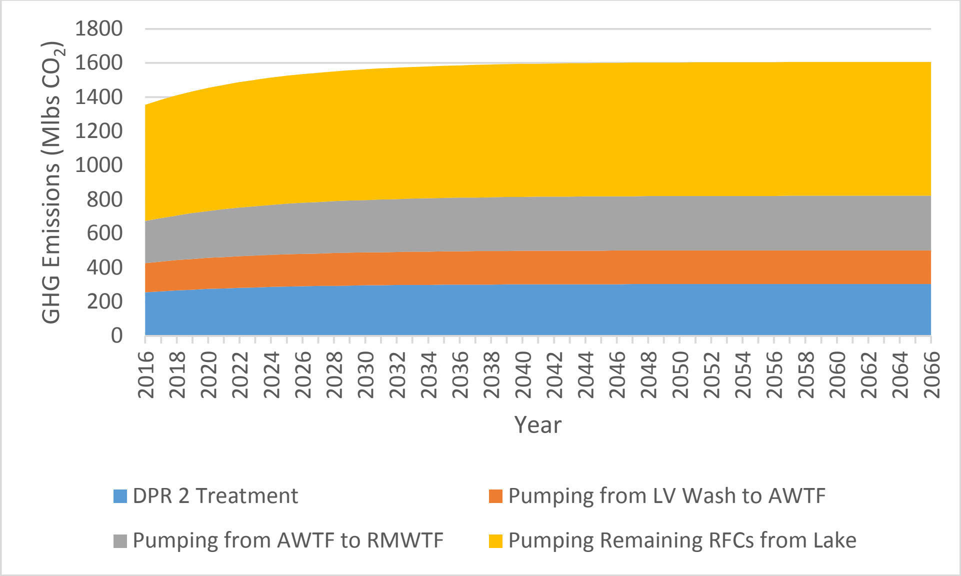

Figure 43: GHG Emissions for DPR 2 - 50% RFCs

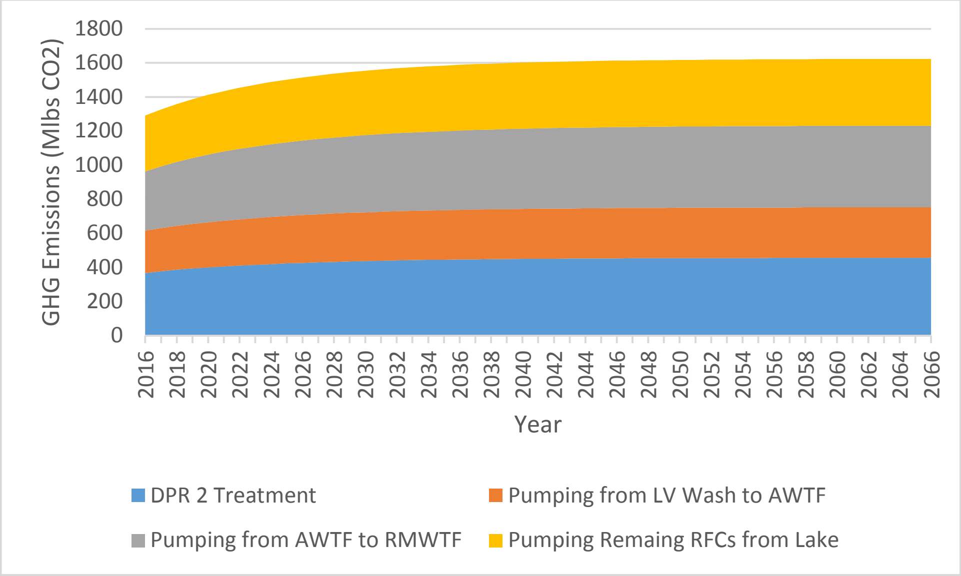

Figure 44: GHG Emissions for DPR 2 - 75% RFCs

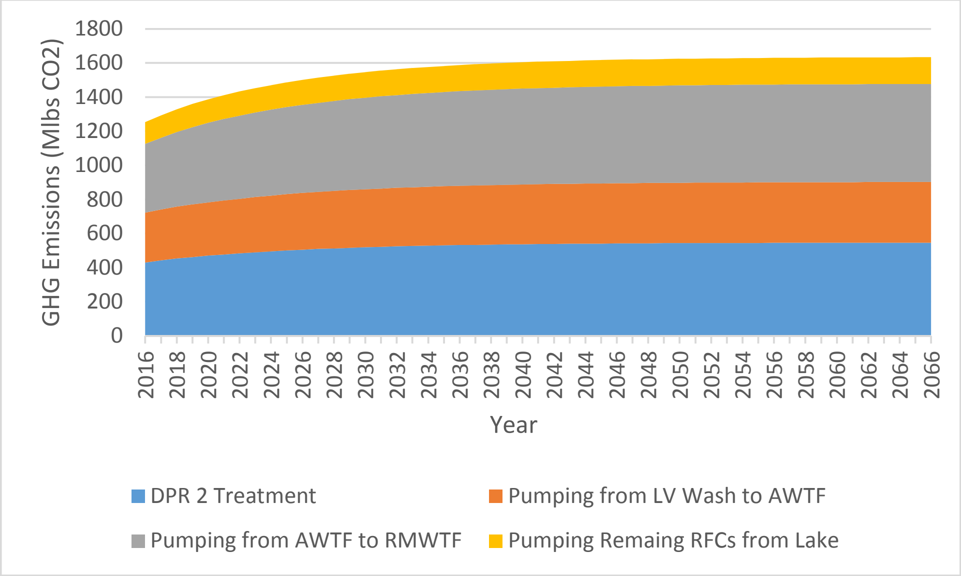

Figure 45: GHG Emissions for DPR 2 - 90% RFCs

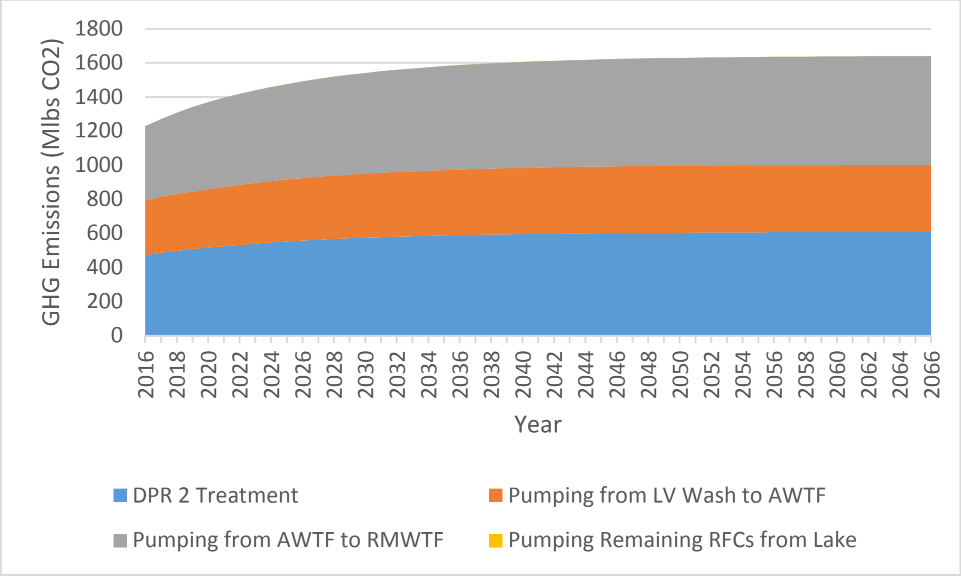

Figure 46: GHG Emissions for DPR 2 - 100% RFCs

Similar to energy costs, pumping the RFCs bypassing the lake account for a significant portion of the GHG emissions. GHG emissions from pumping to bypass the lake account for 16%, 32%, 48%, 57%, and 63% of the overall GHG emissions for scenarios of 25%, 50%, 75%, 90%, and 100% RFCs, respectively.

For the DPR 2 treatment no TDS load was removed from the system. Therefore, TDS concentration increases more rapidly than the other alternatives. TDS concentration entering the RMWTF is shown in Figure 47.

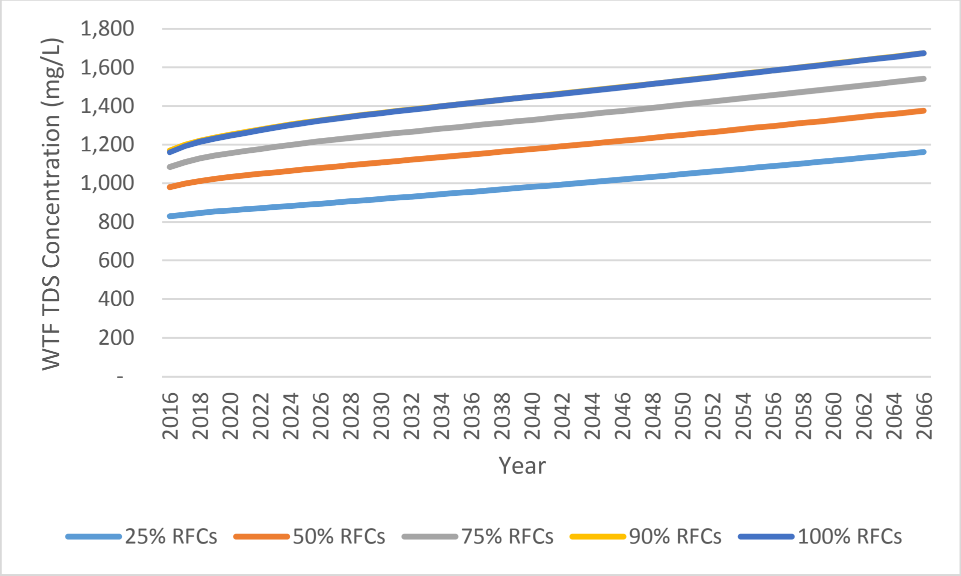

Figure 47: DPR 2 TDS Concentration Entering RMWTF

When bypassing the lake for DPR without removing TDS, the high TDS concentration in the Las Vegas Wash causes concentrations at the RMWTF to increase rapidly.

TP loads entering the lake for DPR 2 are the same as DPR 1 and are shown in Figure 35.

DPR Capital Costs

Capital costs for alternatives DPR 1 and DPR 2 include the cost for the new AWTF, as well as the pipeline that takes it from the Las Vegas Wash to the AWTF and then to RMWTF. The design flows for DPR treatment trains were assumed based off the highest RFC flow over the study period and are summarized in Table 7.

Table 7: Design Flows for DPR AWTFs

% RFCs	DPR Flow (ac-ft/y)	DPR Flow (mgd)
100%	272,840	244
90%	245,556	219
75%	204,630	183
50%	136,420	122
25%	68,210	61

The capital costs for each unit process based on the DPR design flow are summarized in Tables 8 and 9 for DPR 1 and DPR 2, respectively. Costs were developed using capital cost curves from Snyder et al. (2014).

Table 8: Unit Process Capital Costs for DPR 1

% RFCs	MF ($M)	RO ($M)	UV ($M)	Brine Disposal ($M)	Total ($M)
100%	260	519	77	42	898
90%	239	478	70	38	825
75%	207	415	59	32	712
50%	151	302	40	21	515
25%	88	176	21	11	295

Table 9: Unit Process Capital Costs for DPR 2

% RFCs	UF ($M)	O_3 ($M)	BAF ($M)	UV ($M)	Total ($M)
100%	260	28	162	85	535
90%	239	27	148	77	491
75%	207	25	127	65	424
50%	151	21	90	44	306
25%	88	15	50	23	176

The total capital costs for the AWTFs for DPR 1 and DPR 2 are shown in Figure 32 below.

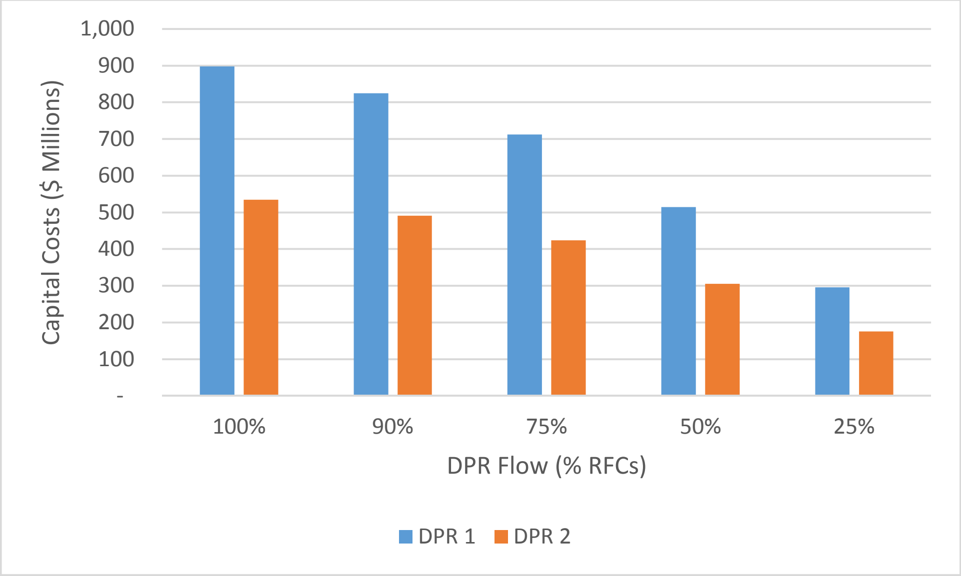

Figure 48: Capital Costs for DPR 1 and DPR 2 AWTF

The values represent costs for the unit processes associated for each DPR alternative. DPR 1 also reflects the cost to dispose of the brine waste associated with RO. Evaporation ponds were assumed to be the most viable option based on open space near the proposed AWTF location. Further, cost estimates were developed for the DPR pipeline based on each flow scenario. Pipe diameters were calculated based on flow and an assumed pipe velocity of 5 feet per second (fps). Pipe diameters were then selected based on typical pipe sizes available and are shown in Table 10.

Table 10: Calculated Pipe Diamter per DPR Flow Condition

RFC %	ac-ft/y	Pipe Diameter (in)
25%	68,210	60
50%	136,420	84
75%	204,630	96
90%	245,556	108
100%	272,840	120

The pipe cost estimates were developed using Carollo Engineers, Inc. Cost Estimating System (CCES) to approximate earthwork and pipe material prices. CCES accounts for material, equipment, and labor based on Carollo's project database. Trench depths were assumed to be 20 ft deep, and trench widths were assumed to be two feet wider that the pipe diameter (one foot on the outside of each side of the pipe). Additionally, the pipeline is approximately 30,265 linear feet in length from the Las Vegas Wash to the AWTF to RMWTF. Since very little is defined for conditions of the pipeline portion of the project, a contingency of 25% was added to the direct cost to account for the various unknowns of the project. Additionally, 10% was added to account for the contractor overhead and profit. Table 11 summarizes the cost estimates for each flow scenario.

Table 11: DPR Pipeline Cost Estimates

Description	**DPR Flow Scenarios**				
	25%	**50%**	**75%**	**90%**	**100%**
Earthwork	$5,926,361	$7,619,607	$8,466,230	$9,312,853	$10,159,476
Pipe & Fittings	$15,974,621	$23,596,125	$27,568,098	$31,595,685	$35,748,649
Estimated Direct Cost	**$21,900,982**	**$31,215,732**	**$36,034,328**	**$40,908,539**	**$45,908,125**
Contingency (25%)	$5,475,245	$7,803,933	$9,008,582	$10,227,135	$11,477,031
Contractor Overhead & Profit (10%)	$2,190,098	$3,121,573	$3,603,433	$4,090,854	$4,590,812
Total Estimation	**$29,566,325**	**$42,141,239**	**$48,646,343**	**$55,226,527**	**$61,975,969**

Pipeline costs are the same for each DPR alternative. The total capital costs for each DPR alternative, which combine both the treatment costs shown in Figure 32 and the pipeline costs in Table 11, are shown in Table 12.

Table 12: Total Estimated Cost for DPR Alternatives

RFC %	DPR 1 Alternative ($M)	DPR 2 Alternative ($M)
25%	$325	$205
50%	$557	$348
75%	$761	$472
90%	$880	$546
100%	$960	$597

The major cost differences for DPR 1 are associated with the TDS removal and disposal. The cost curves used from Snyder et al. (2014) yielded high costs for RO from $176M to $519M for 25% to 100% flow, respectively. Also, the cost for evaporation ponds for TDS brine disposal added a cost ranging from $11M to $42M for 25% through 100% flow, respectively. For DPR 1, the pipeline cost accounted for as much as 9% of the total capital cost for the 25% RFCs scenario down to 6% for the 100% RFCs scenario. Similarly for DPR 2, the pipeline costs accounted for as much as 14% of the total capital cost for the 25% RFCs scenario, down to 10% for the 100% RFCs scenario.

Northern Nevada GDP

SNWA’s GDP was not evaluated as a system dynamics model. The project was already defined in SNWA’s 2012 Conceptual Plan of Development (CPOD) submitted to the Bureau of Land Management (BLM). Information for every metric is not available (i.e. potential GHG emissions, water quality information for TDS, and the anticipated energy needs and costs). Comparison for the GDP alternative will be based on amount of water and cost. However, Chapter 5 will show the effects of adding the GDP to the other alternatives

The GDP includes the following aspects (SNWA, 2012):

- 263 miles of pipelines ranging in size from 16 to 84 inches in diameter
- three pump station facilities
- five regulating tanks in the size range of 3 to 10 million gallons in capacity
- three pressure reducing stations
- one 40 million gallon buried reservoir
- one WTF rated for 110 mgd
- several power facilities including:
    - 272 mile if overhead power lines
    - two primary electrical substations
    - four secondary substations

Additionally, to complete the GDP, 71 to 88 groundwater production wells will need to be installed as well. The location of these wells is still unclear, but their installation will come with the needed associated infrastructure including collector pipelines, pump stations, and additional power facilities. The GDP would supply a total of 134,434 ac-ft/y of additional water to SNWA users in Clark County, NV (SNWA, 2012). The total GDP project was estimated to cost $3.2 billion in 2007 dollars (SNWA, 2011). The Engineering News-Record (ENR) publishes construction cost index (CCI) histories for twenty major cities in the US (www.enr.com). These indices can be used to project past cost estimates with the following equation:

$$\frac{Today's\ CCI}{Past\ CCI} * Past\ Cost = Today's\ Cost$$

The 20 city average CCI was used for June 2007 and June 2016 to project the past GDP cost:

$$\frac{10337}{7939} * \$3.2\ billion = \$4.17\ billion$$

One important factor to note is that not only will the GDP provide a new source of water to SNWA, but all GDP water that would be used indoors and eventually flow through the WWTPs, will contribute to RFCs sent to Lake Mead via the Las Vegas Wash. This will extend SNWA's RFCs resource to withdraw from water from Lake Mead (SNWA, 2015).

Summary of Results

The results of the model were organized in to summary tables comparing the maximum values over the 50-year study period. Table 13 shows the number of years that water supply outlasted demand for the different alternatives. Tables 14, 15, and 16 show the maximum annual results for pumping costs, energy costs for treatment, and GHG emissions, respectively.

Table 13: Number of Years Outlasting Demand

% RFCs Bypassing the Lake	**No. of Years Supply Outlasts Demand (Years)**		
	Status Quo	**DPR 1**	**DPR 2**
0%	21	-	-
25%	-	16	21
50%	-	13	21
75%	-	11	21
90%	-	9	21
100%	-	8	21

Table 14: Maximum Pumping Costs Over the Study Period

% RFCs Bypassing the Lake	**Maximum Pumping Costs Over Study Period ($M/y)**		
	Status Quo	**DPR 1[1]**	**DPR 2[1]**
0%	50.3	-	-
25%	-	44.6	46.0
50%	-	39.2	41.7
75%	-	33.9	37.4
90%	-	30.9	34.8
100%	-	28.8	33.1

1. Accounts for both pumping costs from the Las Vegas Wash and the pumping remaining RFCs from the lake.

Table 15: Maximum Energy Cost for DPR Treatment Over the Study Period

%RFCs	**Maximum Energy Cost for DPR Treatment Over Study Period ($M/y)**	
	DPR 1	**DPR 2**
25%	8.03	4.9
50%	15.8	9.7
75%	23.2	14.6
90%	27.5	17.5
100%	30.3	19.4

Table 16: Maximum GHG Emissions Over the Study Period

% RFCs Bypassing the Lake	**Maximum GHG Emissions Over Study Period (M lbs CO_2/y)**		
	Status Quo[1]	**DPR 1[2]**	**DPR 2[2]**
0%	1570	-	-
25%	-	1,646	1,588
50%	-	1,714	1,606
75%	-	1,782	1,624
90%	-	1,821	1,634
100%	-	1,847	1,640

1. Accounts for GHG emissions form pumping from the lake.

2. Accounts for GHG emissions from treatment and all required pumping.

CHAPTER 5: TRIPLE BOTTOM LINE ANALYSIS OF ALTERNATIVES

Description of Triple Bottom Line Analysis

A triple bottom line analysis (TBL) includes three tiers of criteria to analyze a project: 1) economic, 2) social, and 3) environmental. TBL is not a new concept and has been in practice since the early 1980s (Shimmoller and Kealy, 2014). Although cost is important in identifying the most feasible project, TBL allows a more comprehensive view beyond cost alone. Environmental factors could include but are not limited to effects on natural resources, ecosystems, and atmospheric conditions. Social factors include but are not limited to public perception, public health, quality of life, education, and safety. The specific criteria evaluated for the economic, environmental, and social impacts for the alternatives are described in the following sections.

Description of Criteria and Sub-criteria for Comparison

Economic Criteria

The sub-criteria for economic considerations focused on two areas: net present value (NPV) and potential savings from TDS removal. The NPV was determined based on capital and operational costs over the 50-year study period. The NPV is expressed in dollars per acre-foot ($/AF) and ranked based on cost. The literature clearly showed that there is value in removing TDS, but there is a large range when trying to quantify the value (Borda, 2004). Therefore, the potential economic value to the Las Vegas Water system from removing TDS was included in the evaluation.

Social Criteria

The sub-criteria for social considerations take into account the amount of water that will be able to be used by downstream users on the Colorado River and overall public acceptance of the alternative. RFCs have been a key factor to SNWA’s success of extending their water resources from the Colorado River and helping maintain Lake Mead elevation levels. By implementing DPR, RFCs would be reduced significantly. This was considered in the evaluation based on the amount of RFCs continuing to flow to Lake Mead. Additionally, public perception was also considered in the social sub-criteria. Having public buy-in plays a large part in project success for public water agencies. Public acceptance of DPR is achievable through effective outreach programs, but it is generally more difficult than other water supply options. Lastly, public health protection was also considered in the evaluation based on the anticipated water quality in regards to the potential of trace organic compounds (TOrCs).

Environmental Criteria

Environmental sub-criteria focused on three areas: 1) GHG emissions, 2) Water quality based on TDS load removed from the system, and 3) eutrophication potential. GHG emissions are quantified by lbs of CO_2 per acre-foot over the 50-year study period based on the energy needs of the alternatives. The higher the lbs of CO_2, the less favorable the alternative is. The environmental benefit of removing TDS load could only be quantified for DPR 1. Eutrophication potential was quantified based on the amount of TP entering Lake Mead via the Las Vegas Wash over the study period in units of M lbs of TP. The higher the load of TP entering the lake, the less favorable the alternative is.

Screening of Alternatives

The alternatives were initially screened to narrow the alternatives for TBL analysis and to focus on the most realistic project alternatives. A common flow scenario for the DPR alternatives was selected. The flow scenario is based on having an acceptable amount of flow remaining in the Las Vegas Wash to sustain the existing ecosystem. RFCs sustain life for several species along the wash. There is no minimum amount of flow listed in the literature that states clearly what is needed to sustain the ecosystem. It was assumed that 50% of RFCs remaining in the Las Vegas Wash was sufficient to sustain the existing ecosystem. Only the 50% flow scenario was used for the TBL analysis for alternatives DPR 1 and DPR 2.

Additionally, the GDP as a standalone project was also not included in the TBL due to lack of information. There is no record of the anticipated energy costs associated with pumping the new water source or treating it. Also, the approximate location for groundwater pumping is still unclear. This impacts the cost for the associated infrastructure needed for the pumping operation. This information is needed to calculate an accurate NPV over the study period, as well as to approximate the GHG emissions associated with the energy use. Furthermore, no water quality data is available for the GDP's new water source to anticipate the TDS load effects entering the system. For the reasons summarized above, the final alternatives to be considered for TBL analysis are the following:

- status quo
- DPR 1 - 50% RFCs
- DPR 2 - 50% RFCs

Economic Analysis

The NPV for the 50-year study period was calculated for the final three alternatives. The DPR alternatives at 50% RFCs need to provide treatment for up to 122 mgd over the study period. It was assumed that the prosed AWTF for each DPR alternative would be built out over 3 phases. Starting in 2016, phase 1 would account for a 40 mgd AWTF for the first 16 years. Phase 2 would start in 2032, expand the capacity an additional 40 mgd, and last an additional 16 years. Phase 3 would build out the remaining capacity to meet the full 122 mgd and last the remainder of the study period. Capital and energy costs were adjusted for both DPR alternatives to match the three phases of the proposed buildout. All costs were adjusted for both inflation and discount rates over the study period to account for the change in dollar value over time. The adjustments were made using the following equations:

$$Inflation\ adjustment = O\&M\ Costs \times (1 + rate)^{year}$$

$$Discount\ adjustment = \frac{O\&M\ Costs}{(1 + rate)^{year}}$$

The inflation and discount rates were assumed to be constant for every year at 3% and 4%, respectively. The calculated NPV for the status quo, DPR 1 (50% RFCs), and DPR 2 (50% RFCs) alternatives over the 50-year study period are \$1.96 billion, \$2.54 billion, and \$2.20 billion, respectively. The NPVs were divided by total amount of ac-ft over the 50-year study period and expressed as in \$/AF. This resulted in \$145/AF, \$204/AF, and \$163/AF for status quo, DPR 1 (50% RFCs), and DPR 2 (50% RFCs), respectively.

TBL Decision Matrix

Ranking of Sub-criteria

The goal of the TBL analysis is to identify the most feasible alternative based on a weighted decision matrix. Each major criteria and its associated sub-criteria were assigned a weight in percentage. Certain sub-criteria were quantifiable (i.e. NPV/AF, GHG emissions/AF, and M lbs TP) and others were not. Therefore, a ranking system was established for consistent scoring. The ranking system assigned values of 1 through 3 and defined as the following

- 1: worsens the situation
- 2: neutral or no change to the situation
- 3: improves the situation

Sub-criteria with quantified and values were equated to a ranking of 1 through 3.

The ranking of economic, social, and environmental sub-criteria are summarized in Table 29, 30 and 31 below.

Table 17: Economic Sub-Criteria Ranking

Economic Sub-criteria	**Alternatives**			**Explanation**
	Status Quo	**DPR 1-50% RFCs**	**DPR 2-50% RFCs**	
Minimize NPV	3	1	2	Based on NPVs for alternatives: Status quo $144/AF; DPR 1 $209/AF; $174/AF
Potential Cost Savings from TDS Removal	2	3	1	DPR 1 is the only alternative that can remove TDS; status quo does not change TDS, DPR 2 increased TDS more rapidly
Supply Outlasting Demand	3	1	3	Supply for Status quo and DPR 2 outlasts demand for 21 years, DPR 1 13 years

Table 18: Social Sub-Criteria Ranking

Social Sub-criteria	**Alternatives**			**Explanation**
	Status Quo	**DPR 1-50% RFCs**	**DPR 2-50% RFCs**	
Flow Available to Downstream Users	2	1	1	Status quo continues RFCs to the lake but does not improve
Public Acceptance	2	2	1	The status quo is known and the public is comfortable with the concept, but does not improver perception; DPR 1 would be a challenge for public to accept, but the potential for TDS removal could make it seem appealing; DPR 2 has the same public challenges but without the potential for TDS removal
Public Health Protection	2	3	2	All alternatives are protective of public health; Status quo does not improve water quality but benefits from dilution from lake; DPR 1 uses RO which is capable of remove >95% TOrCs (Trussell et al., 2013) DPR 2 is less than other alternatives due to less dilution and less effective at removing TOrCs

Table 19: Environmental Sub-Criteria Ranking

Environmental Sub-criteria	**Alternatives**			**Explanation**
	Status Quo	**DPR 1-50% RFCs**	**DPR 2-50% RFCs**	
Minimize GHG Emissions	2	1	3	Over the study period status quo produced 5,873 lbs CO_2/AF, DPR 1 produced 6,872 lbs CO_2/AF, and DPR 2 produced 5,865 lbs CO_2/AF; status quo does not improve, DPR 1 worsens GHG emissions, and DPR 2 improves
Decrease TDS	2	3	1	DPR 1 is the only alternative that can remove TDS; DPR 2 increases TDS more rapidly; status quo remains the same
Minimize Eutrophication Potential	2	3	3	Over the study period status quo discharged 7.53 M lbs TP to Lake Mead (no improvement), and DPR 1 and DPR 2 discharged 4.35 M lbs TP

TBL Analysis

The TBL analysis was performed based on a decision matrix from the economic, social, and environmental criteria as previously stated in Tables 29, 30, and 31. Table 32 provides an overall summary the TBL criteria and sub-criteria for each alternative and the associated weighting assigned.

Table 20: Summary of TBL Analysis Results

Water Reuse TBL Criteria	**Weight of Criteria**	**Alternatives**		
		Status Quo	**DPR 1-50% RFCs**	**DPR 2-50% RFCs**
Economic	**55%**			
Minimize NPV	60%	3	1	2
Potential Cost Savings from reduced TDS	25%	2	3	1
Supply Outlasting Demand	15%	3	1	3
Social	**20%**			
Flow Available to Downstream Users	33%	2	1	1
Public Acceptance	33%	2	2	1
Public Health Protection	33%	2	3	1
Environmental	**25%**			
Minimize GHG Emissions	30%	2	1	3
Decrease TDS Load to LV Valley	40%	2	3	1
Eutrophication Potential	30%	2	3	3
Note: Highest ranking is 3, least ranking is 1.				

The weighted scores from the TBL analysis based on Table 32 are shown in Figure 49. The status quo ranked the highest overall, with DPR 1 ranking second and DPR 2 ranking third. Status quo scored the highest in economic and social criteria, but DPR 1 scored the highest in environmental criteria.

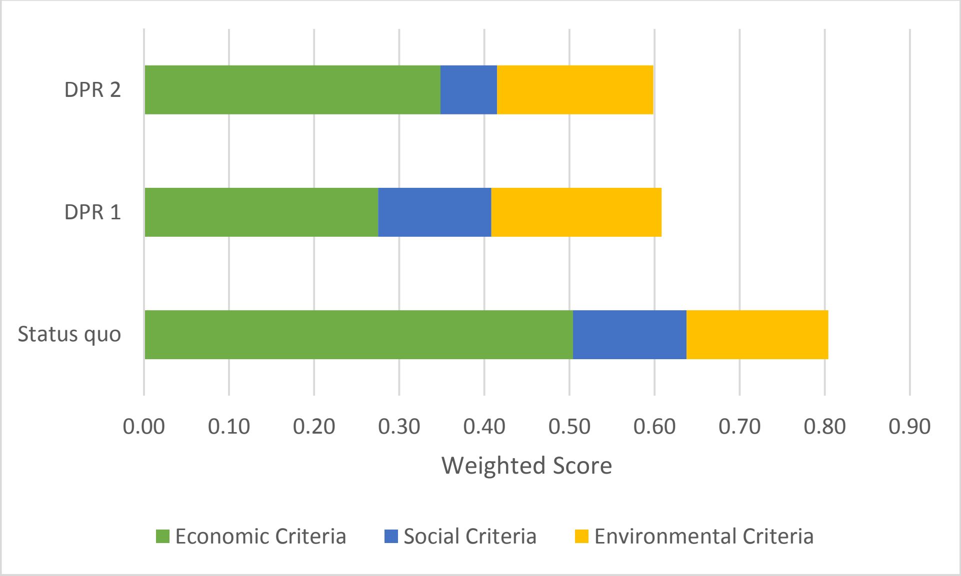

Figure 49: Weighted Scores for TBL Alternatives

CHAPTER 6: CONCLUSIONS AND RECOMMENDATIONS

Key Findings

A system dynamics model was developed to compare alternatives for the Las Vegas Water System. The current operation (or status quo) was compared against two DPR alternatives. The energy and cost savings from reduced pumping by bypassing RFCs from Lake Mead for DPR implementation did not outweigh the energy and costs associated with DPR pumping from the Las Vegas Wash to the RMWTF and the proposed DPR treatment (for either DPR alternative). Additionally, the DPR 1 yielded higher GHG emissions than status quo when taking into account the energy needed for pumping from the Las Vegas Wash to the RMWTF as well as the added DPR AWTF. However, DPR 2 yielded lower GHG emissions than status quo. Further, the DPR alternatives minimized eutrophication potential by bypassing a portion of the flow from the lake, thus reducing the TP load entering the lake. Also, DPR 1 was the only alternative resulting in a water quality benefit in terms of TDS. It does not seem that the DPR 2 treatment train would be an appropriate approach to the Las Vegas Valley since TDS concentrations increased more rapidly than both status quo and DPR 1.

A TBL analysis compared the status quo to both DPR alternatives with 50% of RFCs. When ranking the overall feasibility of the alternatives based on the weighted criteria in Chapter 5, the status quo alternative proved to rank the highest.

This research successfully addressed the research questions presented in Chapter 1. The first question was whether DPR offered a more efficient water management alternative than the

RFC approach. Based on the model that was developed and the assumptions made, DPR is not a more efficient water management alternative than the RFC approach. DPR alternatives were higher in operational costs, and DPR 1 reduced the number of years that water supply outlasted demand. The second question was whether DPR provided a higher cost to benefit ratio than importing new water supplies. This is not entirely clear. Although the cost to implement DPR is less expensive (for any RFC percentage) than the proposed northern Nevada GDP, DPR is not providing a new source of water. Instead, DPR is using the same amount of water in a different way. It is clear, however, that in order to meet future water demands SNWA will need an additional water supply. Permanent water resources will only last until the year 2037 for the status quo approach. Details for O&M needs and the anticipated water quality must be further defined for the GDP to evaluate the potential benefits. The third question was whether DPR provided an overall improvement to the environment, among other more subjective sustainability criteria. Both DPR 1 yielded higher GHG emissions while DPR 2 yielded lower GHG emissions for pumping RFCs from the Las Vegas Wash to the RMWTF and the proposed AWTFs when compared to the status quo of pumping RFCs from the lake. However, DPR 1 improved water quality by removing TDS load. Additionally, the more RFCs that were prevented from entering Lake Mead for DPR implementation, the more TP load was prevented from entering the lake, thus reducing the eutrophication potential. Therefore, the appropriateness of the DPR alternatives will depend more on subjective social and environmental criteria, as the economic criteria suggest that the status quo approach is preferred.

The hypothesis of DPR providing a more sustainable and economical water source was not supported. Further, the hypothesis of DPR improving water quality was only partially supported considering that DPR 1 provided an overall reduction in TDS but DPR 2 did not.

Recommendations for Improvement and Future Evaluations

There are several improvements and future evaluations that can be done to add to and strengthen this research. Several environmental impact inputs were assumed to be constant. For example, to better project environmental impacts in the future, further research into how GHG emissions have and would change over time due to the changing energy portfolio would give more accurate results on what is expected. Further, more research should be done in regards to eutrophication potential. This research assumed a constant concentration all year and that the concentration never exceeded the permitted limit for TP. Data gathering on TP discharges from the four WWTPs could be done to better understand how the load and concentration changes throughout the year.

Potential for DPR in Southern Nevada

There is still potential for DPR implementation in southern Nevada. Further research should be done for potential tie-in locations for DPR alternatives. There is still a significant amount of energy and cost to pump RFCs from the Las Vegas Wash to the RMWTF. As shown in Figures 23 through 27 for DPR 1 and Figures 37 through 41 for DPR 2 in Chapter 4, the overall pumping costs are nearly the same or exceed the energy costs for DPR treatment. The treatment train for DPR 1 is capable of meeting and exceeding drinking water regulations and would be safe to introduce directly into the distribution system. Determining a different location directly into the distribution system that requires less distance and less elevation change would improve the overall feasibility of DPR. Other alternatives to reduce distance and elevation concerns could include evaluating decentralized DPR approaches within the Las Vegas Valley. For example, the amount of energy it takes to send drinking water from Lake Mead to Summerlin (a community located on the far west side of the Las Vegas Valley) is excessive. Implementing a decentralized DPR approach in Summerlin (or other communities farthest away from the lake) would essentially eliminate pumping costs could make the cost benefits swing in favor of DPR. This application could range from single family homes, commercial properties, master planned communities, and even resort properties.

Lastly, pilot scale DPR treatment trains would provide a better insight on operational costs and water quality. This is especially important with RO treatment trains. As technology becomes less energy intensive, more efficient, and the amount of water loss through RO membranes is minimized, RO treatment may become more cost effective and more feasible overall.

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Assisted in wastewater treatment facility operation and maintenance, reviewed offsite sewer plans for design and construction standard compliance, and assisted in wastewater collection system construction and maintenance. (July 2009 – April 2012).

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