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Evaluating the energy and carbon footprint of water conveyance system and future water supply options for Las Vegas, Nevada

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EVALUATING THE ENERGY AND CARBON FOOTPRINT OF WATER CONVEYANCE SYSTEM AND FUTURE WATER SUPPLY OPTIONS FOR LAS VEGAS, NEVADA

by

Eleeja Shrestha

Bachelor of Engineering
Tribhuvan University, Nepal
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A thesis submitted in partial fulfillment of
the requirements for the

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Eleeja Shrestha

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December 2010

ABSTRACT

Evaluating the Energy and Carbon Footprint of Water Conveyance System and Future Water Supply Options for Las Vegas, Nevada

by

Eleeja Shrestha

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Water production requires the use of energy to transport water from distant locations, pump groundwater from deep aquifers and treat water to meet stringent drinking water and wastewater regulations. Energy production based on its source involves the emission of greenhouse gases also known as carbon footprint, which is the leading cause of global warming and climate change. Because of growing concerns of global warming due to these emissions, water providers are required to analyze the energy and associated carbon footprint of existing water production facilities and future water supply options. A system dynamics model is developed to estimate the energy requirements and carbon footprint as its consequence to move water in the distribution laterals of the Las Vegas Valley. The model is also used to evaluate the two future supply options for the Las Vegas Valley: seawater desalination and water conveyance from distant locations using water conveyance infrastructures. The simulation results show that it requires significant amount of energy to lift water from water source to water treatment plants (0.3 million megawatt hours per year (MWh/y)) and then to distribute treated water in distribution laterals (0.55 MWh/y) in 2010. It requires more energy to distribute treated water (65%) when compared to lift water from source to treatment plants (35%). Different scenarios including change in population growth rate, water conservation, increase in water reuse, change in the Lake level, change in fuel sources, change in emission rates, and combination of multiple scenarios are tested to evaluate the change in energy requirements and associated carbon footprint. The increase in water conservation resulted to be the most energy efficient option and consequently generated lower carbon footprint. The reduction of per capita water demand to 753 lpcd (199 gpcd) by 2035 lowered the energy requirements and associated carbon footprint by 16.5%. In addition, reuse of wastewater effluent within the Valley can be an excellent way of saving energy. However, reusing only 77 million cubic meters (MCM) (56 mgd) treated wastewater effluent by 2020 results in the decrease of energy consumption by nearly 3.6%. If 20% of the treated wastewater can be reused within the Valley besides status quo reuse (127 MCM or 92 mgd), the energy consumption and associated carbon footprint is lowered by 9% by the year 2035. Of the two water supply options, seawater desalination is more energy intensive (96% higher) as compared to the water conveyance from remote locations and the associated carbon footprint is 47% higher. However, desalination option is cost efficient. The unit cost of seawater desalination is \$0.56/m^3 and where as \$0.68/m^3 for water conveyance from distant sources.

Keywords: Water; Energy; Carbon footprint; Desalination; Transport; Cost; Las Vegas, NV; System Dynamics

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CHAPTER 1

INTRODUCTION

Even though earth is referred as a “Blue planet”, the water scarcity has been alarming the world. The situation is getting worse as needs for water is increasing with population growth, urbanization and increase in household and industrial uses (WHO, 2009). Of the plentiful water on earth, only 2.5% of it is fresh (Oki et. al, 2006; Von Uexkűll, 2004). Moreover, most of this fresh water is stored in deep groundwater or as glaciers that are not easily accessible. The adequate availability of fresh water is essential for growth and development of human civilization. Almost one fifth of the world's population lives in areas where the water is scarce and nearly one quarter of the global population, living in developing countries face water shortages due to a lack of infrastructure to fetch water from rivers and aquifers (Ringler et al., 2010; Stokes and Horvath, 2009; WHO, 2009). The demand for water has been increasing in many places with the growth in population and urbanization whereas the source of supply is limited. The recent drought in arid areas like the American Southwest can alter surface water flows and limit the availability of fresh supply of water, introducing the need of efficient water production strategies to meet the water needs (Benotti et al., 2010).

Water production requires the use of energy also known as energy footprint. Energy and water are intricately connected (Gleick, 1994). Without substantial input of energy either in the form of electricity or heat, major water transportations, desalination of brackish or seawater and massive pumping from groundwater aquifers would not have been easily possible. Similarly, the production and use of energy often require significant amount of direct or indirect water use. Water is required to mine an energy resource to alter fuel properties, for the construction, operation and maintenance of energy generating facilities, for power plant cooling, and also for disposing waste products (Gleick, 1994). Thus, the conveyance of water requires extensive use of energy and similarly production of energy requires large volume of water (Gleick, 1994; Lampe et al., 2009; Rio Carrillo and Frei, 2009).The growing water demand may limit its use in energy production in future. Likewise, the increasing price of energy and depleting energy resources will constrain the ability to provide adequate fresh water.

Almost all energy used in water production is in the form of electricity. The energy use in a water distribution network depends not only on the quantity of delivered water but also on the spatial distribution of the water sources, end users, the level of water treatment required, and other physical characteristics of the water system (Bakhshi and Demonsabert, 2009; Pelli and Hitz, 2000). High energy consumption is the major expense in water system. Pumping energy represents the main cost of water supply system and energy cost varies with amount of pumped water and energy tariff (Vieira and Ramos, 2009).

Depending on the fuel source for electricity generation, energy use contributes to the carbon footprint, defined as the total set of greenhouse gas emissions released during an activity or over life stages of a product. The emission of greenhouse gases directly depends on the power generation fuel mix for a specific region (Bakhshi and Demonsabert, 2009). Many environmental problems may arise as a result of these emissions such as acid rain, air pollution and the major being the global warming (Cohen, 1990). The resulting damages due to these emissions are termed as externalities. Neither the electric power rates reflect the associated social costs nor do ratepayers directly pay these external costs (Carlin, 1995). Moreover, a typical cost-benefit analysis for the evaluation of water supply options does not consider these associated external costs. The concerns towards sustainable development and climate change have prompted the efficient use of electricity in water network (Kumar and Karney, 2007). For the sustainable implementation of water supply options required to meet the growing water demands, not only the capital cost and electricity cost of the system, but also the greenhouse gas emissions should be considered in the analysis.

1.1 Research Motivation

During the early 1900s the sole water source for the Las Vegas was artesian wells. In 1928, the Boulder Canyon Project Act apportioned Nevada 0.4 cubic kilometers (km^3) (300,000 acre-feet) of Colorado River water per year (SNWA, 2009a; USBR, 2008). Since, the area was sparsely populated, groundwater seemed plentiful and this allocation was not used until mid 1950s. Currently about 90% of the water used in southern Nevada comes from Colorado River through Lake Mead (SNWA, 2009a). The remaining 10% is withdrawn from the deep groundwater aquifers to meet the peak water demand during summer (SNWA, 2010). Lake Mead is one of the primary reservoirs in the Colorado River system created in 1930s due to Colorado River flow obstruction by Hoover Dam (Allen, 2003). There are two intake pumping stations supplying water to the Las Vegas. The Las Vegas Valley is approximately 1200 feet above the Lake level. This requires massive energy for pumping water. As the Lake levels decline, the pumping energy requirements increase. The annual average inflow to the Lake Mead system was 66 percent of the normal between 1999 and 2008 (SNWA, 2009a). The continuity of this drought condition can lead to two primary consequences: possible reduction in the amount of available Colorado River water and intake supply and operation challenges due to decline in water level at Lake Mead.

Under these conditions, the future water needs can be met either by reducing the demand or by augmenting the supply. The Southern Nevada Water Authority (SNWA), that manages the water resources in the Las Vegas, offers various water conservation programs some of which include:

- Desert Landscaping
- Pool Cover
- Rain Sensor
- Irrigation Controller
- Water Smart Car Wash
- Water Efficient Technologies
- Water upon Request in Restaurants

The application of these conservation programs decreased the annual water consumption by nearly 0.08 km^3 (21 billion gallons) between 2002 and 2008, although there was a population growth of 400,000 during that period (SNWA, 2009b).

Conversely, the increasing water demand and prolonging drought conditions have also introduced a need to pursue additional water resources. SNWA has been actively pursuing the development of additional in-state and out-of state water resources (Cooley et al., 2007). The resource development options considered by SNWA include:

- Seawater Desalination
- Clark, Lincoln and White Pine Counties Groundwater Development

- Water Banks in Arizona, Southern Nevada and California
- Coyote Spring Valley and Three Lakes Valley Groundwater Rights
- Pre-Compact Virgin and Muddy River Water Rights and Post-Compact Virgin River Water Rights
- Augmentation Credits for in-state, non-Colorado River resources
- Additional Conservation
- Surplus and Interim Surplus Colorado River Water
- Additional wastewater reuse

This study will mainly focus on the energy consumption and the subsequent carbon footprint associated with the conveyance of water from source to the distribution laterals in the Las Vegas Valley and two potential future supply options: seawater desalination and Clark, Lincoln and White Pine Counties groundwater development. The conveyance of water in the distribution laterals in the Las Vegas Valley explores the current and future energy requirements and associated carbon footprint of moving water; and variations in the footprint due to change in population growth rate, water conservation, increase in wastewater reuse within the Valley, change in the Lake level, change in fuel sources, and change in emission rates. Seawater desalination is a paper-trade agreement between Nevada and California or Mexico in which Nevada will build a desalination plant in California or Mexico and in exchange pump equivalent amount of California or Mexico apportionment of Colorado River water from the Lake Mead. Clark, Lincoln and White Pine counties groundwater development option consists of the transfer of groundwater via buried pipeline from hydrographic basins in Lincoln and White Pine Counties located in northern Nevada. This water conveyance project from distant location would approximately convey 304,000 cubic meters per day (m^3/d) (90,000 acre-feet per year (afy)) of water, to the Las Vegas Valley. Both options considered for augmenting water supply to meet future water needs in the Las Vegas are associated with energy use and hence, increased carbon footprint. Due to potential future greenhouse gas emissions targets and rising energy costs, it necessitates the consideration of energy and carbon footprints when evaluating water supply options.

1.2 Research Objective

There are two main objectives of this research which are as follows:

- To determine energy consumption and associated carbon footprint of conveying water from Lake Mead to the Las Vegas Valley. This will involve evaluating variations on the footprint due to changes in population growth rate, water conservation, increase in wastewater reuse within the Valley, change in the Lake level, change in fuel sources, and change in emission rates.
- To compare the two water supply alternatives: seawater desalination and water conveyance from distant location, in terms of cost analysis and associated carbon footprint based on the energy requirements for each alternative.

In order to fulfill the above mentioned research objectives, the following research questions are investigated:

1. What are the energy and carbon footprints of the current water supply system in the Las Vegas Valley?
2. What are the energy and carbon footprints of the future water supply options for the Las Vegas Valley?

3. Which water supply option is more sustainable in terms of cost and carbon footprint?

To investigate the research questions, a system dynamics simulation model is developed following the sequence of tasks as listed below:

Task 1: A dynamic simulation model is developed to evaluate the sustainable water resource options that determine the energy requirements for water supply and conveyance for current and future supply options.

Task 2: The model is calibrated and verified using historic data for population and water demand of the Las Vegas Valley.

Task 3: The energy requirements to move water from source to the distribution laterals of the Las Vegas Valley are estimated.

Task 4: The carbon footprint associated with the energy use is determined.

Task 5: The two supply options are compared for their potential to increase water supply in terms of cost analysis and associated carbon footprint due to energy use.

1.3 Scope of the Research

The energy use for moving water in the Valley considers only the energy requirements to pump water from source to the treatment plants and from treatment plants to the distribution laterals of the Valley. The distribution laterals end in storage tanks or reservoirs. The energy required to further distribute water to the end users is not considered in this study. Also, energy required for treating water in water and wastewater treatment plants is not considered.

The thesis is presented in a manuscript style. Chapter 2 and chapter 3 are presented in a way in which they will be submitted for publication. Chapter 2 describes the present and future energy requirements to move water in the Las Vegas Valley distribution laterals and reports associated carbon footprint. The impact or variation in the energy and associated footprint is analyzed testing different scenarios. Chapter 3 looks into the future supply options for the Las Vegas Valley and compares the two potential supply options in terms of cost, energy and associated carbon footprint. Conclusions followed by recommendations for further study are listed in chapter 4.

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CHAPTER 2

THE CARBON FOOTPRINT OF WATER TRANSPORT IN AN URBAN ARID REGION

Abstract

The growing concerns of global warming and climate change has forced water providers to scrutinize the energy for water production and the greenhouse gas (GHG) emissions associated with it. The carbon dioxide (CO_2) emissions as an outcome of electricity use in the water conveyance system in the Las Vegas Valley located in Nevada, USA have been increasing with the population and economic growth. A system dynamics model is developed to estimate the energy requirements to move water from the water source to the distribution laterals of the Las Vegas Valley and to analyze the carbon footprint associated with it. The results show that at present nearly 0.85 million megawatt hours per year (MWh/y) energy is required for conveyance of water in distribution laterals of the Valley from Lake Mead, located 32.2 km (20 miles) southeast of the Las Vegas at an elevation of nearly 366 m (1200 ft) below the Valley, resulting in approximately 0.53 million metric tons of CO_2 emissions per year. Considering the current mix of fuel source, the energy and CO_2 emissions will increase to 1.34 million MWh/y and 0.84 million metric tons per year, respectively by the year 2035. Various water management scenarios including change in population growth rate, water conservation, increase in water reuse, change in the Lake level, change in fuel sources, change in emission rates, and combination of multiple scenarios are analyzed to study their impact on energy requirements and associated CO_2 emissions. The results show that the fluctuation in Lake Mead levels considered in this study does not affect significantly the total energy and associated CO_2 emissions. However, conservation measures and increase in water reuse rate significantly lowers the future energy requirements. The reduction in per capita water demand to 753 lpcd (199 gpcd) by 2035 can lower the energy and associated CO_2 emissions by nearly 16.5%. If 20% of the treated wastewater effluent other than status quo reuse amount is reused within the Valley, the energy requirements can be lowered by as much as 0.12 million MWh compared to status quo scenario by 2035 (9% reduction in energy use), sufficient enough to supply electricity for nearly 11,000 homes per year in the Unites States. However, the reuse rate is predicted to increase to 77 million cubic meters (MCM) (56 mgd) by 2020. This results in the decrease of energy use and associated emissions by nearly 3.6%. Similarly, change in population growth rate by ±0.5% can change the energy requirements and associated CO_2 emissions by nearly 12.8%. The combination scenario which includes water conservation, increase in reuse of treated wastewater effluent and increasing renewable resources in the fuel mix decrease the energy use by nearly 20.7% and associated emissions by nearly 46%, resulting to be the most efficient scenario.

Keywords: Water conveyance; Energy; Carbon footprint; Arid region; Las Vegas, NV

2.1 Introduction

Water is the most vital element for the growth and development of human civilization. So, ensuring its sufficient supply is essential for human well-being (Oki and Kanae, 2006). The demand for water has been increasing in many places with the growth in population and economic development (Morrison et al., 2009). The world population almost doubled from 3 billion to 6 billion during a 40 year period from 1959 to 1999.

Current world population is approximately 6.8 billion, and is expected to reach to 9 billion by 2035 (USCB, 2009). Satisfying the water needs of growing population requires increasingly large volumes of water.

The quality of existing freshwater sources is declining due to increasing water pollution as untreated wastewater is directly disposed into natural water sources in most of the developing countries (Eltawil et al., 2009; Von Uexkü̈ll, 2004). In addition, over exploitation of groundwater is affecting the quantity of freshwater availability (Eltawil et al., 2009). This has introduced the need for efficient and sustainable water production strategies to ensure the availability of current and future water needs. Sustainable water production refers to satisfying the current needs while ensuring the availability of water to meet the future needs as well (Darwish et al., 2008). For this, it requires that the rate of use of renewable water resources both surface and groundwater should not exceed the rate of their regeneration.

Water and energy are inextricably linked and both are equally important for economic and population growth (Lampe et al., 2009; Rio Carrillo and Feri, 2009). Water production involves extraction, treatment, transmission, distribution, use and disposal of water. This requires use of energy. Reduction in energy use is a major goal for sustainable development of water supply systems (Vieira and Ramos, 2009). Thus, water related energy use should be minimized. Because of the carbon footprint associated with energy generation, the rate of use of non-renewable energy resources (e.g. coal, oil, etc.) used in water production should not exceed the developing rate of their sustainable substitutes (Darwish et al., 2008). In order to maintain a safe and reliable water supply, environmental impacts of water production due to greenhouse gas emissions should be minimal (Darwish et al., 2008; Strutt et al., 2008).

With the growth in population and economic development, cities expand and require the transport of water from remote sources using storage and delivery infrastructures such as reservoirs, dams, aqueducts, pipelines and pumping stations. Many cities which could not be supported by their local water resources have bloomed in the desert with water transported from hundreds and even thousands of miles away (Gleick, 2001). Bringing water from long distance sources requires massive water production infrastructure and extensive use of energy. Vast amount of energy is consumed to extract, process, and deliver clean water (Morrison et al., 2009). In fact, electricity used for the purpose of water transport compared to treatment and distribution is the major source of greenhouse gases and the corresponding carbon footprint for water provision, which thereby contributes to global warming and climate change (Stokes and Horvath, 2009). The related energy consumption depends not only on the quantity of water but also on the topography of the distribution network (Bakhshi and Demonsabert, 2009; Pelli and Hitz, 2000;Reiling et al., 2009). Elevation and the distance from the water treatment plant play a significant role in the amount of energy consumption (Bakhshi and Demonsabert, 2009). In other words, the spatial distribution of water users from water sources is the chief energy use determinant (Pelli and Hitz, 2000). The energy consumption in water production accounts for the major expense in water systems with pumping energy cost being the higher (Vieira and Ramos, 2009).

Nearly 3-4% of the total US electricity use is for moving and treating water and wastewater (EPRI, 2002; Reiling et al., 2009; USDOE, 2006; USEPA, 2009a). Costs associated with energy or electricity use accounts for nearly 80% of municipal water processing and distribution costs (EPRI, 2002). On average, 85% of this electricity is used for pumping water in the distribution system, 9% for pumping raw water to the treatment plant and 6% for the treatment processes (Reiling et al., 2009). The reduction in energy use can have dual benefits: reduction in the cost of water and reduction in emissions of GHGs.

The use of energy contributes to carbon footprint. The carbon footprint is a measure of the total amount of greenhouse gases, expressed as carbon dioxide equivalents (CO_2e), that directly and indirectly result from an activity or are accumulated over the life stages of a product (Strutt et al., 2008; Wiedmann and Minx, 2008). The principal greenhouse gases entering the atmosphere due to human activities and contributing most to the carbon footprint are carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and fluorinated gases such as hydrofluorocarbons, perfluorocarbons, sulfur hexafluoride, etc. (Strutt et al., 2008; USEPA, 2010a). Each of these gases has different potential to trap the heat in the atmosphere, the least being CO_2. However, CO_2 is produced in such a large quantity that all greenhouse gases are converted into CO_2 equivalent (CO_2e) to ease the calculation of the total footprint of all gases. For a 100 year time horizon, the global warming potential for anthropogenic GHGs as compared to CO_2 is 21 for CH_4, 310 for N_2O, and for fluorinated gases it varies from 140 to 23,900 (Forster et al., 2007; USEPA, 2009b).

Since, the energy consumption required to move water from one location to another is the major contributor to carbon footprint, the efforts to lower carbon footprint mainly focus on the energy efficiency of water production (Strutt et al., 2008). Depending on the source of energy for electricity generation, the size of carbon footprint varies. For example, fossil fuels have the highest carbon footprint where as renewable technologies such as geothermal, hydroelectric, solar, wind, etc have the lowest. The carbon footprint related to water in the U.S. accounts for 5% of all U.S. carbon emissions (Griffiths-Sattenspiel and Wilson, 2009). The emissions due to water use are likely to increase in the future due to growing water demand, limited and remote locations of the freshwater sources, and stringent and energy intensive water treatment regulations and technologies (Griffiths-Sattenspiel and Wilson, 2009).

At present the Las Vegas Valley gets most of its water from Lake Mead in the Colorado River, which is 32.2 km (20 miles) southeast of the Las Vegas (Feroz et al., 2007). To move water from Lake Mead to the Valley requires nearly a lift of 365.8 meters (m) (1200 feet (ft)), which consumes huge pumping energy and has an associated large carbon footprint. The main objective of this research is to estimate energy use and carbon footprint of conveying water from Lake Mead to the Las Vegas Valley and to evaluate change in energy use and footprint due to changes in population growth rate, water conservation, increase in wastewater reuse, change in the Lake level, change in fuel sources, and change in emission rates.

2.2 Research Approach

The potable water system of the Las Vegas Valley, Nevada, USA is used in this research to demonstrate how water conservation policies, water reuse, and fuel sources affect energy and carbon foot print of water transport. The approach used here and the policies tested, however, have broader application to potable water systems throughout the world.

The Las Vegas is located in a semi-arid desert valley in Clark County in southeastern Nevada (Buckingham and Whitney, 2007; Gorelow and Skrbac, 2005). The Valley contains a drainage basin of about 4100 km^2 (1,586 square miles) and runs from Spring Mountains in the west to Lake Mead in the east (Stave, 2003). It receives an average annual precipitation of 10.4 centimeters (cm) (4.1 inches) (Cooley et al., 2007). The study area is shown in Figure 2.1.

The major water source for the Valley is Colorado River water passing through Lake Mead. Almost 90% of the water needs are met by Colorado River water (SNWA, 2009a). The remaining 10% comes from local groundwater sources (SNWA, 2010a). Nevada has the consumptive water use right of 0.4 km^3 (300,000 acre-feet) of Colorado River water per year (LVVWAC, 2009). Southern Nevada Water Authority (SNWA), which manages the water supply and distribution to local water agencies in the Las Vegas Valley, operates two intake systems to lift Colorado River water from Lake Mead to either of its two water treatment plants, the Alfred Merritt Smith Water Treatment Facility (AMSWTF) and the River Mountains Water Treatment Facility (RMWTF). Drought conditions have caused decline in the Lake Mead water level and is expected to decline even more in coming years (Barnett and Pierce, 2008; Feroz et al., 2007; USBR, 2010). The existing intake pumping station 1 cannot be in operation if the Lake levels fall below 320 m (1050 ft) above mean sea level (amsl) (Feroz et al., 2007). If Lake levels continue to decline as per the historic trend as shown in Figure 2.2, intake 1 may be out of operation before 2015. Thus, SNWA is building a third intake with design capacity of 53

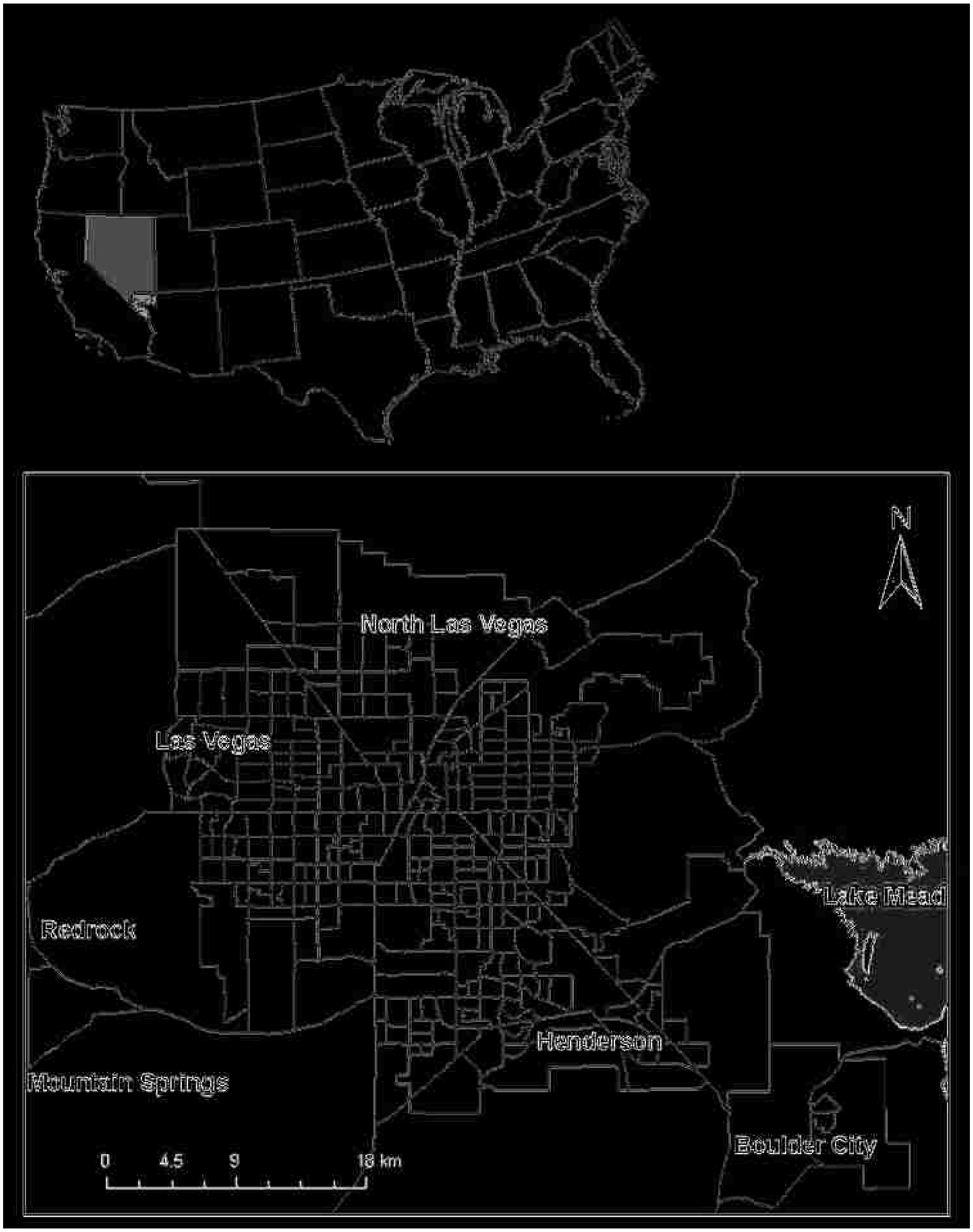


Figure 2.1: Study area: Las Vegas Valley located in Southern Nevada

cubic meters per second (m^3/s) (1,200 million gallons per day (mgd)) at an intake elevation of 305 m (1000 ft) amsl to assure the existing system capacity is kept if Lake levels fall below intake 1 (Feroz et al., 2007; SNWA, 2010b).

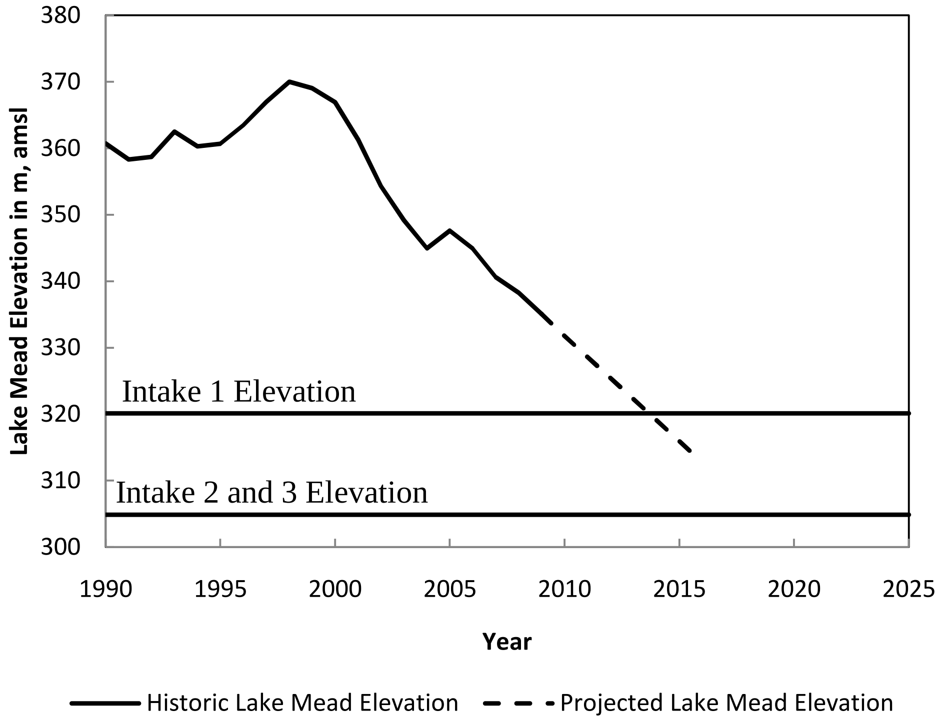


Figure 2.2: Lake Mead elevation as compared to intake elevations (SNWA, 2009b; USBR, 2010)

The schematic of water conveyance in the Las Vegas Valley is shown in Figure 2.3. Two major intake pumping stations and two booster pumping stations deliver water to the water treatment plants. The AMSWTF is designed to treat 26.3 m^3/s (600 mgd) and RMWTF can treat up to 13.1 m^3/s (300 mgd) (SNWA, 2010c). RMWTF is designed in such a way that it can expand to 26.3 m^3/s (600 mgd) to meet future water needs (SNWA, 2010c). The treated water from AMSWTF is transmitted to the Las Vegas Valley through

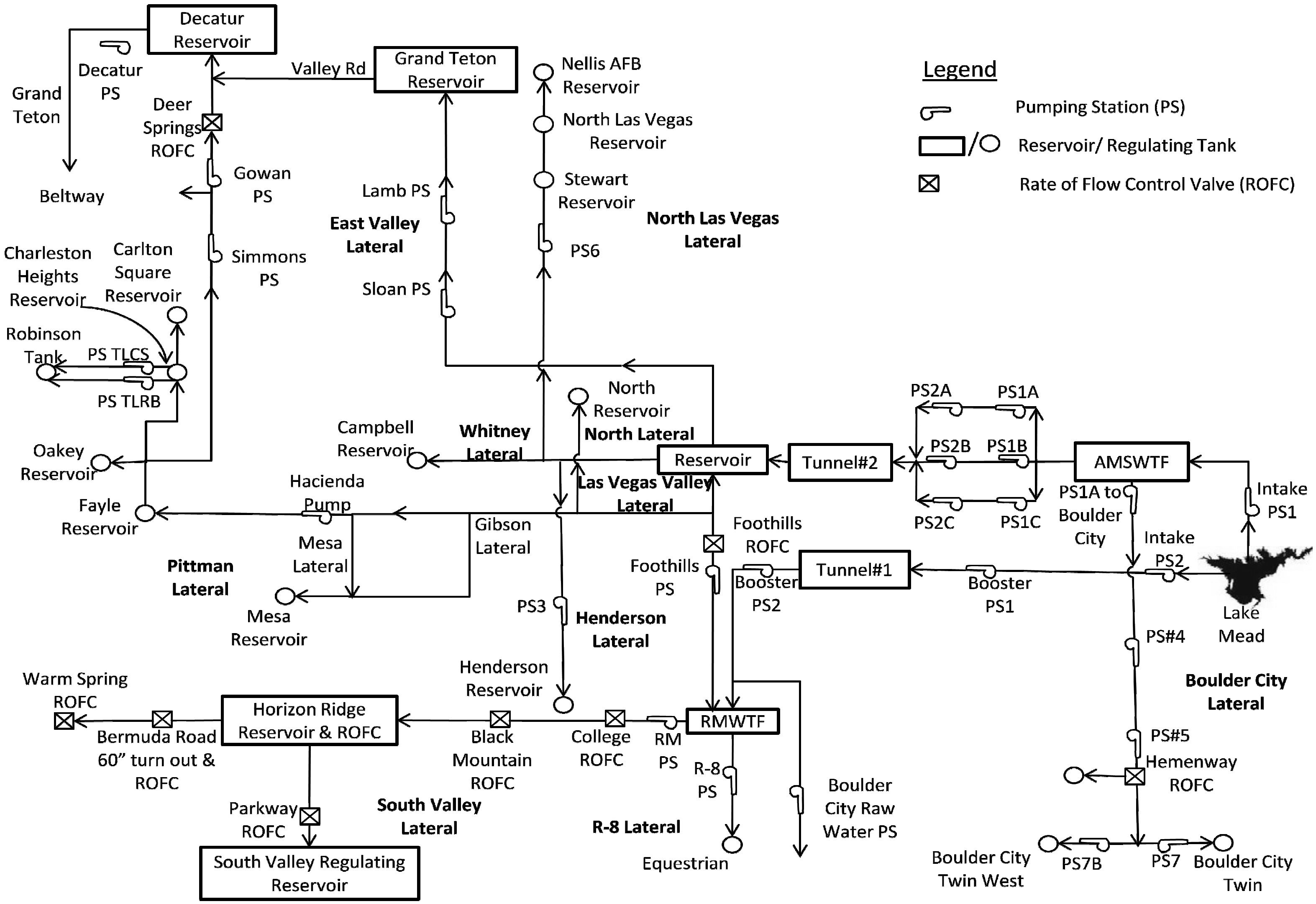


Figure 2.3: Schematic of water conveyance system in the Las Vegas Valley

five major laterals, namely, Boulder City lateral, East Valley lateral, North Las Vegas lateral, Pittman lateral and the Henderson lateral. The treated water from AMSWTF is also pumped to RMWTF through the Foothills pumping station when required. Similarly, treated water from RMWTF is distributed to the South Valley and R-8 laterals. In addition, untreated water from upstream of RMWTF is pumped to a golf course in Boulder City through Boulder City Raw Water pumping station. There are more than two dozen pumping stations at present to facilitate the conveyance of the treated water. The associated energy requirements and the corresponding carbon footprint of moving water are likely to increase in future because of increase in water demand due to population growth and the increased pumping head due to declining Lake level (static lift) and increased friction head (dynamic head).

The energy associated with pumping depends on the flow rate, pumping head, pump and motor efficiencies, and pump operating hours. The total dynamic head used in the calculation of pumping power incorporates only the head loss due to friction in the pipeline. The minor losses such as head loss at pipe bends, valves, etc. are not included in the calculation. Also, it is assumed that pumps are operated 90% of the time. The -energy calculation is only for moving water from the source to the distribution laterals. It does not include energy requirements for water moving in the potable water distribution system, or the energy requirements in the wastewater collection and treatment systems.

The water distributed in the Valley is either used indoors or outdoors. The water used outdoor for landscape or in golf courses irrigation, due to the arid environment, is lost to the atmosphere through evaporation and evapotranspiration, contributes to shallow subsurface soil moisture, or flows to the Las Vegas Wash as urban runoff (Stave, 2003).

The indoor used water is sent to one of the three wastewater treatment plants. The treated effluent from the wastewater treatment plants is returned back to Lake Mead through the Las Vegas Wash. The Las Vegas Wash also receives urban runoff and intercepted shallow groundwater flows that account for return flow credits.

According to Clark County Sewage and Wastewater Advisory Committee (SWAC) reports, 43% of the water supplied is currently used indoors, while 57% is used outdoors and is generally for landscape purposes. The indoor used water is treated in three wastewater treatment plants. Almost 90% of the treated effluent is discharged back into Lake Mead through the Las Vegas Wash while the remaining is used for landscape irrigation and cooling tower make-up water. Depending upon the amount of treated wastewater discharge, Nevada can actually withdraw more water than it is apportioned. This additional amount is known as return flow credits. The Las Vegas Wash flows are comprised of not only treated wastewater effluent, but also urban runoff, intercepted shallow groundwater, and stormwater. Nevada actually receives return flow credits only for the Colorado River water returned back to Lake Mead (LVWCAMP, 1999). Thus, return flow credits also account for Colorado River water contained in urban runoff and intercepted shallow groundwater due to over irrigation, also known as accruals or unmeasured returns, in addition to the treated wastewater effluent (LVWCAMP, 1999). However, Nevada does not get credits for returned stormwater and the Las Vegas Valley groundwater that ends up in the Las Vegas wash.

2.3 Method

A dynamic simulation model using system dynamics (SD) is developed to facilitate the computation of energy use and carbon footprint of water conveyance through major laterals in the Las Vegas Valley. For this purpose, the SD software Stella® (www.hps-inc.com) is used. Water resources management involves problems which often have long term effects and the complexity can be reduced by applying system dynamics (Winz et al., 2009). System dynamics is a method to understand behavior of complex systems over time, in which all objects interact with one another (Sterman, 2000).). It is an appropriate method to fill the gap between the nature of the problem and the ability to understand it (Richmond, 1993). It involves the formation of simulation models of complete systems over time in which the variable components are linked with each other through feedback loops (Spang, 2007). Simulation models play an important role to understand the behavior of complex problems addressed in water resources management. System dynamics simulation models have been used over the years to address the water resources management problems (Winz et al., 2009) including water consumption model to understand the system behavior due to water saving, wastewater reuse and water transfer (Zhang et al., 2009), a simulation model for municipal water conservation policy analysis (Prashar and Ahmad, 2010), decision-support model for community-based water planning (Tidwell et al., 2004) and for investigating water trading/leasing and transfer schemes (Gastelum et al., 2010), water balance model for irrigation management (Khan et al., 2009), reservoir operation model (Ahmad and Simonovic, 2000) and spatial system dynamics model developed by integrating system dynamics and geographic information system (Ahmad and Simonovic, 2004) for flood management, object-oriented model for water resources policy analysis (Simonovic and Fahmy, 1999), and a simulation model for public understanding of the importance of water conservation (Stave, 2003).

The SD model developed estimates the energy requirement and consequent carbon footprint of water supply and conveyance in the Las Vegas Valley and is comprised of three major sectors – water demand sector; water supply, distribution and wastewater collection sector; and carbon footprint sector. These sectors are directly or indirectly connected influencing the behavior of one another.

The water demand sector computes total water demand and demand fulfilled by Colorado River water based on the population and per capita water demand for the simulation period ranging from 2003 to 2035. The population includes only permanent population of the Valley and does not include tourist population. The permanent population in the year 2003 was nearly 1.6 million, which gradually increased to around 1.9 million in the year 2009 and is projected to reach approximately 3.2 million by the year 2035 (CBER, 2009). The historical annual population growth rate has averaged 3.4% per year between 2003 and 2009, and the average annual forecasted population growth rate is estimated to be 1.6% (CBER, 2009). The future population growth rate used in the model is in accordance with the CBER forecasted growth rate. However, the model allows for variation of the future population growth rate.

The per capita water demand in the Las Vegas Valley has decreased from 1,113 liters per capita per day (lpcd) (294 gallons per capita per day (gpcd)) in 2003 to 908 lpcd (240 gpcd) in 2009 (SNWA, 2009c), and it is expected to decrease to 753 lpcd (199 gpcd) by the year 2035 (SNWA, 2009a). The total water demand is a function of population and per capita water demand. The water demand to be fulfilled by Colorado River water is computed by subtracting the groundwater resource and wastewater reuse.

Water supply, distribution and wastewater collection sector is the main sector of the system that incorporates all the major pumping stations and computes the energy requirements. Water flow in the system shown in Figure 2.3 is captured in this sector along with the stocks and flows for water use in the Valley, wastewater collection, water reuse and discharge of treated effluent back into the Lake Mead.

Carbon footprint sector calculates the associated carbon footprint of moving water in the system based on the energy source used in pumping water. Since, the source of energy used in the water conveyance system in the Las Vegas Valley has changed over time, the state of Nevada's energy mix from 2003 to 2007 is used to calculate the historic carbon footprint of the water conveyance system in the Valley. For 2008 and later years, the 2007 Nevada's energy mix is used as it is the latest available. However, the model provides the flexibility of varying state's future energy mix. The electric power sources for the state of Nevada until 2006 were coal, natural gas, petroleum, hydroelectric power, and geothermal (USEIA, 2009). In 2007, solar/PV provided 0.13% of the state's electric power supply as shown in Table 2.1.

The total carbon footprint is then calculated using the CO_2 emission rates. The emission rates vary depending upon the electricity generating plant efficiency, its technological options and carbon/heat content of the fuel when electricity generation is due to direct combustion of fuel (Evans et al., 2009; Weisser, 2006). The range of emission rates in gram CO_2e per kilowatt hour (g CO_2e/kWh) based on different studies is shown in Table 2.2. For the purpose of this study, the average of the emission rates obtained from literature review, as listed in Table 2.2, is used to calculate the total carbon footprint of the system.

Table 2.1: 2003 and 2007 electricity source distribution for the state of Nevada (USEIA, 2009)

Source	**Percent of total electric power sector consumption in**	
	2003	**2007**
Coal	52.67	25.95
Natural Gas	35.26	58.59
Oil	0.06	0.03
Hydro	5.35	6.57
Geothermal	6.66	8.73
Solar/PV	-	0.13

Different scenarios are evaluated to compare and quantify the energy use and CO_2 emissions associated with moving water in the Las Vegas Valley distribution laterals. A status quo scenario is simulated to provide a baseline for comparison of different policy options. The effects on energy and associated CO_2 emissions due to various scenarios are evaluated. The scenarios include (i) Status quo, (ii) Change in estimated population growth rate, (iii) Water conservation, (iv) Water reuse increase (v) Change in the Lake level, and (iv) Combination of multiple scenarios.

Status quo relates to the water transport to the Las Vegas Valley from the Lake Mead as it is currently, that is water is pumped from a static lift of nearly 365.8 m (1200 ft) and a distance of 32.2 km (20 miles). Approximately 57% of the water pumped into the Valley is used for landscape irrigation and is lost to the soil and to the air through infiltration and evapotranspiration. About 43% of the water used indoors ends up as wastewater. The wastewater is treated and returned back to the Lake Mead.

The change in estimated population growth rate scenario involves the change in forecasted population growth rate by ±0.5%. The decrease in population growth rate would lower the water demand and less water would have to be pumped from the Lake Mead and vice versa. Water conservation by reducing indoor or outdoor water use can save significant amounts of energy.

The water reuse increase scenario involves using the treated wastewater effluent within the Valley, for example as landscape and golf courses irrigation water. If treated wastewater is reused within the Valley, then less fresh water would be required to be pumped from the Lake Mead, lowering the pumping energy requirements and associated carbon footprint.

The change in the Lake level affects the static lift from the Lake Mead for the intake pumping stations. The lower the lake level, higher the pumping head and higher pumping energy requirements and CO_2 emissions as its consequence. The level below which intake pumping stations will not be in operation is not considered in this study.

A combination of multiple scenarios including water conservation, increase in reuse of treated wastewater effluent within the Valley and increase in the use of renewable energy sources is also evaluated. According to USEIA (2009), the percent use of renewable energy source for electricity generation is nearly 15% for Nevada and 54% for California. The increase in renewable energy sources for Nevada to 50% (nearly equal to that of California) is assumed to see the variation in the footprint.

Table 2.2: CO_2 emission rates in g CO_2e/kWh for different energy sources

Reference	**Fuel type**								
	Coal	**Oil**	**Natural gas**	**Solar/PV**	**Hydroelectric**	**Wind**	**Nuclear**	**Biomass**	**Geothermal**
USEPA, 2010b	1005.2	212	433	-	-	-	-	-	-
Evans et al., 2009	1004	-	543	90	41	25	-	-	170
Varun et al., 2009	-	-	-	9.4-300	18-74.88	16.5-123.7	-	-	-
Fthenakis and Kim, 2007	-	-	-	17-49	-	16-55	-	-	-
Weisser, 2006	750-1250	500-1200	360-780	43-73	1-34	8-30	2.8-24	35-99	-
Dones et al., 2005	-	-	485-990	-	-	-	5-12	-	-
Hondo, 2005	975.2	742.1	518.8-607.6	26-53.4	11.3	20.3-29.5	22.2-24.2	-	15
Meier et al., 2005	1006	742	466	39	18	14	17	46	15
Dones et al., 2003	949-1280	519-1190	485-991	79	3-27	14-21	8-11	92-156	-
Sample Size	8	7	11	11	9	12	9	5	3
Average	1022.9	779.6	605.9	70.8	25.4	31.1	14	85.6	66.7

2.4 Results

The SD model is developed to analyze energy requirements and associated carbon footprint as its consequence to move water in the conveyance system of the Las Vegas Valley. Before any policy is analyzed, the model should be verified against the observed data. Model verification provides a sense of credibility and confidence that the model is based on some level of reality and is able to replicate the historic behavior. The 7 year period from 2003 to 2009 is used as a verification period in the model and the 26 year period from 2010 to 2035 is used as a planning horizon with a yearly time step. The model was able to accurately replicate the historic population trend. The historic population data was obtained from Clark County Department of Comprehensive Planning, Demographics (www.accessclarkcounty.com).

In a similar way, the model simulation for water demand of the Las Vegas Valley was comparable to historic water demand of the Valley. For the comparison, the historic water demand data was obtained from SNWA (2009c). The model was also tested for extreme conditions. Extreme condition tests check if the behavior of the model is appropriate when the extreme values are provided as an input (Sterman, 2000). Some of the extreme condition tests included zero population, no change in population and zero Lake level. In all these tests, the model behavior was as anticipated.

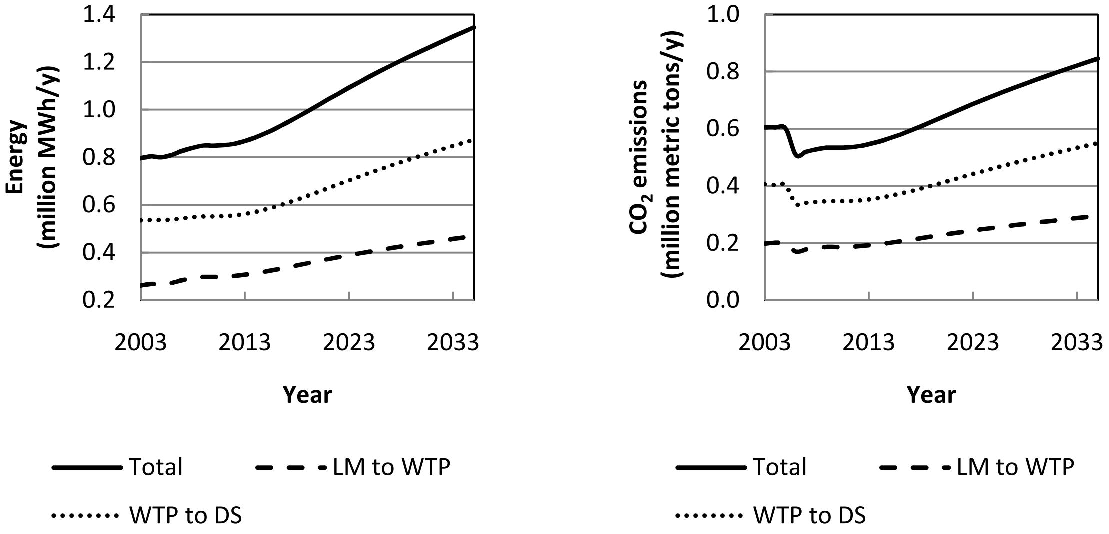
2.4.1 Status Quo

For the status quo scenario, it is assumed that the population varies as predicted by CBER and the per capita demand is assumed to remain constant at 908 lpcd (240 gpcd) as in 2009 and onwards. Also, of the total water supplied, 43% is used indoors while the remaining is used outdoors. The reuse flow rate of treated effluent from wastewater treatment plants is assumed to remain constant at nearly 30 million cubic meter (MCM) (22 mgd) in the year 2009 and onwards and assumed to remain constant onwards. The remaining treated effluent is returned back to Lake Mead through the Las Vegas wash. The supply of water is assumed to be unlimited. The Lake level does not fluctuate. There is no variation in the state's fuel source for electricity. The same assumptions are used for other scenarios as well unless otherwise mentioned. Some of these assumptions are later explored through sensitivity analysis.

For status quo scenario, Figure 2.4 shows the total energy and associated carbon footprint for moving water from source to the conveyance system in the Valley, and also in the disaggregate form in terms of moving water from source to water treatment plants and then from water treatment plants to the conveyance system of the Valley. The total energy consumption in the year 2009 is nearly 0.85 million MWh enough to light nearly 77,000 homes on average for a year in the US, based on an average annual electricity consumption of 11,040 kWh for a US residential home in 2008 (USEIA, 2010)..

It requires approximately 35% of the total energy use, on average, to lift water from Lake Mead to the water treatment plants. There are only four pumping stations for this purpose. As compared to more than 2 dozen pumping stations in the distribution system, 35% of the total energy only to lift water from source to water treatment plants is substantial.

There is a gradual rise in energy consumption from the historical period and the trend continues in the future as well. This is because demand for water has been increasing and is predicted to grow and the energy consumption is directly proportional to the water demand. The CO_2 emissions are based on the state's electricity mix and the emission rates for each energy source (Table 2.2). The CO_2 emissions gradually increased with each year till 2005 when there was a sudden drop of approximately 0.09 million metric tons of CO_2 (nearly 15.5% drop) although the energy consumption during that period increased by 1.3%. This is due to the fact that in the year 2005, the coal consumption rate was decreased by nearly 45% and in turn the consumption rate of natural gas was increased approximately by the same amount. There was not much variation in the total energy consumption; however, because coal has higher CO_2 emission potential as compared to natural gas (Table 2.2), there was a decrease in the total CO_2 emission by nearly 0.09 million metric tons.



(a) Energy

(b) CO_2 emissions

Figure 2.4: Energy for moving water from Lake Mead (LM) to water treatment plant (WTP), from WTP to distribution system (DS), and total energy for the whole system, and corresponding CO_2 emissions

The emission of greenhouse gases depend on the carbon content of the fuel, fuel categories such as black coal, brown coal, etc., electricity generation technologies such as steam turbine, open cycle gas turbine, combined cycle gas turbine, etc., thermal efficiency of fuel and plant capacity factor (IPCC, 2000; Lenzen, 2008). It can also vary based on locations. So, the use of average emission rate based on different literature review (Table 2.2) may not be a realistic scenario. To account for the uncertainty associated with it, a model scenario is run many times (thousand), each time with an uncertain emission factor chosen randomly by the model within the distribution of uncertainty specified initially to calculate the total CO_2 emissions for water distribution (IPCC, 2000). A uniform distribution is chosen for the purpose because there is no useful information available on the distribution of emission factors (Winiwarter, 2001). Figure 2.5 shows the box plot of the range of total CO_2 emissions associated with the water production in the Las Vegas Valley due to change in emission factor. The centre line in the rectangular box represents the median of the data set. The upper and lower lines of the rectangular box stand for the third quartile (75th percentile) and first quartile (25th percentile), respectively. The lines that extend from the rectangular box, also known as whiskers, give the minimum and maximum value of the data set. The CO_2 emissions can vary between 0.73 million metric tons/y (first quartile) to 1.02 million metric tons/y (third quartile) in 2035.

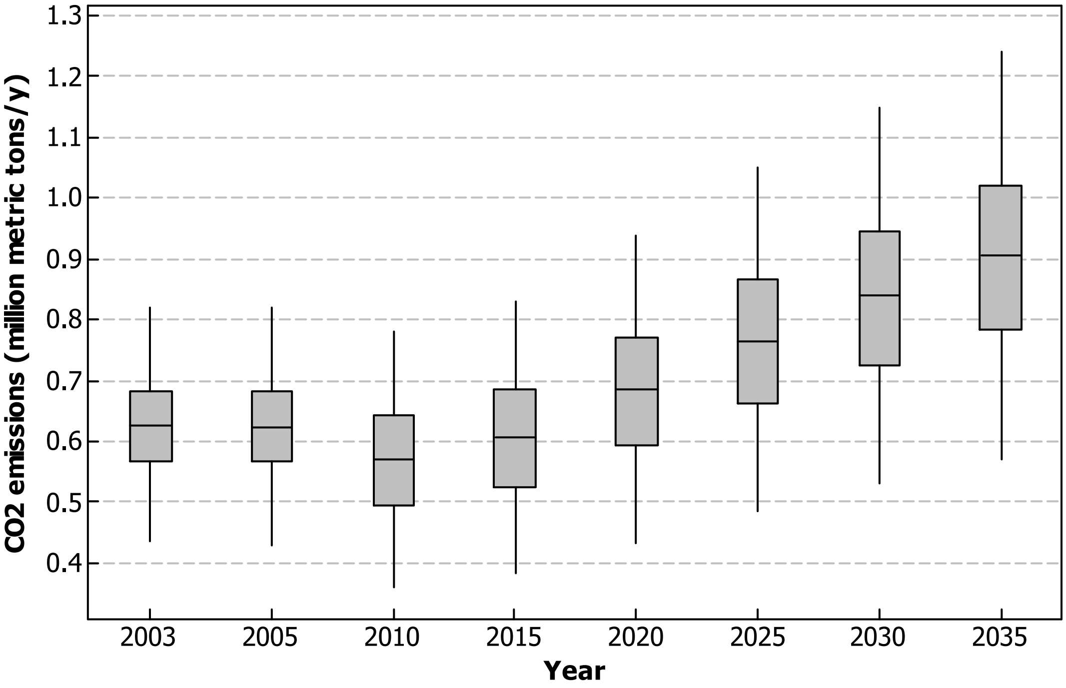


Figure 2.5: Box plot of total CO_2 emissions

Figure 2.6 shows the CO_2 emissions due to each source of energy. The total CO_2 as shown in Figure 2.4(b) is due to the aggregation of CO_2 due to individual energy sources in accordance with the state's electricity mix. The non-renewable energy sources are the major contributors of total CO_2 emissions except oil. The emission due to oil consumption and other renewable resources are almost negligible. The use of oil for electricity generation as compared to other sources is quite small.

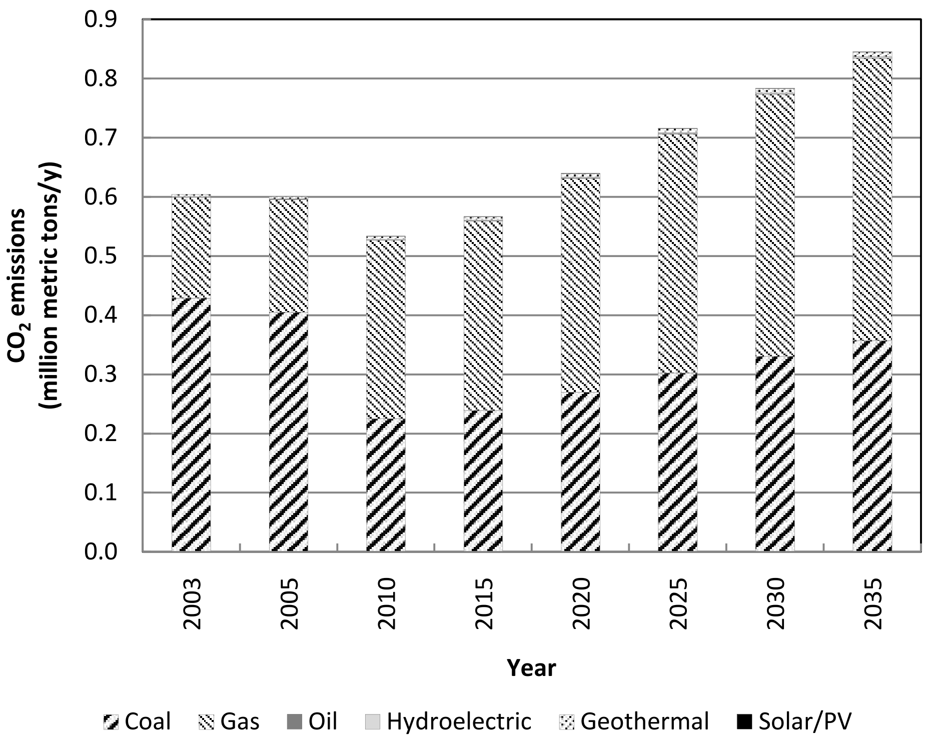


Figure 2.6: CO_2 emissions due to each source of energy

According to current electricity resource mix for the state of Nevada, nearly 85% of the total resource mix comprise of non-renewable resources (coal, oil and natural gas while the remaining comes from renewable resources (solar, geothermal and hydroelectric). To compare CO_2 emission due to change in resource mix, a model simulation was carried out varying the contribution of non-renewable resources in the generation mix from 100% to 0% and correspondingly the percent contribution due to renewable resources. The change in CO_2 emissions are shown in Figure 2.7. The use of 100% renewable resources may not be a completely realistic scenario from an operational point of view, but if the resource mix change such that the percent contribution due to non-renewable and renewable resources is equal (50%), it results in the decrease of total CO_2 emissions by nearly 31.7% (0.27 million metric tons/y) by 2035.

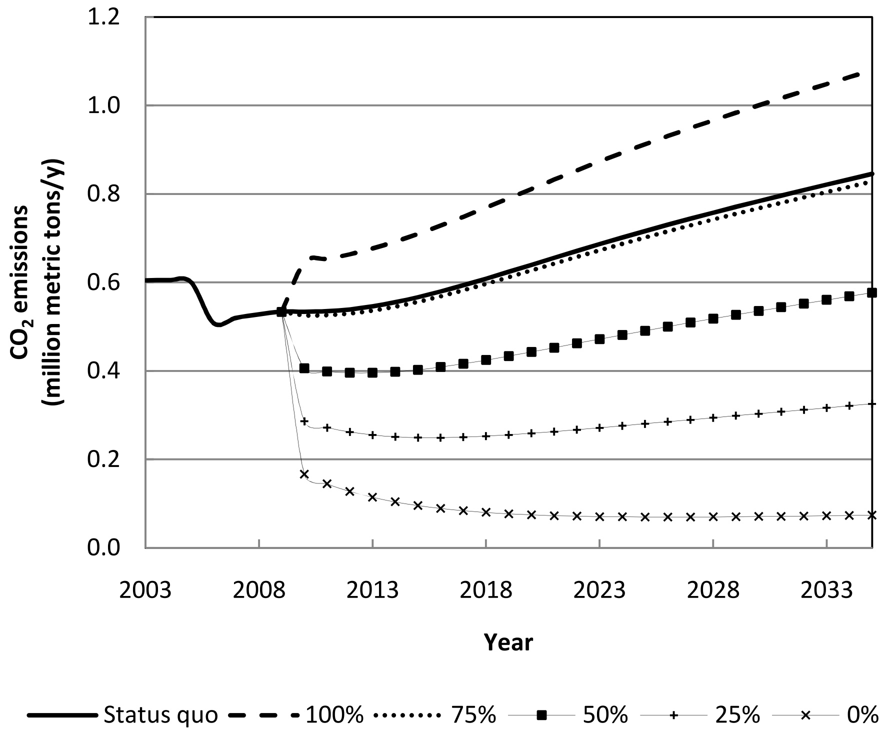
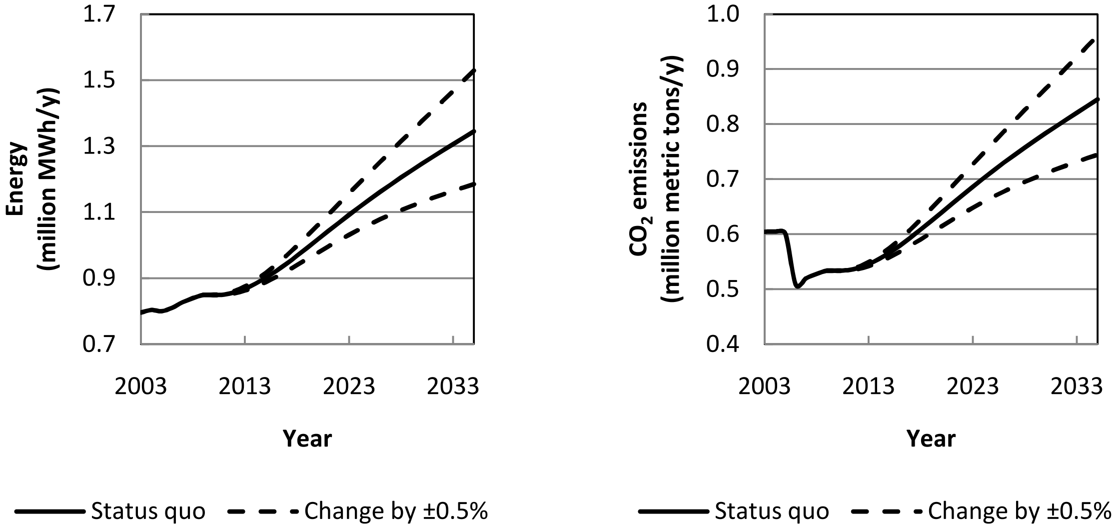


Figure 2.7: CO_2 emissions in Nevada due to varying non-renewable resource contribution in the total resource mix

2.4.2 Change in Estimated Population Growth Rate

If the population grows as predicted by CBER, by 2035 it will require nearly 1.3 million MWh/y of energy to move water from source to the distribution system and result in the release of nearly 0.84 million metric tons of CO_2 per year as its consequence as shown in Figure 2.8. If the predicted population growth rate is varied by ±0.5%, the energy and associated CO_2 varies by 12.8% on average. This means that even a 0.5% change in predicted population growth rate could lower or augment the energy requirements by 0.17 million MWh/y (adequate to light nearly 15,400 homes for a year in the US) or 0.11 million metric tons of CO_2 per year by 2035. A 0.5% change in estimated population growth rate results in change in population by 0.41 million as compared to 3.1 million status quo population in the year 2035.

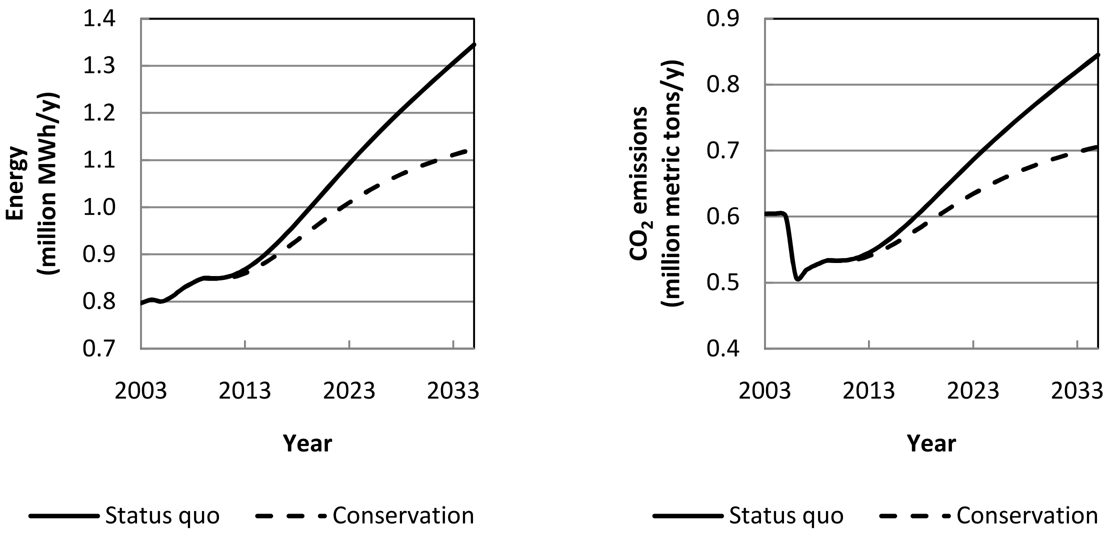


(a) Energy (b) CO_2 emissions

Figure 2.8: Energy and corresponding CO_2 emissions when annual population change rate is increased or decreased by 0.5% in the Las Vegas Valley

2.4.3 Water Conservation

The per capita water demand has decreased from 1,113 lpcd (294 gpcd) in the year 2003 to 908 lpcd (240 gpcd) in the year 2009 and the goal is to further decrease it to 753 lpcd (199 gpcd) by the year 2035. Figure 2.9 shows the energy and corresponding CO_2 emissions assuming that the conservation goal of 753 lpcd (199 gpcd) water demand is fulfilled by the year 2035.



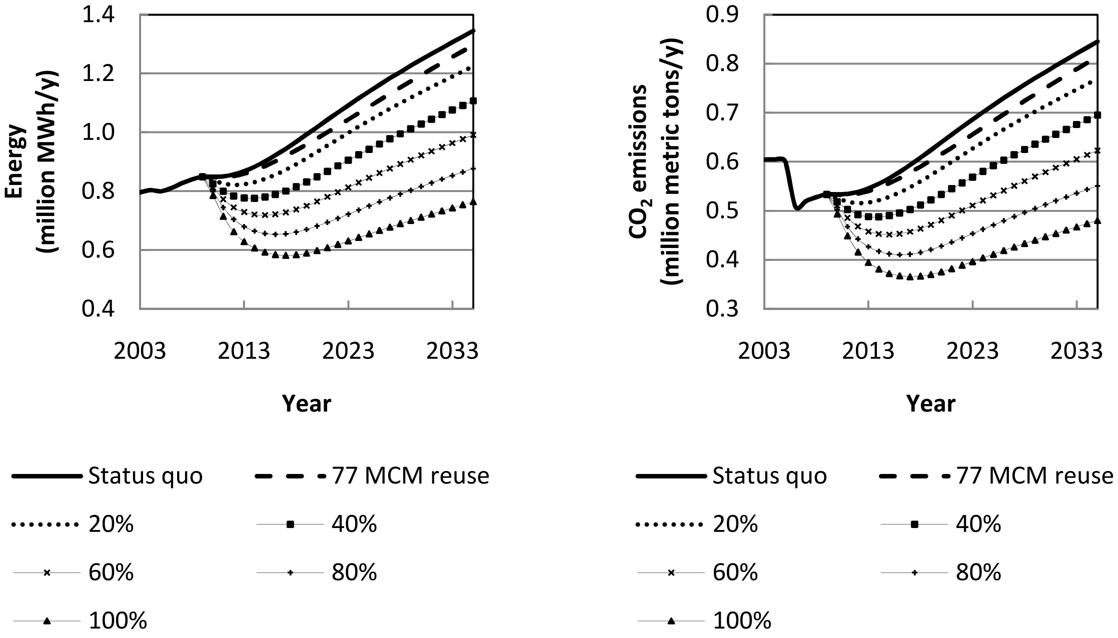
(a) Energy (b) CO_2 emissions

Figure 2.9: Energy and associated CO_2 emissions for indoor and outdoor conservation scenario

Water conservation decreased the energy requirements by 16.5% as compared to the status quo scenario. This corresponds to as much as 0.22 million MWh/y (adequate for nearly 20,000 US homes for a year) energy or 0.14 million metric tons of CO_2 per year.

2.4.4 Water Reuse Increase

On average, 10% of the treated effluent from wastewater treatment is reused. However, the reuse of treated effluent has increased from 25 MCM (18 mgd) in 2003 to nearly 30 MCM (22 mgd) in 2008 and is expected to reach 77 MCM (56 mgd) by 2020 (CCN, 2000). Figure 2.10 shows the energy requirements and associated CO_2 emissions for the cases due to change in reuse rates. In 77 MCM reuse scenario (Figure 2.10) it is assumed that the reuse rate will vary gradually from 30 MCM (22 mgd) in the year 2009 to 77 MCM (56 mgd) by 2020 and remain constant onwards. This results in the decrease of energy use and associated CO_2 emissions by nearly 3.6% by 2035. The energy use is decrease by nearly 0.05 million MWh/y (sufficient for nearly 4,500 US residential homes on average) and associated CO_2 emissions by nearly 0.03 million metric tons/y. The other scenarios are for reusing treated effluent other than status quo reuse amount at the reuse rate varying from 20% to 100% reuse. For example, reusing 20% of the treated wastewater (nearly 127 MCM or 92 mgd) within the Valley can reduce the energy requirements and the CO_2 emissions by nearly 9% by 2035 as when compared with the status quo. This is a total decrease in energy consumption by 0.12 million MWh/y (enough to light 11,000 US homes on average for a year) and associated CO_2 emissions by 0.08 million metric tons/y.



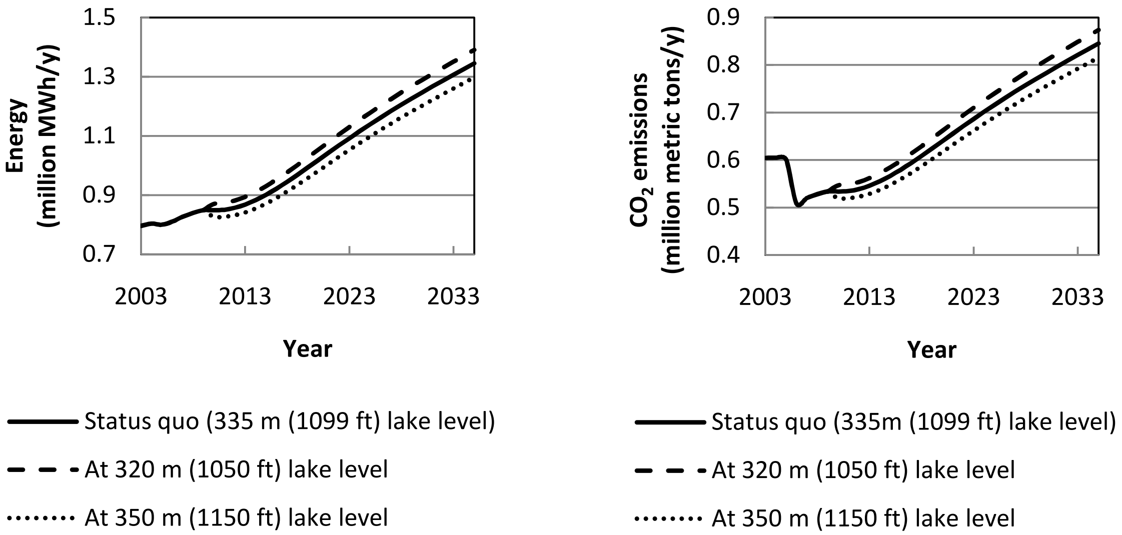
(a) Energy

(b) CO_2 emissions

Figure 2.10: Energy and CO_2 emissions when reuse is varied from 77 MCM reuse by 2020 to 100% reuse at an increase interval of 20%

2.4.5 Change in the Lake Level

The Lake level has been continuously declining since 1997 (Figure 2.2). If the Lake level declines to 320 m (1050 ft), the level below which intake 1 will be out of operation, the total energy requirements as compared to status quo (335 m (1099 ft) Lake level) will increase by 3.3%. Also, the CO_2 emissions will increase by the same rate. Likewise, the rise in lake level to 350 m (1150 ft) will alter the energy and CO_2 emissions by same ratio (Figure 2.11).

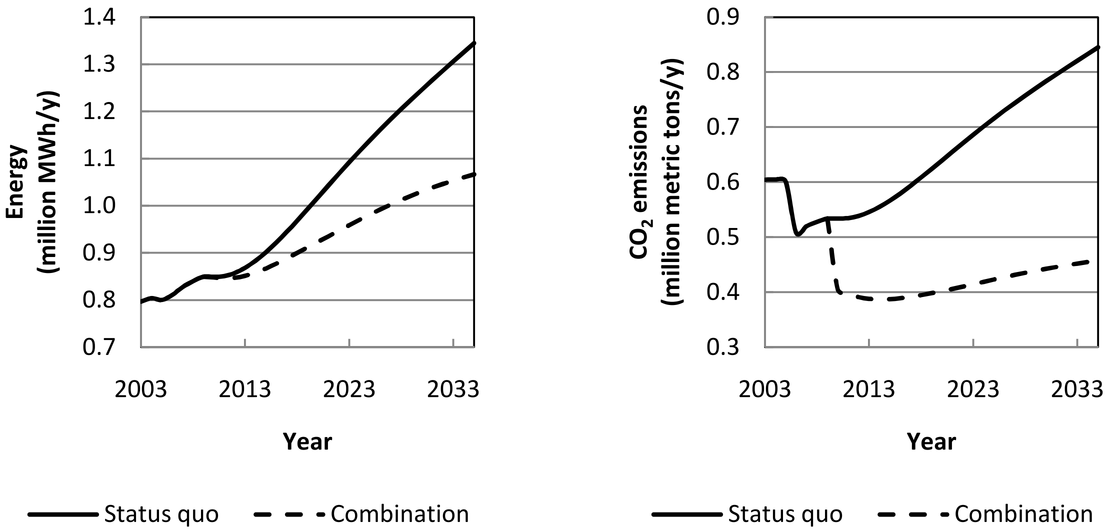


(a) Energy (b) CO_2 emissions

Figure 2.11: Energy and CO_2 emissions when Lake level is altered

2.4.6 Combination Scenario

Combination scenario involves water conservation to 753 lpcd (199 gpcd) by 2035, reuse increase to 77 MCM (56 mgd) by 2020 within the Valley and change in fuel mix such that 50% of the total resource mix is due to non-renewable resources and remaining 50% is due to renewable resources. The result shown in Figure 2.12 illustrate that the combination of these scenarios results in the decrease of energy use by 20.7% (0.28 million MWh/y) and associated CO_2 emissions by 46% (0.39 million metric tons/y) as compared to the status quo scenario adequate to light nearly 35,300 US homes on average for a year.



(a) Energy

(b) CO_2 emissions

Figure 2.12: Combination of scenarios - water conservation, increase in reuse of treated wastewater, and increase in use of renewable energy sources

2.4.6 Summary of Results

The summary of results due to above mentioned scenarios are shown in Table 2.3. The values reported are for the year 2035.

Table 2.3: Summary of results

Scenario	**Energy (million MWh/y)**	**CO_2 emissions (million metric tons/y)**	**Percent change from status quo**
Status Quo	1.34	0.84	
Change in Estimated Population Growth Rate			
+0.5%	1.53	0.96	±12.8%
-0.5%	1.18	0.74	
Water Conservation	1.12	0.71	-16.5%
Water Reuse Increase to 77 MCM by 2020	1.3	0.81	-3.6%
Change in the Lake Level			
+15m	1.3	0.82	±3.3%
-15m	1.39	0.87	
Change in Resource Mix as 1:1 Non-renewable to Renewable resource	1.34	0.58	(-31.7%)
Combination Scenario	1.07	0.46	-20.7% (-46%)*

*The number in parenthesis is for CO_2 emissions for respective scenario

2.5 Discussion

A system dynamics model was developed to analyze the energy requirements for water conveyance in the Las Vegas Valley and carbon footprint of the system as its consequence. This study explored the relationship of energy for water and associated CO_2 emissions. The model simulations showed that a significant amount of energy is required to satisfy the water needs of the Las Vegas Valley and it will increase substantially (nearly 58%) by the year 2035, provided that the population growth is as predicted by CBER. Similarly, CO_2 emissions will rise to 0.84 million metric tons by 2035 (58% increase). Considerable amount of energy is required to pump water from Lake Mead to water treatment plants. It comprised nearly 35% of the total energy requirements for water production in Nevada, unlike US average of 9% for pumping raw water to the treatment plant. However, the major portion of total energy requirement is consumed to move treated water in the distribution system (65%). In California, the water related energy use is 19% of the states' total energy use which includes energy for conveyance, storage, treatment, distribution, wastewater collection, treatment and discharge (CEC, 2007).

Population growth rate change scenario indicated that the change in population growth rate by even 0.5% (±0.41 million) can change the energy and CO_2 emissions by 12.8% as compared to status quo (3.1 million). Likewise, change in the Lake levels considered in this study did not vary the energy requirements and CO_2 release by significant amount. But conserving water resulted in 16.5% reduction in energy consumption and associated CO_2 emissions. Reducing water use can lower energy consumption by significant amount. For instance, Natural Resources Defense Council (NRDC) (2004) reported that applying water conservation measures in San Diego can save enough energy to provide electricity for 25% of all of the households in San Diego.

Increasing the reuse rate of treated wastewater effluent within the Valley can lower the energy requirements and associated CO_2 emissions of moving water in the Las Vegas Valley by considerable amount. However, the increase in reuse to 77 MCM (56 mgd) by 2020 within the Valley lowers the energy use by only 3.6%, sufficient enough to light approximately 4,500 US homes on average for a year based on an average annual electricity consumption of 11,040 kWh for a US residential home in 2008 (USEIA, 2010). Reusing water is far less energy intensive than transporting water from distant source locations. A water recycling system in Orange County in California uses only half the amount of energy required to transport the same volume of water from northern

California (NRDC, 2004). This results in the reduction of CO_2 emissions by 79% which is equivalent to taking nearly 500 cars off the road for a year (Taffler et al., 2008).

The combination of multiple scenarios including water conservation, increase in reuse of treated wastewater within the Valley and increase in the use of renewable sources decreased the energy requirements by nearly 20.7% and associated CO_2 emissions by about 46%. This is the reduction in energy and associated CO_2 emissions by approximately 0.28 million MWh/y and 0.39 million metric tons/y, respectively when compared with the status quo scenario. The combination scenario appears to be the most energy efficient scenario. However, it is just a hypothetical scenario and the subsequent change in water demand, reuse rates and fuel sources is difficult to achieve.

This study focuses mainly on the energy consumption and CO_2 emissions as its consequence in moving water in the Las Vegas Valley. Due to lack of data availability, some of the parameters are not included in the study. For instance, in this study, the flow in each of the pumping stations is based on the water demand, capacity of water treatment plants and capacity of reservoirs in the distribution system. The accurate prediction of energy requirements in each of the pumping stations could have been achieved if the water flow equations were developed based on the historical or actual flow at these stations. Also, the total dynamic head calculation required for power calculation included only head loss due to friction. Minor losses were ignored.

Electricity mix for state of Nevada was considered in determining the energy source which comprised 85% non-renewable resources and 15% renewable resources. According to the Renewable Portfolio Standard (RPS), the percent share of renewable energy by 2025 should be 25% of the total energy use in Nevada (www.leg.state.nv.us).

This can be achieved by developing renewable resources which include but are not limited to biomass, fuel cells, geothermal energy, solar energy, hydropower and wind. However, the switch to renewable resources such as solar energy makes use of water as a cooling agent, thus increasing stress in water scarce region such as arid American southwest. Hence, the consideration of actual source of energy for electricity to be used in water conveyance system along with their possible consequences will provide more accurate estimate of the CO_2 emissions. Moreover, this study considers only operational energy requirements. The complete life cycle energy analysis is beyond the scope of this research. The consideration of life cycle energy requirements will result in more accurate emission analysis because emissions can be both direct and indirect. Direct emissions are those that are released during the operation phase, while indirect emissions refer to those that are emitted during non-operational phase of the plant life cycle. The life cycle energy analysis for power plant sector will include the energy associated in the extraction, processing and transportation of fuels, building of power plants, production of electricity, waste disposal and finally decommissioning of the plant at the end of its life.

2.6 Conclusions

Water management decisions should consider energy to improve the resource management. The reflection of critical link between water and energy in water planning and policy can lead to significant energy saving and reduction in the CO_2 emissions associated with it. Water production requires energy. Energy production contributes to carbon footprint, the leading cause of global warming. Climate change in turn has greater potential to affect water supply. In Nevada, climate change may lead to greater risk of drought or water shortages. Thus, the integration of energy issues into water policy decision making is important.

The conveyance of treated water in the distribution laterals dominates the energy use for water provision in the Las Vegas Valley. Saving water can be an excellent way to save energy and reduce CO_2 emissions. Conservation eliminates the energy required to pump, move and treat fresh water from the source and also the energy required to collect it as wastewater, treat and dispose or reuse. In addition, the reuse of treated wastewater effluent within the Valley also appear to be an energy efficient water source because this would also eliminate the water transport energy requirements from source to the reuse points.

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CHAPTER 3

COMPARING DESALINATION VERSUS WATER CONVEYANCE FROM DISTANT LOCATIONS FOR CARBON FOOTPRINT AND COST

Abstract

The increasing water demand due to population and economic growth; and pollution and over exploitation of existing surface and groundwater sources has forced water providers to look for alternative sources of water supply. Almost 97% of the earths' water is seawater. So, one of the potential and promising water supply options is seawater desalination by reverse osmosis. Since, reverse osmosis is a pressure driven membrane technology, it has high operational energy requirements and more greenhouse gas emissions are associated with it. However, for water stressed cities not located in coastal regions, seawater desalination may not be a feasible option. One option to satisfy the water needs for inland cities is to transport water from remote water source locations using water conveyance infrastructures including pipelines, pumping stations, regulating tanks, etc. This study compares the cost and the carbon footprint of two potential water supply options: seawater desalination and groundwater transport from remote locations using conveyance infrastructures. System Dynamics modeling, using the Software Stella, is used in the evaluation, employing the water resources system and future needs of the arid Las Vegas Valley, located in Nevada, US as an example case. The cost analysis is done for whole life (50 years) of the facility. Since, Las Vegas is not a coastal city, the seawater desalination supply option for the Valley is actually a paper- transfer agreement between Nevada and California or Mexico in which Nevada will build a desalination plant in the Pacific Ocean of California or Mexico and in turn will be allowed to withdraw an equivalent amount of water from Lake Mead in the Colorado River. The conveyance option involves pumping water from the northern Nevada counties, located 421 km away, to the Las Vegas Valley. The analysis showed that the energy for the seawater desalination option (0.53 million MWh/y) is 96% higher as compared to the water conveyance (0.27 million MWh/y). Similarly, associated CO_2 emissions for seawater desalination supply option (0.25 million metric tons/y) is 47.5% higher than water transport option (0.17 million metric tons/y). However, the unit cost of water by seawater desalination option is lower ($0.56/m^3) compared to water transport option ($0.68/m^3) because desalination plant is built in phases and requires lower initial capital cost as compared to the capital cost for water conveyance infrastructures.

Keywords: Desalination; Water transport; Energy; CO_2 emissions; Cost; Las Vegas; System dynamics

3.1 Introduction and Objectives

Water systems are major users of energy and as a consequence produce greenhouse gases. Energy is consumed in every step of water production. Energy is required to transport water from remotely located water sources, or pump water stored in groundwater aquifers, and also required to treat it to meet stringent drinking water regulations (Gleick, 1994). The use of energy contributes to carbon footprint of water production. The carbon footprint is the measure of total quantity of greenhouse gases, expressed as carbon dioxide equivalents (CO_2e), that directly and indirectly result due to an activity or is accumulated over the life stages of a product (Strutt et al., 2008; Wiedmann and Minx, 2008).

The water related energy demand has been increasing with the growth in population at most places. Moreover, pollution and over exploitation of groundwater aquifers and surface water; industrial and agricultural growth; higher living standards; and droughts are exerting stress on fresh water resources, requiring water managers to look for alternative and sustainable water supply options, which are more energy intensive (Agus and Sedlak, 2010; Fritzmann et al., 2007). Some of the supply options to meet the increasing water needs include desalination of seawater or brackish water, water transport from distant water source locations, application of water conservation measures and reuse of wastewater. Desalination and water conveyance from distant locations are two potential options to increase supply.

Desalination is one of the alternative water sources gaining popularity as a feasible option for potable water production (Oh et al., 2009). A number of desalination technologies have been developed over years and they can be classified based on their separation mechanism as phase-change/thermal and membrane processes (Gilau and Small, 2008; Zhou and Tol, 2005). Some of the thermal desalination technologies include multi-stage flash distillation (MSF), multi-effect distillation (MED), vapor compression distillation (VCD), freezing, humidification/dehumidification and solar stills. The membrane processes comprise reverse osmosis (RO), nanofiltration (NF), and electrodialyis (ED). Of these technologies, MSF and RO are the most widely used technologies (Fritzmann et al., 2007). At present, high pressure RO is the most preferred technology for seawater desalination (Akgul et al., 2008; Darwish and Al-Najem, 2000).

Nearly 97% of the earth’s water stored in the ocean is too salty for anthropogenic uses with total dissolved solids (TDS) concentration more than 30,000 milligrams per litre (mg/l) (Zhou and Tol, 2005). In the United States, drinking water regulations require TDS concentration to be less than 500 mg/l (USEPA, 2009). Hence, converting salty water for potable use using RO desalting technology requires intensive use of energy (Atikol and Aybar, 2005; Gilau and Small, 2008). Energy consumption for seawater desalting depends on several factors including feed water salinity concentration, physical and chemical characteristics of feed water, type of energy recovery system, operating conditions, location of the desalination plant, and plant capacity (Avlonitis et al., 2003).

Seawater desalination has been expanding rapidly in recent decades to supply water for municipal and industrial uses in arid, semi-arid or water-stressed regions (Zhou and Tol, 2005). Some of the water-stressed countries that currently meet their water supply by desalting include Cyprus, Israel, Saudi Arabia, Abu Dhabi, Australia, and USA (Florida, California). In Cyprus, the desalinated water totals nearly 40% of the total domestic water consumption (Tsiourtis, 2004). A number of desalination plants have come into operation recently including Hadera desalination plant in Israel and Kurnell desalination plant in Australia with a design capacity of 388,000 m^3/d and 250,000 m^3/d, respectively (Dreizin et al., 2008; El Saliby et al., 2009). Tampa Bay seawater desalination plant in Florida is the largest desalination facility in USA producing 94,000 m^3/d of drinking water (Wolf et al., 2005). The declining desalination costs due to technological advances have also played an important role in the worldwide expansion of desalination technology (Dore, 2004).

Desalination is a promising technology for communities near coastal region. However, inland water stressed regions require the transport of water from remote sources using water transport and storage infrastructures such as pipelines, pumping stations, reservoirs, dams, aqueducts, tunnels etc (Gupta and van der Zaag, 2008). Many cities with limited water resources to support their demand have bloomed in the desert with water transport from hundreds and even thousands of miles away (Gleick, 2001). The transfer of water from areas of relative abundance to the areas where water is scarce has evolved over centuries (Jain et al., 2005; Meador, 1992; Muller, 2000). A number of water transport schemes are currently operating in many countries such as Spain (Ballestero, 2003), South Africa (Gupta and van der Zaag, 2008; Muller, 2000), China (Cai, 2008; Gupta and Zaag, 2008, Liu and Zheng, 2002), Iran (Karamouz et al., 2010), Egypt (Lamei et al., 2007); and in many cities of the US including California (Hanak, 2007),Virginia (Cox, 2007), Arizona (Hanemann, 2002) and many other cities of the world for industrial, domestic and irrigation uses. Conveying water from long distance water sources requires massive water production infrastructures and intensive use of energy. Substantial energy is consumed to extract, process, and deliver clean water (Morrison et al., 2009).

Since, the energy consumption either in desalination or in water transport is most likely the major contributor to carbon footprint, the efforts to lower carbon footprint should mainly focus on the energy efficiency of water production (Strutt et al., 2008). Depending on the source of energy for electricity generation, the size or the quantity of carbon footprint differs. For instance, fossil fuels have the highest carbon footprint where as renewable technologies such as geothermal, hydroelectric, solar, wind, etc. have the lowest. Water managers may be able to decrease the carbon footprint of water production by switching to or implementing renewable energy sources. According to a study by Griffiths-Sattenspiel and Wilson (2009), the carbon footprint related to water production in the U.S. accounts for 5% of all U.S. carbon emissions. These emissions are likely to rise in the future due to growing water demand, limited and remote location of the freshwater sources, and stringent and energy intensive water treatment regulations and technologies.. The main objective of this research is to compare the two water supply alternatives: seawater desalination and water conveyance in terms of cost analysis and associated carbon footprint based on the energy requirements for each alternative. System dynamics modeling is used in the evaluation. The water supply needs of the arid Las Vegas Valley (LVV), located in Nevada, USA is used as the example case. However, the method employed and the research findings can be applied to other communities with limited water resources.

3.2 Water Supply Options

3.2.1 Example Water System

For the system dynamics model, the LVV water system is used as an example. The LVV located in an arid valley in Clark County in southern Nevada has a drainage basin of about 4,100 km^2 (1,586 square miles) and runs from Spring Mountains in the west to Lake Mead in the east (Buckingham and Whitney, 2007; Gorelow and Skrbac, 2005; Stave, 2003). The average annual precipitation in the Valley is 10.4 centimeters (cm) (4.1 inches) (Cooley et al., 2007). Almost 90% of the Valley's water demand is fulfilled by Colorado River water passing through Lake Mead (SNWA, 2009a), while the remaining comes from local groundwater sources (SNWA, 2010a). The consumptive water use right for Nevada is 0.4 km^3 (300,000 acre-feet) of Colorado River water per year (LVVWAC, 2009). Southern Nevada Water Authority (SNWA) manages the water supply and distribution to local water agencies in the LVV withdrawing water from Lake Mead. Drought conditions have caused decline in the Lake Mead water level, and water level is expected to decline even more in coming years (Feroz et al., 2007; USBR, 2010). The persistence of this drought condition can lead to two primary consequences: possible reduction in the amount of available Colorado River water; and intake supply and operation challenges due to decline in water level at Lake Mead (SNWA, 2009b). In addition, possible increase in future water demands, estimated based on population projection by CBER, will require LVV to explore additional water supply options.

The two potential future water supply options for the LVV considered include seawater desalination and conveyance of water from groundwater sources located 421 km (263 miles) from the LVV. Seawater desalination supply involves negotiating a paper-transfer agreement with California or Mexico in which Nevada will build a desalination plant in California or Mexico and in exchange will pump California or Mexico apportionment of Colorado River water from Lake Mead, Nevada. Water conveyance from groundwater sources involves the transfer of groundwater via buried pipeline from hydrographic basins in Lincoln and White Pine Counties located in northern Nevada. The water conveyance from distant location plans to transport approximately 526,000 cubic meters per day (m^3/d) (155,755 acre-feet per year (afy)) of water (SNWA, 2010b). However, SNWA has obtained the water rights for only 304,000 m^3/d (90,000 afy) so far. So, this flow rate is used as a design flow rate for the comparison of the supply options. The water conveyance location and potential desalination sites are shown in Figure 3.1. Both options considered for augmenting water supply to meet future water needs in the LVV are associated with energy use and hence, increased carbon footprint. Due to potential future greenhouse gas (GHG) emissions targets and rising energy costs, it necessitates the consideration of energy and carbon footprints when evaluating water supply options.

Figure 3.1: Water conveyance pipeline location and potential desalination sites (SNWA, 2010b; SNWA, 2009b)

3.2.2 Option 1-Seawater Desalination Supply

Desalination is a process of separating dissolved solutes from seawater, brackish water or treated wastewater in order to bring the salinity to a level consistent with the drinking water standards. Based on the separation mechanism, it can be thermal or membrane based technology (Gilau and Small, 2008). Thermal desalination technology involves the separation of dissolved solutes by evaporation and condensation whereas in the membrane separation mechanism, water diffuses through a membrane, retaining almost all solutes. The decision for the type of desalination technology is influenced by several factors such as feed water salinity, required product water quality and various site-specific factors, which include labor cost, available area, energy cost and local demand for electricity (Fritzmann et al., 2007).

Reverse osmosis (RO) is currently the fastest growing technology for water desalination (Peinemann and Nunes, 2010). RO is a pressure-driven desalination process, which uses a semi-permeable membrane to remove salts or other dissolved solutes from water. It is a continuous separation process in which there is no backwash (Crittenden et al., 2005). Osmosis is the process of movement of water from a low concentration zone to a higher concentration zone through a partially permeable membrane. The application of excess pressure on the higher concentration zone can reverse the process, which is known as reverse osmosis (Alghoul et al., 2009). So, in reverse osmosis, the hydrostatic pressure must exceed the osmotic pressure of the saline solution for the water molecules to pass from the high concentrated solution to the low concentrated solution through the semi-permeable membrane. The feed water is then separated into two parts: one more concentrated in dissolved salts called concentrate or brine and the other almost pure called permeate. The permeate stream exits at nearly atmospheric pressure while the concentrate remains nearly at the feed pressure.

Location of Desalination System and Flow Rate

In this research, the seawater reverse osmosis (SWRO) desalination facility is assumed to be built in California. The design flow for the comparison purpose is 304,000 m^3/d (90,000 afy). Since, RO facility can be built in phases, it is assumed in the analysis that the RO facility with a capacity of 60,800 m^3/d (18,000 afy) will be built in the initial phase and the capacity will be increased every five years after the operation of the first plant ending up with the total design flow of 304,000 m^3/d (90,000 afy) at the end of 20 years. Building RO facility in phases is possible because membrane systems can be built in modules and added as water demand increases. For the analysis, the assumed installation year of the first phase is 2011 and the final installation year to meet the total design flow is 2032. The construction period is assumed to be 2 years for each phase.

3.2.3 Option 2-Water Conveyance from Distant Locations

This option involves conveying the same amount of water from northern Nevada as that obtained from desalination. In the case of the LVV, SNWA currently holds approximately 304,000 m^3/d (90,000 afy) groundwater rights to be conveyed to the LVV in the hydrographic basins of Spring Valley, Cave Valley, Dry Lake Valley and Delamar and the remaining is pending applications for groundwater rights in Snake Valley. Hence, for the analysis purpose the design flow is assumed to be 304,000 m^3/d (90,000 afy) and all the facilities, as proposed by SNWA (2010b), are considered in the analysis except for the facilities in Snake Valley. The water conveyance from distant location includes the construction and operation of groundwater production facilities such as wells and pumps, water conveyance and treatment facilities. The treatment facilities required is assumed to be for disinfection only.

Proposed Facilities

The proposed facilities for the groundwater transfer considered for this study are as follows:

- Groundwater production wells are estimated to be 69 in number in average, 457 m (1,500 feet (ft)) deep and yielding 4,361 m^3/d (800 gallons per minute (gpm)) of water.
- Approximately 421 kilometers (km) (263 miles) of buried main and lateral water pipelines, varying from 76 centimeters (cm) (30 inches (in)) to 183 cm (72 in) in diameter.
- Three pumping station facilities.
- Five regulating tanks, each with capacity of approximately 38,000 m^3 (10 million gallons).
- One buried storage reservoir with 152,000 m^3 (40 million gallons) capacity.
- Up to 304,100 m^3/d (80 million gallons per day (mgd)) water treatment facility.

The hydrographic basins and corresponding permitted groundwater rights and applications considered in the analysis from each hydrographic basin are tabulated in Table 3.1. The pipeline and pumping station configurations considered for the groundwater conveyance are as listed in Table 3.2 and Table 3.3, respectively.

Table 3.1: Groundwater rights and applications planned to be conveyed from distant location (SNWA, 2010b)

Hydrographic Basin	**Ground water rights and applications**	
	m^3/d	**afy**
Spring Valley	230,000	68,000
Cave Valley	15,800	4,678
Dry Lake Valley	39,100	11,584
Delamar Valley	8,400	2,493
Total	293,300	86,755

Table 3.2: Pipeline configuration (SNWA, 2010b)

Pipeline	**Diameter**		**Length**	
	cm	**in**	**km**	**miles**
Main pipeline	183	72	325	203
Spring Lateral	137	54	61	38
Cave Lateral	76	30	35	22
		Total	421	263

Table 3.3: Pumping station configuration (SNWA, 2010b)

Pumping Station	**No. of pumps**[1]	**Pump horsepower**	**Total dynamic head**[2]	
		HP	**m**	**ft**
Spring Valley North Pumping Station	6	500	53	175
Spring Valley South Pumping Station	10	1250	137	450
Lake Valley Pumping Station	11	1250	152	500

[1] Includes one standby unit.

[2] Based on the SNWA pump station design

The two scenarios are evaluated for water conveyance from distant locations using groundwater conveyance from northern Nevada counties to the LVV, as an example case:

(i) Limited supply and (ii) Full supply. In limited supply scenario, it is assumed that the water from northern counties will be transported only when the demand cannot be fulfilled by the existing Colorado River water resources and the LVV groundwater resources. In order to save the energy required to transport water from northern counties, it is assumed that the water deficit will be fulfilled from the sources nearer to the LVV. Distant sources will be explored only when the nearer sources are not sufficient to satisfy the LVV needs. The groundwater source locations in terms of closeness to the LVV can be assorted as Delamar Valley, Dry Lake Valley, Cave Valley and Spring Valley being the farthest one. In full supply scenario, it is assumed that the water from northern Nevada counties is transported at design flow throughout the year (304,000 m^3/d).

3.3 Research Method

3.3.1 RO Design

The design of an RO system typically depends on the characteristics of the feed water, treated water quality and quantity requirements. The major design parameters involved in the RO design are shown in Table 3.4.

IMSdesign software by Hydranautics (www.membranes.com) is used in the design and for the analysis of energy requirements for SWRO. The main inputs to the model include the feed water type, its chemical characteristics, pH, temperature, desired product recovery percentage and the permeate flow rate. Then, a configuration of a number of passes, number of stages in each pass, number of pressure vessels in each stage, number of elements in each pressure vessel and the type and age of membrane is determined. After performing the calculations, the model provides the required feed pressure to obtain the desired recovery, power requirements, chemical dosing requirements and other membrane element parameters.

Table 3.4: Major design parameters and fundamentals of RO design

Parameter	**Unit**	**Value/ Equation**	**Fundamentals**	**Reference**
Permeate Flow rate	m^3/d	60,800	Design flow	-
Water flux (J_w)	$L/m^2.h.bar$	$k_w(\Delta P-\Delta\pi)$	Mass balance	Crittenden et al., 2005
Solute flux (J_s)	$mg/m^2.h$	$k_s(\Delta C)$	Mass balance	Crittenden et al., 2005
Osmotic pressure (π)	bar	$1.12*(273+T)*\Sigma m_i$	van’t Hoff equation	Cheremisinoff, 2002
Concentration polarization mass transfer coefficient (k_{CP})	m/s	$0.023*\frac{D_L}{d_H}*(Re)^{0.83}*(Sc)^{0.33}$	Gilliland correlation	Crittenden et al., 2005
Concentration polarization factor (β)	-	$\exp\left(\frac{J_w}{k_{CP}}\right)*Rej+(1-Rej)$	Film theory and mass balance	Crittenden et al., 2005
Salt rejection (Rej)	-	$1-\frac{C_P}{C_F}$	Mass balance	Crittenden et al., 2005
Recovery (r)	-	$\frac{Q_P}{Q_F}$	Flow balance	Crittenden et al., 2005
Solute concentration (C_C)	mg/l	$C_F=\left[\frac{1-(1-Rej)r}{1-r}\right]$	Mass and flow balance	Crittenden et al., 2005
Reynolds number (Re)	-	$\frac{\rho v d_H}{\mu}$	Fluid mechanics	Crittenden et al., 2005
Schmidt number (Sc)	-	$\frac{\mu}{\rho D_L}$	Diffusion	Crittenden et al., 2005
Hydraulic diameter (d_H)	m	$\frac{4(flow\ cross\ section)}{wetted\ perimeter}$	Fluid mechanics	Crittenden et al., 2005

where, k_w = mass transfer coefficient for water flux
k_s = mass transfer coefficient for solute flux
ΔP = applied pressure gradient
$\Delta\pi$ = osmotic pressure gradient
ΔC = concentration gradient across membrane
T = absolute temperature

Σm_i = sum of molality concentration of all constituents in feed water
D_L = diffusion coefficient
C_P = concentration in permeate
C_F = concentration in feed water
Q_P = permeate flow rate
Q_F = feed water flow rate
ρ = feed water density
v = velocity in feed channel
μ = feed water dynamic viscosity

The raw seawater quality parameters used in the design of SWRO system are obtained from Agus and Sedlak (2009) and Ladner et al. (2010) (Table 3.5). The permeate flow rate of 60,800 m^3/d (16 mgd) is used in the design with an average flux rate of 13.6 litre per square meter per hour (l/m^2-hr). A single pass two stage design is considered. A 20.32 cm (8-inch) membrane element, SWC5, with an active membrane area of 37.1 m^2 (400 square feet (ft^2)) by Hydranautics is used. The membrane specifications are shown in Table 3.6. There are 500 pressure vessels in the first stage and 334 pressure vessels in the second stage with a total of 834 number of pressure vessels in the design. Each pressure vessels contains 6 membrane elements.

Table 3.5: Raw seawater quality for the SWRO design

(Agus and Sedlak, 2009; Ladner et al., 2010)

Analyte	**Units**	**Concentration**
pH	pH Units	7.9
Temperature	°C	21
Calcium	mg/l	200
Magnesium	mg/l	650
Sodium	mg/l	5200
Potassium	mg/l	190
Ammonia nitrogen	mg/l	0.1
Strontium	mg/l	7.4

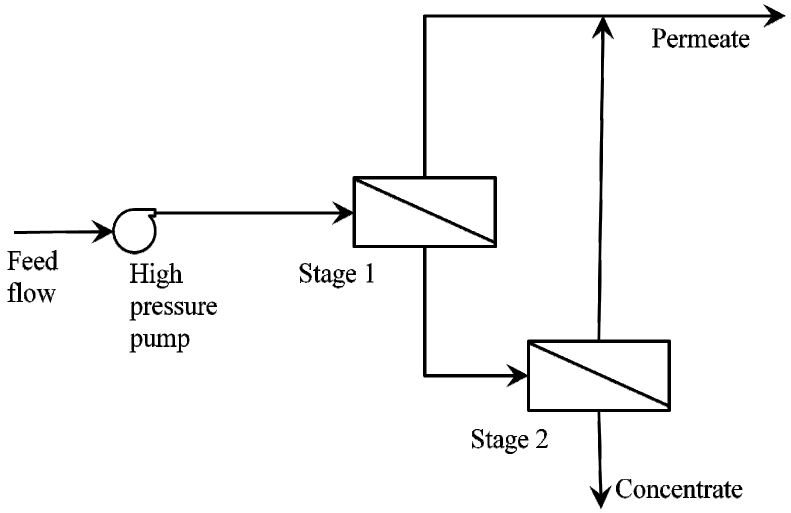
Analyte	Units	Concentration
Bicarbonate alkalinity	mg/l	110
Sulfate	mg/l	3000
Chloride	mg/l	19000
Fluoride	mg/l	0.9
Boron	mg/l	2.4
Silica	mg/l	3.5

Table 3.6: SWC5 membrane specifications (Hydranautics, 2009)

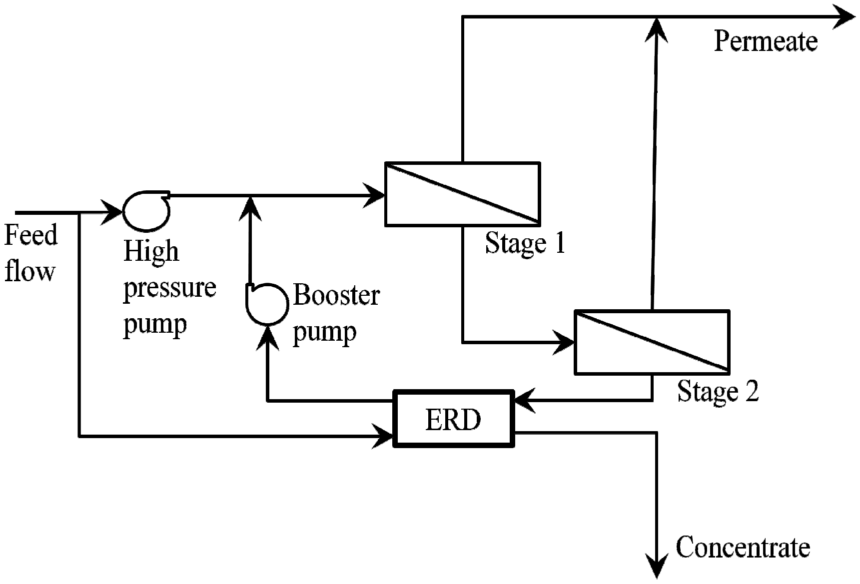
Parameter	Description
Membrane type	Composite polyamide spiral wound
Maximum operating temperature	45°C (113°F)
Maximum operating pressure	8.27 Mpa (1200 psig)
Maximum pressure drop	0.7 bar (10 psi)
pH range	2-11
Maximum feed flow	17 m^3/h (75 gpm)
Maximum feed SDI	5
Maximum chlorine concentration	<0.1 ppm
Single element recovery	10%
Active surface area	37.1 m^2 (400 ft^2)
Salt rejection	99.8%
Boron rejection	92%

As SWRO is a pressure-driven membrane process, the major portion of the energy required for the SWRO facility is consumed by the high pressure pumps. More than 50% of the energy supplied by the high pressure pumps is lost with the ejected brine of the RO modules (Wang et al., 2010). The energy cost in the SWRO process is usually about 30% to 50% of the total production cost of water and depending on the cost of electricity, it can be as much as 75 % of the operating cost (Farooque et al., 2004; Stover, 2008). Thus, it is important to recover the pressure energy using energy recovery devices (ERDs) otherwise lost in the reject stream. There are two different types of ERDs currently in use: the positive displacement type and the centrifugal type (Peñate et. al, 2010; Wang et al., 2010). With the use of positive displacement type ERD such as pressure/work exchanger, the pressure energy in the brine stream can be recovered by as much as 60% and used in the feed stream to decrease the overall energy requirements for the SWRO process (Stover, 2008). The positive displacement type ERD has become one of the most efficient ERDs and has been globally adopted for SWRO desalination (Peñate et. al, 2010). Figure 3.2 shows the schematic of two stage RO process with and without using ERD. For this study, the RO is also designed with and without using ERD.

The seawater desalination water supply option for the LVV incorporates the construction and operation of an SWRO facility in California and in exchange requires the pumping of equivalent entitlement of Colorado River water from Lake Mead. Thus, the total energy requirements should also include the energy requirements for water conveyance in the existing water conveyance facility operated by SNWA in the LVV. Hence, the total energy requirement for seawater desalination supply option are divided into two components and addressed as SWRO and water conveyance in the LVV lateral in this study. SWRO component includes the operating energy requirements of the SWRO facility in California. The other component - water conveyance in the LVV lateral includes only the energy requirements for water conveyance from Lake Mead to Grand Teton Reservoir through East Valley Lateral. The details of the water conveyance network in the LVV are shown in Figure 3.3 highlighting the water path from Lake Mead to East Valley Lateral. This lateral is selected because it is assumed that the water transported from distant location will be delivered around the periphery of the end of this lateral near Grand Teton reservoir.



(a) without ERD



(b) with pressure/work exchanger as ERD

Figure 3.2: Schematic of two stage RO system

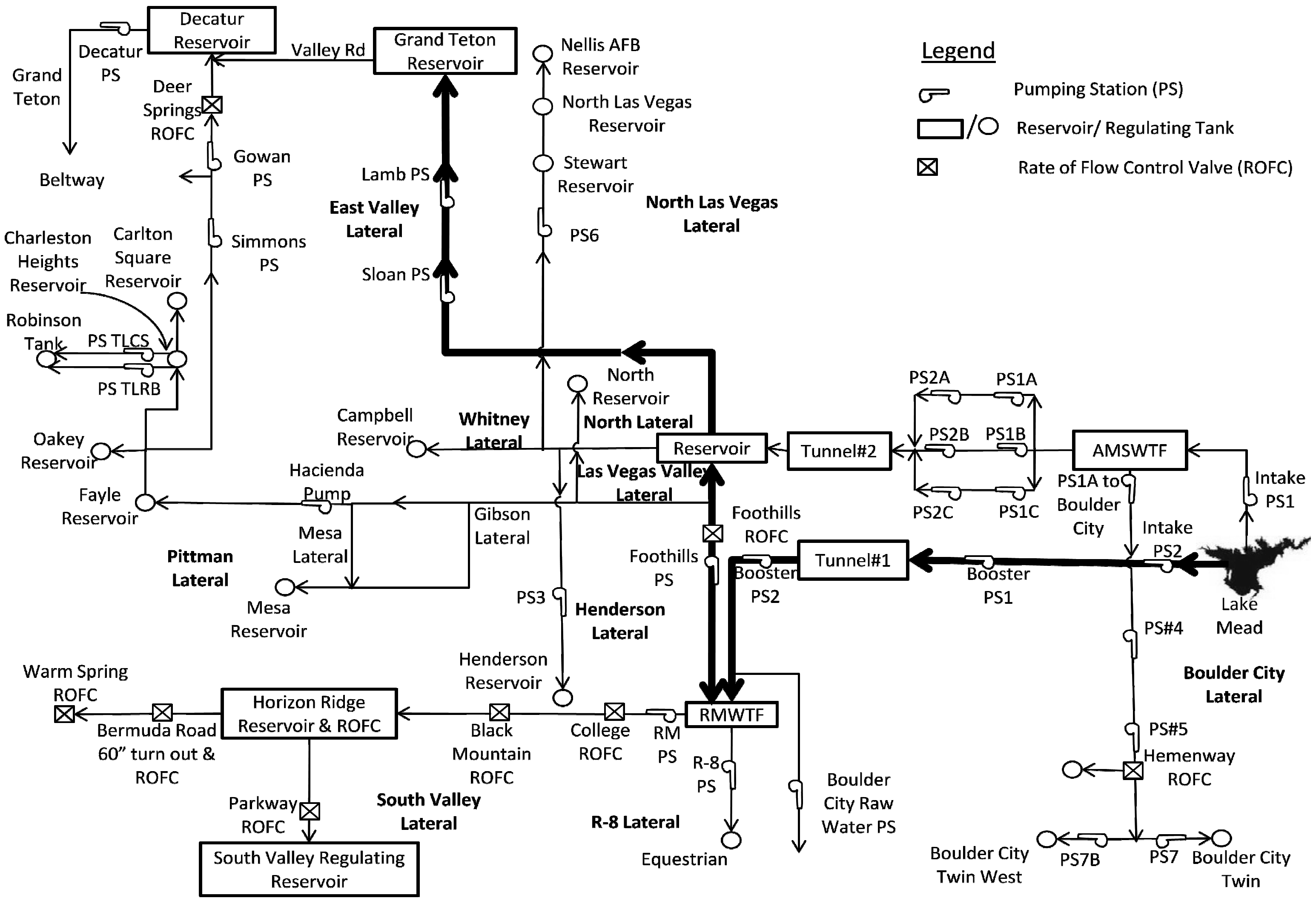


Figure 3.3: Schematic of water conveyance system in the Las Vegas Valley

3.3.2 System Dynamics Model

A system dynamics (SD) simulation model is developed to facilitate the computation of energy use and carbon footprint of water conveyance through major laterals in the LVV and the energy required to pump approximately 457 m (1500 ft) deep groundwater to the surface and convey it from a distance of 421 km (263 miles) to the Valley.

The SD model developed estimates the energy requirement and consequent carbon footprint of existing water supply and conveyance in the Las Vegas Valley and future supply option of conveying water from distant location. It is comprised of four major sectors – water demand sector; water supply, distribution and wastewater collection sector; groundwater conveyance sector and carbon footprint sector. These sectors are directly or indirectly connected influencing the behavior of one another.

The water demand sector basically computes total water demand and demand fulfilled by Colorado River water based on the population and per capita water demand for the simulation period ranging from 2003 to 2035. The population includes only permanent population of the Valley and does not comprise tourist population. The total water demand is a function of population and per capita water demand.

Water supply, distribution and wastewater collection sector incorporates all the major pumping stations and computes the energy requirements. Water flow in the system shown in Figure 3.3 is captured in this sector along with the stocks and flows for water use in the Valley, wastewater collection, water reuse and discharge of treated effluent back into the Lake Mead.

Groundwater conveyance sector includes the computation of the energy requirement of pumping groundwater to the surface and moving water from distant location to the

LVV. The pumping facilities depicted in Figure 3.4 are captured in the model along with pumping energy for groundwater extraction.

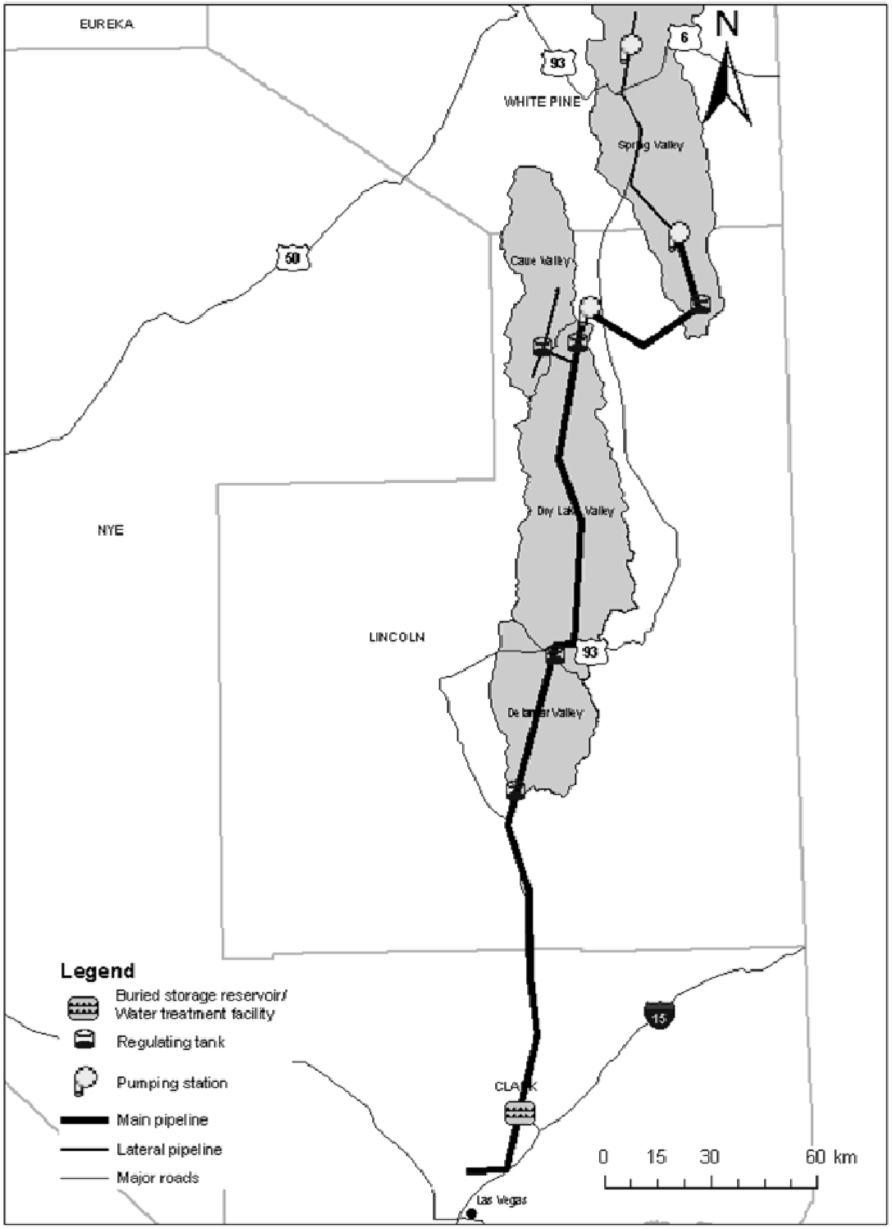


Figure 3.4: Proposed facilities for water conveyance from distant location (SNWA, 2010b)

Carbon footprint sector calculates the associated carbon footprint of pumping and moving water in the system based on the energy source used in pumping water. The 2007 Nevada's energy mix is used as source of energy as it is the latest available. However, the model provides the flexibility of varying state's future energy mix. The total carbon footprint is calculated by multiplying the energy use with the CO_2 emission rates. The basics of carbon footprint computation are described in the following section.

The SD model is also used to calculate the energy requirements and associated CO_2 emissions for one component of seawater desalination supply option-water conveyance in the LVV lateral. The energy use for moving water from Lake Mead to Grand Teton Reservoir through East Valley Lateral (Figure 3.3) only is considered for this computation.

3.3.3 Carbon Footprint Computation

The carbon footprint of the supply alternatives is calculated assuming that the source of energy for electricity generation is distributed as shown in Table 3.7. The average of the CO_2 emission rates, estimated from published studies and summarized in Table 3.8 is used in the calculation of the carbon footprint of the system. These CO_2 emission rates can vary depending upon the electricity generating plant efficiency, its technological options and carbon/heat content of the fuel when electricity generation is due to direct combustion of fuel (Evans et al., 2009; Weisser, 2006).

Table 3.7: 2007 electricity source distributions used in the computation (USEIA, 2009)

Source	**Percent of total electric power sector consumption**	
	Nevada	**California**
Coal	25.95	1.20
Oil	0.03	1.15
Natural gas	58.59	43.97
Solar/PV	0.13	0.28
Hydroelectric	6.57	13.80
Wind	-	2.82
Nuclear	-	19.18
Biomass	-	3.65
Geothermal	8.73	13.95

3.3.4 Cost Analysis

The two supply options as discussed in previous sections are compared for energy use, associated carbon footprint and cost. Cost analysis is done using the Net Present Value (NPV) method. To calculate the unit cost of water, the cost items are projected over the life cycle of the water supply alternative using Engineering News Record Construction Cost Index (ENR CCI) for capital costs and average inflation rate (2.5%) based on the inflation rate of last 10 years for annual operation and maintenance cost (ENR, 2010). For seawater desalination supply alternative, it is assumed that the RO facility with equal capacity is added every five year after the operation of the first facility. At the end of 25 years life time of the facility, the plant is dismantled and the new RO facility with same capacity is installed in its place. This process is continued for 50 years life cycle since the operation of first facility. Hence, the cost analysis also includes the dismantling cost and it is assumed to be 10% of the total capital cost. At the end of 50 years of operation, not all of the installed RO facility will have completed its life span of 25 years. Thus, to account for the unused life of the facilities, straight line depreciation is

Table 3.8: CO_2 emission rates in g CO_2e/kWh summarized based on literature review

Reference	**Fuel type**								
	Coal	**Oil**	**Natural gas**	**Solar/PV**	**Hydroelectric**	**Wind**	**Nuclear**	**Biomass**	**Geothermal**
USEPA, 2010	1005.2	212.03	432.96	-	-	-	-	-	-
Evans et al., 2009	1004	-	543	90	41	25	-	-	170
Varun et al., 2009	-	-	-	9.4-300	18-74.88	16.5-123.7	-	-	-
Fthenakis and Kim, 2007	-	-	-	17-49	-	16-55	-	-	-
Weisser, 2006	750-1250	500-1200	360-780	43-73	1-34	8-30	2.8-24	35-99	-
Dones et al., 2005	-	-	485-990	-	-	-	5-12	-	-
Hondo, 2005	975.2	742.1	518.8-607.6	26-53.4	11.3	20.3-29.5	22.2-24.2	-	15
Meier et al., 2005	1006	742	466	39	18	14	17	46	15
Dones et al., 2003	949-1280	519-1190	485-991	79	3-27	14-21	8-11	92-156	-
Sample size	8	7	11	11	9	12	9	5	3
Average	1022.9	779.6	605.9	70.8	25.4	31.1	14	85.6	66.7

used to calculate the salvage value at the end of the 50 years life span. The cost items also include the cost of moving Lake Mead water in the LVV lateral and the cost of water treatment in the existing water treatment facilities. The existing infrastructures of the water conveyance system in the LVV have the capacity to pump and treat additional volume of water considered for the comparison purpose. The unit cost of water is then obtained by converting all cost items to net present value using discount rate of 6% per annum and dividing it by total volume of water produced during the entire life of the project.

Similarly, the cost items for water conveyance from distant locations are based on the cost items estimated by Texas Water Development Board (TWDB) (2010). The cost items are then multiplied by city cost index (1.16) to obtain the cost for the Las Vegas (ENR, 2010). The unit cost of water is then calculated by projecting the cost items over the life cycle of the water transport facility, which is assumed to be 50 years, using ENR CCI for capital costs and average inflation rate (2.5%) for annual operation and maintenance cost. Also, the unit cost of water is calculated each year during the entire life of the two water supply facilities using annualized method in which each cost items is projected over the life of the supply facility using discount rate of 6% per annum.

3.4 Results and Discussion

3.4.1 Option 1-Seawater Desalination Supply

RO Design without Using ERD

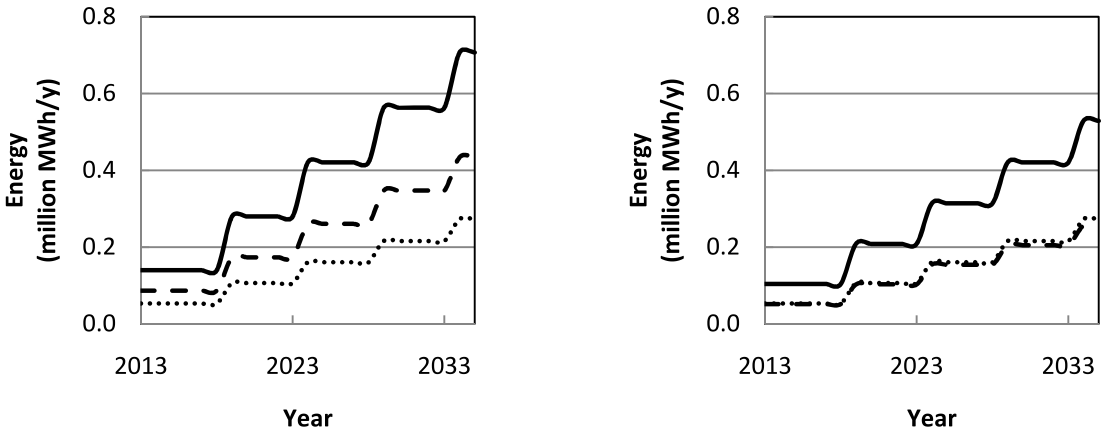
For seawater desalination without using ERD, the RO design reveals that a maximum pressure of 63.7 bar must be applied to the feed water and the concentrated brine flows out of the system at 60.8 bar with a design recovery of 54%. The TDS concentration in the permeate water is reduced to 311 mg/l from 35,398 mg/l. The energy required for the RO process is 4.34 kWh/m^3 of treated water.

RO Design Using ERD

In this case, the maximum required applied pressure to the feed water is 65.7 bar and the concentrated brine flows out of the system at 62.8 bar with a design recovery of 54%. In order to recover the pressure energy of the concentrate stream, a pressure/work exchanger is used as the ERD. A boost pressure of 2.9 bar is required to overcome the pressure drop in the membrane system. The TDS concentration in the permeate water is reduced to 322 mg/l from 35,398 mg/l. Compared to the TDS concentration in the permeate water in the absence of ERD, the TDS concentration increased by 3.6%. However, the permeate TDS concentration is within the U.S. Environmental Protection Agency (USEPA) goal requirements of 500 mg/l for drinking water (USEPA, 2009). The energy required for the RO process is 2.56 kWh/m^3 of treated water. The energy use decreased by nearly 41% as compared with the RO system with no ERD.

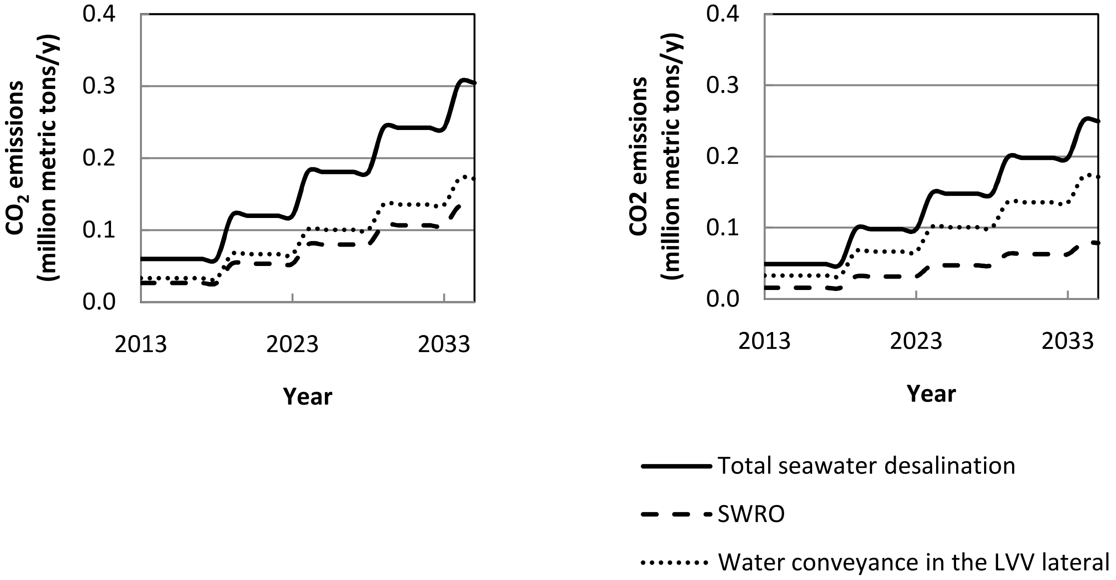
Figure 3.5 shows the energy and associated CO_2 emissions for the seawater desalination supply option for the LVV with and without using ERD. The energy and associated CO_2 emissions for seawater desalination supply option are divided into two components: SWRO and water conveyance in the LVV lateral. SWRO represents the operational energy requirements and associated CO_2 emissions to run an SWRO facility in California. Water conveyance in the LVV lateral is the energy and associated CO_2 emissions of lifting and moving equivalent amount of water in the LVV lateral. At the beginning of the operation, the energy and corresponding CO_2 emissions are lower and as new RO modules are installed in the future, the energy requirements and associated CO_2 emissions increase with the plant capacity. This water supply alternative requires nearly 0.71 million MWh of total energy per year by 2035, which results in the total CO_2 emissions of approximately 0.3 million metric tons per year by 2035 when ERD is not used.

The use of ERD results in the decrease of total energy requirements by nearly 25%. Similarly, the total CO_2 emissions decrease by nearly 18% as compared to the case without ERD. By the year 2035, the total energy requirements and associated CO_2 emissions will be approximately 0.53 million MWh per year and 0.25 million metric tons per year, respectively when a positive displacement type ERD such as pressure/work exchanger is used.



(a) Without ERD

(b) With ERD



(c) Without ERD

(d) With ERD

Figure 3.5: Energy and associated CO_2 emissions for the seawater desalination option with and without using ERD

Limited Supply

The energy requirements during the beginning of its operation phase is nearly 0.07 million MWh per year and it gradually increases to 0.27 million MWh per year by the year 2035 as shown in Figure 3.6. Similarly, the associated CO_2 emissions increase from approximately 0.04 million metric tons per year in 2020 to 0.17 million metric tons per year by the end of 2035.

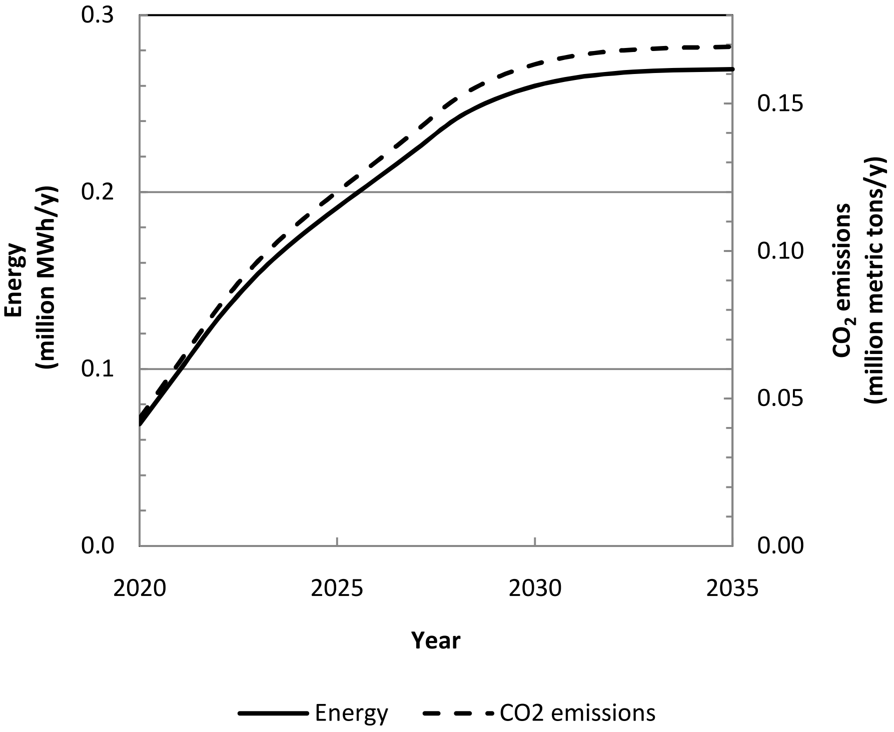


Figure 3.6: Energy and associated CO_2 emissions for the water conveyance from distant location with limited supply

Full Supply

When the water from distant location is brought at its full flow rate (304,000 m^3/d), it requires nearly 0.27 million MWh of electricity per year. The energy considered here is the energy required to pump water from the ground to the surface (0.11 MWh/y) and the energy required to transport water to the LVV (0.16 MWh/y). Nearly 59% of the total energy is required to transport water while the remaining is to pump the groundwater to the surface. When run at full supply, water conveyance from distant location generates nearly 0.17 million metric tons of CO_2 emissions per year. These CO_2 emissions are based on the electricity fuel resource mix for the state of Nevada for the year 2007. The total emission is likely to change with the change in fuel source type for the generation of electricity in future. The increase in use of renewable sources of energy such as hydroelectric, geothermal, solar/PV, etc. will decrease the total CO_2 emissions because of their lower CO_2 emission rates as compared to the fuels like coal, oil and gas.

3.4.3 Comparison of the Two Supply Options

Energy and CO_2 Emissions Comparison

For comparison, the design with the inclusion of ERD is considered for the RO facility and the full supply scenario is considered for the long distance transport alternative. The comparison is based on the total design flow rate of 304,000 m^3/d (90,000 afy) for both water supply options. The energy requirements for the RO facility only, represented by SWRO in Figure 3.7, indicate that it requires less energy to operate SWRO facility in California as compared to the water transport from a remote location in northern Nevada. However, seawater desalination option will also require lifting equal quantity of water from Lake Mead and transporting it to the delivery location in the LVV. Incorporating the energy requirements for water conveyance in the LVV lateral increases the total energy requirements for seawater desalination supply option. When compared with the energy requirements for the water conveyance from distant location, the energy requirement for the SWRO only is 5.1% lower whereas addition of energy requirements for water conveyance in the LVV lateral in SWRO energy requirements increases the total energy requirements for seawater desalination supply option by 96%, which is almost double the energy requirement of water conveyance from distant location.

Similarly, only SWRO option has CO_2 emissions 53.6% lower than the emissions associated with the water conveyance from distant location, and addition of CO_2 emissions generation during the water conveyance in the LVV lateral increases the total CO_2 emissions for seawater desalination supply option by 47.5% compared to water conveyance option from distant location. The energy requirements for two components of seawater desalination supply option i.e. SWRO and water conveyance in the LVV lateral is nearly same (0.26 MWh/y and 0.27 MWh/y, respectively), however, the CO_2 emissions associated with the SWRO facility is much lower. This is because, according to the electricity source distribution for the state of California, California uses a higher percentage of fuel source with lower CO_2 emission rates. For the two components of seawater desalination to result in equivalent CO_2 emissions, the percentage composition of renewable and non-renewable fuel sources for Nevada must be nearly 60% and 40%, respectively, unlike 15% and 85% currently. However, this change in fuel mix of Nevada will also lower the CO_2 emissions associated with water conveyance from distant location increasing the percentage difference between the two supply alternatives. If California and Nevada is assumed to have same fuel mix, the percentage difference in associated CO_2 emissions between the two supply alternatives increases in either case making water conveyance supply option from distant location more preferable in terms of carbon footprint.

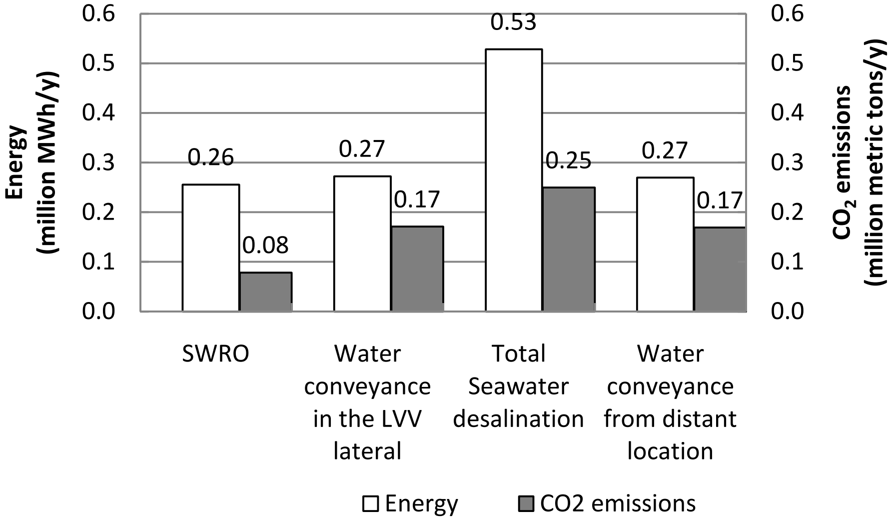


Figure 3.7: Comparison of energy and associated CO_2 emissions of seawater desalination and water conveyance option from distant location

Cost Analysis and Comparison

The basic cost items for the RO facility used in the cost analysis of the facility for the comparison purpose is as shown in Table 3.9. The details of these cost items can be found in Watson et al. (2003). The unit cost of water for seawater desalination supply option is calculated to be \$0.56/m^3 using the net present value method.

Table 3.9: Estimated cost items for RO facility

Cost Summary	
Project Description: Seawater desalination by reverse osmosis	
Desalting Plant Type: SWRO	**Capacity: 60,800 m^3/d (16 mgd)**
Annual Plant Factor: 90%	**Plant Life: 25 years**
Annual Production: 20 Mm^3	
CAPITAL COSTS	
Capital Cost Items	**Estimated Cost**
Desalting plant	$101,953,577
Concentrate disposal	$237,426
Pretreatment	Inc. in process
Water intake	$4,888,185
Feed water pipes	$1,536,287
General site development	$335,190
Post-treatment	Inc. in process
Auxiliary equipment	$6,997,088
Building and structures	Inc. in process
Sub-total Direct Capital Cost (DCC)	***$115,947,752***
Engineering, financial and legal services, and contingencies	$40,581,713
Total Capital Costs	***$156,529,466***
ANNUAL COSTS	
Annual Cost Items	**Estimated Cost / Year**
Operation and Maintenance Labor	$539,068
Chemicals	$1,796,892
Electric power	$6,930,871
Repairs and spares	$1,159,478
Membrane Replacement Cost	$740,582
Total Operation and Maintenance cost	***$11,166,891***

In a similar way, the basic cost items for water conveyance from distant location for cost analysis are listed in Table 3.10. The unit cost of water using the net present value of all cost items divided by total volume of water produced during the entire life period is obtained as $0.68/m^3.

Table 3.10: Estimated cost items for water conveyance from distant location

Cost Summary	
Project Description: Water conveyance from distant location	
Project Type: Groundwater development	**Capacity: 304,100 m^3/d**
Annual Plant Factor: 90%	**Project Life: 50 years**
Annual Production: 100 Mm^3	
CAPITAL COSTS	
Capital Cost Items	**Estimated Cost***
Pipelines	$2,189,839,830
Pumping stations	$145,975,262
Regulating tanks	$36,337,913
Water treatment facilities	$25,315,759
Buried storage reservoir	$17,589,219
Groundwater production wells	$133,624,599
Total Capital Costs	***$2,548,682,582***
ANNUAL COSTS	
Annual Operation and Maintenance Cost Items	**Estimated Cost / Year**
Pipelines	$16,844,922
Pumping stations	$12,734,456
Regulating tanks	$269,170
Water treatment facilities	$2,001,455
Buried storage reservoir	$130,291
Groundwater production wells	$11,807,902
Total Operation and Maintenance cost	***$43,788,194***

*Cost items include Engineering, financial and legal services, and contingencies

The unit cost comparison of the two water supply options using annualized method is shown in Figure 3.8. The unit cost for desalination supply is lower during the initial operational phases as compared to the water conveyance supply option from distant location due to small plant capacity and lower initial capital cost. The unit cost increases in future as the other phases are installed in future increasing the capital and operational cost. The unit cost obtained from this method cannot be compared with the values obtained from NPV method.

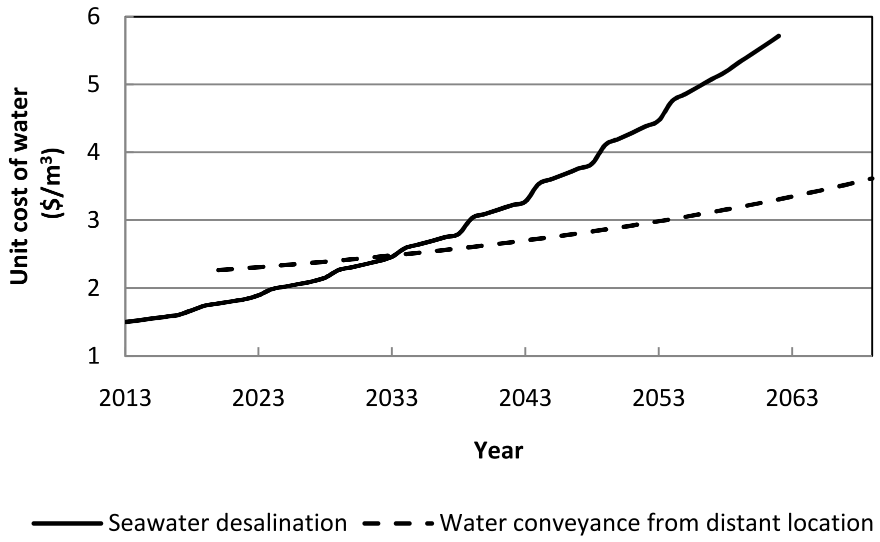


Figure 3.8: Unit cost comparison of two water supply options

3.5 Summary and Conclusions

This study explored the energy requirements, CO_2 emissions as its consequence, and cost analysis of the two water supply options for the LVV. For the seawater desalination supply options, two cases with and without using ERD are investigated. The results showed that the use of pressure/work exchanger as the ERD can significantly reduce the energy consumption for the RO facility in seawater desalination supply option, consequently reducing the total CO_2 emissions for this supply option.

For the water conveyance supply option from distant location, two scenarios are considered- limited supply scenario and full supply scenario. In the limited supply scenario, the water from the distant location is transported only when the current water resources for the LVV will not be able to satisfy the water needs. In full supply scenario, the water is transported at its full capacity throughout the year.

To compare the two supply alternatives, RO design using ERD and water conveyance from distant location at full supply is considered. Since, the desalination supply option also includes the cost, energy and emissions associated with the transport of water in one of the laterals in the LVV, the results show that the seawater desalination supply option for the LVV is more energy intensive and as its consequence, results in more CO_2 emissions. However, the unit cost of water is calculated to be cheaper for the desalination supply option as compared to the water conveyance option from distant location. Hence, if only cost comparison is done, the seawater desalination supply option seems more feasible as compared to the water conveyance supply option from distant location. But the CO_2 emissions are higher for the seawater desalination supply option. The incorporation of cost incurred to the society due to emissions in the cost analysis may change the preference. The findings of the research are study specific and different distance from source or different lift and conveyance combination may result different scenario.

The RO facility is built in phases and requires lower initial capital and operational costs. If the population in LVV does not increase as predicted or water demand lowers considerably, the existing water resources may be sufficient to fulfill the water needs in the Valley. This will prolong the time lag between the installation of additional RO units resulting in lower cost, energy and emissions. Also, the drought condition is lowering the water level in Lake Mead. If the drought prolongs, limiting water withdrawal from Lake Mead, Nevada may not benefit from building a huge RO facility in California.

The energy requirement for the RO facility is based on the specific energy given by the RO design using IMSdesign by Hydranautics and it does not include the energy requirements for pretreatment and post-treatment. Also, the environmental impact of brine disposal is not included in the cost analysis. For the CO_2 analysis, electricity mix for the year 2007 for the state of Nevada and California is used as the energy source. Actual source of energy may differ when the plants will be in operation which will change the emissions due to each fuel source type eventually changing the total emissions. Additionally, the CO_2 emissions are based on the operational energy requirements only. The life cycle energy analysis for the energy and corresponding CO_2 emissions will give a more accurate energy and associated CO_2 emissions associated with it. The emissions generated during the other stages of life such as extraction, construction, decommission, etc. of the plant are not considered. Also, the total quantity of water delivered within the 50 years life time for seawater desalination option is less compared to the water transport option from the distant location.

Whether to choose a water supply alternative based on cost or carbon footprint depends solely on the decision makers’ goals and preferences. Considering that different criteria (energy use, associated emissions and cost) favor different projects, multi-criteria decision making framework that reflects society’s preferences may be used to choose the project.

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CHAPTER 4

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

This study explored the interrelation between water and energy, specifically energy needs for water and CO_2 emissions associated with it. For a region where water users are at a higher elevation than the source of supply, it often requires more energy to move water from source to the distribution points. The energy requirements grow with the distance and elevation, and so does the associated CO_2 emissions. With the growing concern for emissions and associated environmental costs, it is necessary for a sustainable development to analyze the CO_2 emissions associated with water production and transport. This helps in improving the existing water systems and making future water systems energy efficient. A System Dynamics model was developed to analyze the energy and associated CO_2 emissions of lifting and moving water in the Las Vegas Valley water distribution laterals. The conclusions that can be drawn from this research are as follows:

- The model simulations show that currently (2009) significant amount of energy is required (0.85 million MWh/y) to satisfy the water needs of the Las Vegas Valley and it will increase substantially (nearly 58%) by the year 2035 assuming no change in per capita demand of 908 lpcd (240 gpcd) from 2010 and onwards, provided that the population growth is as predicted by CBER.
- When a conservation scenario is assumed in which per capita demand gradually lowers to 753 lpcd (199 gpcd) by 2035, the rise in energy requirements is approximately 32% as compared to the present energy requirements.

- Considerable amount of energy is required to pump water from Lake Mead to water treatment plants. It comprised nearly 35% of the total energy requirements. These energy requirements tend to rise as the Lake level declines. However, the major portion of total energy (65%) is consumed to move treated water in the distribution system.
- Even a small change in population growth rate, can vary the future energy requirements and associated emissions by substantial amount. Variation in population growth rate by 0.5% can change the energy and CO_2 emissions by around 12.8% as compared to the status quo. So, the future emissions can vary if there is different growth in population compared to what is currently forecasted by CBER.
- The change in the lake levels considered in this study resulted in the change in energy requirements and CO_2 release by 3.3% when compared with the total CO_2 emissions.
- Conserving water from 908 lpcd (240 gpcd) to 753 lpcd (199 gpcd) results in a significant reduction in the energy consumption and associated CO_2 emissions. The energy and CO_2 emissions in the year 2035 decreased 16.5% as compared to the status quo scenario. Increasing the reuse rate of treated wastewater effluent lowered the energy requirements and associated CO_2 emissions of moving water in Las Vegas Valley by considerable amount. At present the reuse rate is nearly 30 MCM (22 mgd) and is expected to reach 77 MCM (56 mgd) by 2020 which will result in nearly 3.6% energy saving as compared with no change in reuse rate. However, if 20% of the treated wastewater is reused the energy use can lower by

9%, sufficient enough to light approximately 11,000 US homes on average for a year based on an average annual electricity consumption of 11,040 kWh for a US residential home in 2008 (USEIA, 2010).

- A combination of multiple scenarios in which water demand is reduced to 753 lpcd (199 gpcd) by 2035, wastewater reuse is increased to 77 MCM by 2020 and renewable energy sources is increased to 50%, resulted in the decrease of energy requirements by nearly 0.28 million MWh/y (20.7%) and CO_2 emissions by 0.39 million metric tons/y (46%) by 2035 when compared with the status quo.
- Different scenarios were tested for energy and associated CO_2 emissions for water production in the Las Vegas Valley including change in population growth rate, water conservation, increase in water reuse, change in the Lake level, change in fuel sources, and change in emission rates. Among these scenarios, water conservation turned out to be the most energy efficient. Although increasing reuse of treated wastewater lowers the return flow credits, but in turn it lowers the water demand to be fulfilled by Colorado River water, hence, omitting the need for lifting, treating and distributing Lake Mead water.
- For the scenarios tested for future water supply options in the Las Vegas Valley, the seawater desalination supply option is more energy intensive and as its consequence results in more CO_2 emissions as compared to the water conveyance supply option from distant location. Seawater desalination supply option requires nearly 0.53 million MWh/y which is almost 96% higher than energy requirements for water conveyance supply option (0.27 million MWh/y) from distant location. Similarly, associated CO_2 emissions for seawater desalination supply option (0.25

million metric tons) is 47.5 % higher than water conveyance supply option (0.17 million metric tons) from distant location. The energy and associated CO_2 emissions are higher for seawater desalination supply option because this supply option also includes the energy and emissions associated with the lifting of water from Lake Mead and transport of water in one of the laterals in LVV.

- Cost comparisons show that the unit cost of water is cheaper for the desalination supply option ($0.56/m^3) as compared to the water conveyance supply option ($0.68/m^3) from distant location.
- The seawater desalination supply option seems more feasible as compared to the water conveyance supply option from distant location, if only cost comparison is done. But the energy consumption and CO_2 emissions are higher for the seawater desalination supply option. The inclusion of the cost incurred to the society due to CO_2 emissions in the cost analysis may change the preference.

Recommendations

This study is focused mainly on the energy consumption and CO_2 emissions as its consequence in moving water in the Las Vegas Valley, and cost, energy and emission comparison for two supply options for the Las Vegas Valley. Energy calculation for moving water depends mainly on the flow rate and the total dynamic head to lift the water. In this study, the flow rate in each of the pumping stations is based on the demand, capacity of water treatment plants and capacity of reservoirs in the distribution system. The more precise prediction of energy requirements in each of the pumping stations could be achieved if the water flow equations are developed based on the historical or actual flow rate at these stations. Also, the energy required in treating water and wastewater in water and wastewater treatment facilities could be significant and is recommended for further study.

CO_2 emissions depend on the fuel type used in the generation of electricity for water production. Since, actual source of energy for electricity used by SNWA in water distribution system was not certain, electricity mix for state of Nevada was used as the energy source. The more detail study determining the fuel source for water production will provide more accurate CO_2 emission estimates. Moreover, the state's electricity resource mix is assumed to be constant in future. The variation in future electricity mix is recommended for further study. Also, this study considers only operational energy requirements. The consideration of life cycle energy requirements is necessary for better emission analysis. Emissions can be both direct and indirect. Direct emissions are referred to those that are released during the operation phase, whereas indirect emissions are released during non-operational phase of the plant life cycle such as emissions associated with the extraction, processing and transportation of fuels, building of power plants, production of electricity, waste disposal and finally decommissioning of the plant at the end of its life.

One important element in determining total CO_2 emissions is emission factor. The emission factors used in this study are based on the literature review. The emission factors can be different for different locations based on electricity generating plant efficiency, its technological options and carbon/heat content of the fuel when electricity generation is due to direct combustion of fuel. To account for the uncertainty associated with emission factors, uncertainty analysis was done using numerous uniformly distributed emission factors. Site specific emission factor of the electricity generation plant for water production will be more appropriate for CO_2 emission calculation.

The RO facility is built in phases and requires lower initial capital and operational costs. If the population in LVV does not increase as forecasted or water demand lowers significantly, the existing water resources may be sufficient to fulfill the water needs in the Valley. This will prolong the time lag between the installation of additional RO units resulting lower cost, energy and related emissions. Also, the drought is declining the water level in Lake Mead. Prolonging drought may limit water withdrawal from Lake Mead making RO plant in California unfeasible for Nevada. Hence, climate change and its impact on the availability of water in Lake Mead is important consideration in the decision for future supply options.

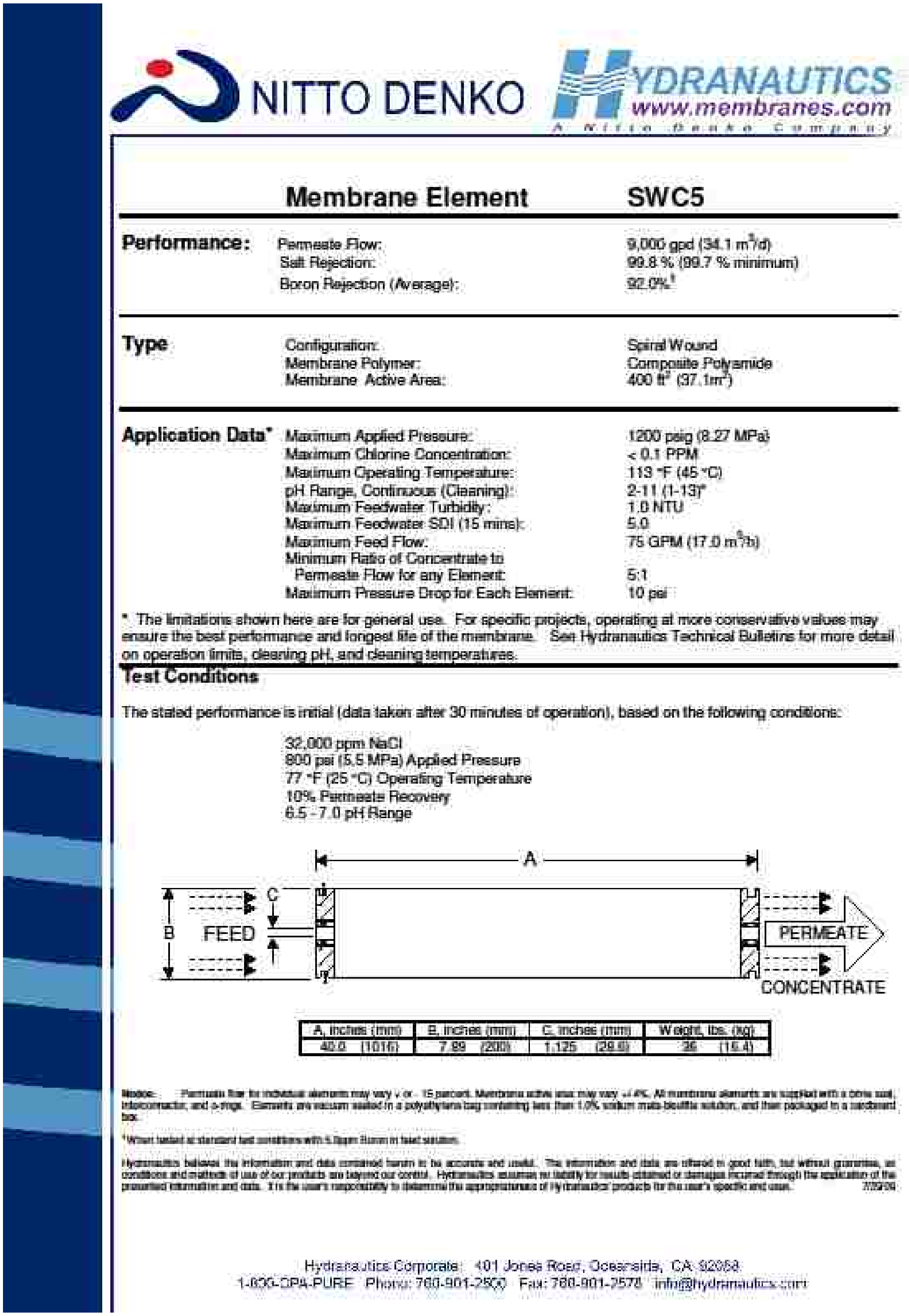
Also, the withdrawal of groundwater in the water conveyance supply option from distant location may lower the groundwater requiring more pumping energy and associated CO_2 emissions. The rate of groundwater recharge in the northern counties is an essential factor to be determined. These recommendations can be summed up as follows:

- The use of historical or current flow rate data at pumping stations to determine the pumping energy requirements.
- Inclusion of energy and associated CO_2 emissions for treating water and wastewater in the water and wastewater treatment facilities, respectively.
- Determination and use of actual source of energy for electricity generation used for water production.
- Consideration of life cycle energy requirements and emissions.
- Analyzing the uncertainty in emission factor.

- Study the impact of climate change and rate of groundwater recharge on the availability of future supply options considered.

APPENDIX

Membrane Specification Sheet



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Membrane Element SWC5

Performance:	Permeate Flow:	9,000 gpd (34.1 m^3/d)
	Salt Rejection:	99.8 % (99.7 % minimum)
	Boron Rejection (Average):	92.0%[†]
Type	Configuration:	Spiral Wound
	Membrane Polymer:	Composite Polyamide
	Membrane Active Area:	400 ft^2 (37.1m^2)
Application Data*	Maximum Applied Pressure:	1200 psig (8.27 MPa)
	Maximum Chlorine Concentration:	< 0.1 PPM
	Maximum Operating Temperature:	113 °F (45 °C)
	pH Range, Continuous (Cleaning):	2-11 (1-13)*
	Maximum Feedwater Turbidity:	1.0 NTU
	Maximum Feedwater SDI (15 mins):	5.0
	Maximum Feed Flow:	75 GPM (17.0 m^3/h)
	Minimum Ratio of Concentrate to Permeate Flow for any Element:	5:1
	Maximum Pressure Drop for Each Element:	10 psi

* The limitations shown here are for general use. For specific projects, operating at more conservative values may ensure the best performance and longest life of the membrane. See Hydranautics Technical Bulletins for more detail on operation limits, cleaning pH, and cleaning temperatures.

Test Conditions

The stated performance is initial (data taken after 30 minutes of operation), based on the following conditions:

32,000 ppm NaCl
800 psi (5.5 MPa) Applied Pressure
77 °F (25 °C) Operating Temperature
10% Permeate Recovery
6.5 - 7.0 pH Range

A, inches (mm)	B, inches (mm)	C, inches (mm)	Weight, lbs. (kg)
40.0 (1016)	7.89 (200)	1.125 (28.6)	36 (16.4)

Notice: Permeate flow for individual elements may vary + or - 15 percent. Membrane active area may vary +/-4%. All membrane elements are supplied with a brine seal, interconnector, and o-rings. Elements are vacuum sealed in a polyethylene bag containing less than 1.0% sodium meta-bisulfite solution, and then packaged in a cardboard box.

[†] When tested at standard test conditions with 5.0ppm Boron in feed solution.

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RO Design using IMSdesign by Hydranautics

RO Design without using ERD

BASIC DESIGN

RO program licensed					
Calculation created	Eleeja Shrestha				
Project name:	SWRO		Permeate flow:	60829.00	m3/d
HP Pump flow:	4693.6	m3/hr	Raw water flow:	112646.3	m3/d
Feed pressure:	63.6	bar	Permeate recovery:	54.0	%
Feedwater	21.0	C(70F)			
Feed water pH:	7.9		Element age:	5.0	years
Chem dose, ppm	0.0	H2SO4	Flux decline % per	6.9	
			Fouling factor:	0.70	
			Salt passage increase,	10.0	
Average flux rate:	13.6	lm2hr	Feed type:	Seawater - open intake	

Stage	Perm. Flow m3/hr	Flow/Vessel Feed m3/hr	Flow/Vessel Conc m3/hr	Flux l/m2-hr	Beta	Conc.andThrot. Pressures bar	Conc.andThrot. Pressures bar	Element Type	Elem. No.	Array
1-1	2158.5	9.4	5.1	19.4	1.02	62.3	0.0	SWC5	3000	500x6
1-2	376.1	7.6	6.5	5.0	1.01	60.7	0.0	SWC5	2004	334x6

	Raw water		Feed water		Permeate		Concentrate	
Ion	mg/l	meq/l	mg/l	meq/l	mg/l	meq/l	mg/l	meq/l
Ca	200.0	10.0	200.0	10.0	0.399	0.0	434.3	21.7
Mg	650.0	53.5	650.0	53.5	1.297	0.1	1411.5	116.2
Na	12237.5	532.1	12237.5	532.1	116.960	5.1	26466.0	1150.7
K	190.0	4.9	190.0	4.9	2.268	0.1	410.4	10.5
NH4	0.1	0.0	0.1	0.0	0.001	0.0	0.2	0.0
Ba	0.000	0.0	0.000	0.0	0.000	0.0	0.000	0.0
Sr	7.400	0.2	7.400	0.2	0.015	0.0	16.070	0.4
CO3	8.0	0.3	8.0	0.3	0.008	0.0	17.5	0.6
HCO3	110.0	1.8	110.0	1.8	1.876	0.0	236.9	3.9
SO4	3000.0	62.5	3000.0	62.5	7.136	0.1	6513.4	135.7
Cl	19000.0	536.0	19000.0	536.0	180.435	5.1	41092.5	1159.2
F	0.9	0.0	0.9	0.0	0.017	0.0	1.9	0.1
NO3	0.0	0.0	0.0	0.0	0.000	0.0	0.0	0.0
B	2.40		2.40		0.688		4.41	
SiO2	3.5		3.5		0.02		7.6	
CO2	0.76		0.76		0.76		0.76	
TDS	35409.8		35409.8		311.1		76612.7	
pH	7.9		7.9		6.6		8.5	

	Raw water	Feed water	Concentrate
CaSO4 / Ksp * 100:	12%	12%	32%
SrSO4 / Ksp * 100:	28%	28%	73%
BaSO4 / Ksp * 100:	0%	0%	0%
SiO2 saturation:	3%	3%	6%
Langelier Saturation Index	0.49	0.49	1.77
Stiff and Davis Saturation	-0.42	-0.42	0.76
Ionic strength	0.66	0.66	1.44
Osmotic pressure	25.7 bar	25.7 bar	55.7 bar

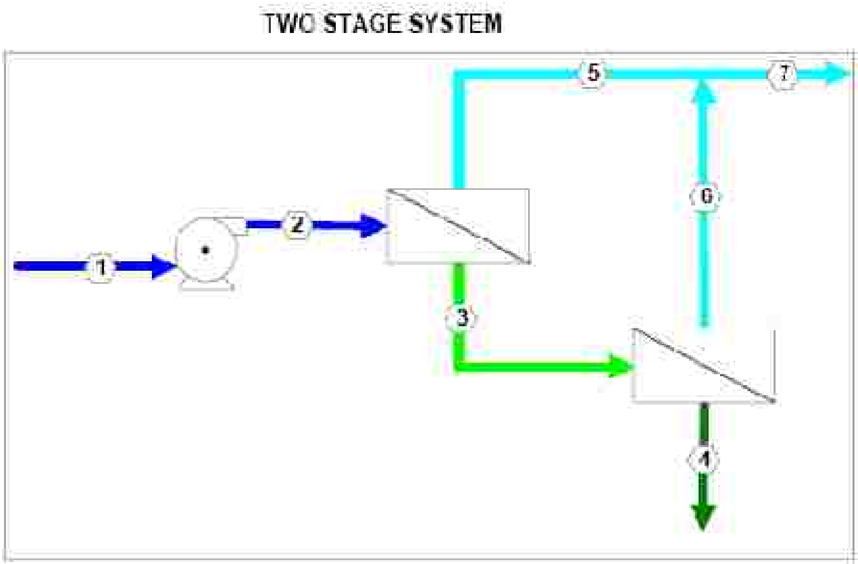
BASIC DESIGN

RO program licensed					
Calculation created	Eleeja Shrestha				
Project name:	SWRO		Permeate flow:	60829.00	m3/d
HP Pump flow:	4693.6	m3/hr	Raw water flow:	112646.3	m3/d
Feed pressure:	63.6	bar	Permeate recovery:	54.0	%
Feedwater	21.0	C(70F)			
Feed water pH:	7.9		Element age:	5.0	years
Chem dose, ppm	0.0	H2SO4	Flux decline % per	6.9	
			Fouling factor:	0.70	
			Salt passage increase,	10.0	
Average flux rate:	13.6	lm2hr	Feed type:	Seawater - open intake	

Stage	Perm. Flow m3/hr	Flow/Vessel Feed m3/hr	Flow/Vessel Conc m3/hr	Flux l/m2-hr	Beta	Conc.and Pressures bar	Throt. Pressures bar	Element Type	Elem. No.	Array
1-1	2158.5	9.4	5.1	19.4	1.02	62.3	0.0	SWC5	3000	500x6
1-2	376.1	7.6	6.5	5.0	1.01	60.7	0.0	SWC5	2004	334x6

St	Ele no.	Fee pres bar	Pre drop bar	Perm flow m3/h	Perm Flux lm2h	Bet	Per sal TDS	Con osm pres	Concentrate saturation levels CaSO	SrSO	BaSO	SiO	Lang
1-1	1	63.6	0.3	1.1	30.1	1.05	90.5	29.2	14	33	0	3	1.2
1-1	2	63.3	0.3	0.9	25.4	1.04	105.2	33.0	16	38	0	3	1.2
1-1	3	63.0	0.2	0.8	20.9	1.04	122.0	36.9	19	44	0	4	1.3
1-1	4	62.8	0.2	0.6	16.7	1.03	141.5	40.7	21	49	0	4	1.4
1-1	5	62.6	0.2	0.5	13.1	1.02	163.7	44.3	24	55	0	5	1.4
1-1	6	62.4	0.2	0.4	10.1	1.02	188.3	47.6	26	60	0	5	1.5
1-2	1	62.1	0.2	0.3	7.8	1.01	206.6	49.6	27	63	0	5	1.5
1-2	2	61.8	0.2	0.2	6.3	1.01	225.8	51.2	29	66	0	5	1.5
1-2	3	61.6	0.2	0.2	5.2	1.01	246.0	52.6	30	68	0	5	1.5
1-2	4	61.4	0.2	0.2	4.2	1.01	266.9	53.8	30	70	0	6	1.6
1-2	5	61.2	0.2	0.1	3.5	1.01	288.6	54.8	31	71	0	6	1.6
1-2	6	60.9	0.2	0.1	2.8	1.01	311.0	55.7	32	73	0	6	1.6

Stage	NDP bar
1-1	26.5
1-2	10.2



		1	2	3	4	5	6	7
Flow	m3/hr	4693.6	4693.6	2535.1	2159.1	2158.5	376.1	2534.5
Pressure	bar	0.0	63.6	62.3	60.7	0.0	0.0	0.0
TDS (ppm)		35409.6	35409.6	65397.1	76612.7	189.8	1007.6	311.1

Figure A1: Schematic of two stage RO system without using ERD

Power Calculation for RO Design without using ERD

BASIC DESIGN

RO program licensed					
Calculation created	Eleeja Shrestha				
Project name:	SWRO		Permeate flow:	60829.00	m3/d
HP Pump flow:	4693.6	m3/hr	Raw water flow:	112646.3	m3/d
Feed pressure:	63.6	bar	Permeate recovery:	54.0	%
Feedwater	21.0	C(70F)			
Feed water pH:	7.9		Element age:	5.0	years
Chem dose, ppm	0.0	H2SO4	Flux decline % per	6.9	
			Fouling factor:	0.70	
			Salt passage increase,	10.0	
Average flux rate:	13.6	lm2hr	Feed type:	Seawater - open intake	

Stage	Perm. Flow m3/hr	Flow/Vessel Feed m3/hr	Conc m3/hr	Flux l/m2-hr	Beta	Conc.andThrot. Pressures bar	bar	Element Type	Elem. No.	Array
1-1	2158.5	9.4	5.1	19.4	1.02	62.3	0.0	SWC5	3000	500x6
1-2	376.1	7.6	6.5	5.0	1.01	60.7	0.0	SWC5	2004	334x6

CALCULATION OF POWER REQUIREMENT

	Main Pump
Feed pressure, bar	63.6
Concentrate pressure, bar	60.7
Permeate flow,m3/d	60829.0
Recovery ratio, %	54.0
Pump efficiency, %	83.0
Motor efficiency, %	93.0
ERT efficiency, %	0.0
ERT backpressure, bar	0.0
Pumping energy, kwhr/m3	4.33
Pumping power, kw	10979.3
Recovered power, kw	0.0
Power requirement, kw	10979.3

RO Design with using ERD

BASIC DESIGN WITH Pressure/Work Exchanger

RO program licensed					
Calculation created	Eleeja Shrestha				
Project name:	SWRO		Permeate flow:	60829.00	m3/d
HP Pump flow:	61347.2	m3/hr	Raw water flow:	112646.3	m3/d
Feed pressure:	65.6	bar	Permeate recovery:	54.0	%
Feedwater	21.0	C(70F)			
Feed water pH:	7.9		Element age:	5.0	years
Chem dose, ppm	0.0	H2SO4	Flux decline % per	6.9	
			Fouling factor:	0.70	
			Salt passage	10.0	
Average flux rate:	13.6	lm2hr	Feed type:	Seawater - open intake	

Stage	Perm. Flow m3/hr	Flow/Vessel Feed m3/hr	Flow/Vessel Conc m3/hr	Flux l/m2-hr	Beta	Conc.andThrot. Pressures bar	Conc.andThrot. Pressures bar	Element Type	Elem. No.	Array
1-1	2166.6	9.4	5.1	19.4	1.02	64.3	0.0	SWC5	3000	500x6
1-2	368.0	7.6	6.5	4.9	1.01	62.8	0.0	SWC5	2004	334x6

Ion	Raw water mg/l	Adjusted mg/l	Feed water mg/l	Permeate mg/l	Concentrate mg/l	ERD Reject mg/l
Ca	200.0	200.0	206.8	0.414	449.0	434.2
Mg	650.0	650.0	672.0	1.345	1459.4	1411.3
Na	12237.5	12237.5	12649.2	121.238	27356.0	26458.0
K	190.0	190.0	196.4	2.351	424.1	410.2
NH4	0.1	0.1	0.1	0.001	0.2	0.2
Ba	0.000	0.000	0.000	0.000	0.000	0.0
Sr	7.400	7.400	7.651	0.015	16.615	16.1
CO3	8.0	8.0	8.5	0.008	18.6	17.9
HCO3	110.0	110.0	113.7	1.945	244.8	236.8
SO4	3000.0	3000.0	3101.7	7.399	6734.1	6512.3
Cl	19000.0	19000.0	19639.3	187.036	42474.6	41080.2
F	0.9	0.9	0.9	0.018	2.0	1.9
NO3	0.0	0.0	0.0	0.000	0.0	0.0
B	2.40	2.40	2.46	0.701	4.52	4.4
SiO2	3.5	3.5	3.6	0.03	7.8	7.6
CO2	0.76	0.78	0.78	0.78	0.78	0.78
TDS	35409.8	35409.8	36602.4	322.5	79191.9	76591.2
pH	7.9	7.9	7.9	6.6	8.5	

	Raw water	Feed water	Concentrate
CaSO4 / Ksp * 100:	12%	13%	33%
SrSO4 / Ksp * 100:	28%	29%	76%
BaSO4 / Ksp * 100:	0%	0%	0%
SiO2 saturation:	3%	3%	6%
Langelier Saturation Index	0.49	0.52	1.80
Stiff and Davis Saturation	-0.42	-0.39	0.79
Ionic strength	0.66	0.69	1.49
Osmotic pressure	25.7 bar	26.6 bar	57.6 bar

H.P. Differential of Pressure/Work Exchanger:	0.5	bar	Pressure/Work Exchanger	1
Pressure/Work Exchanger Pump Boost	1.8	bar	Volumetric Mixing:	6

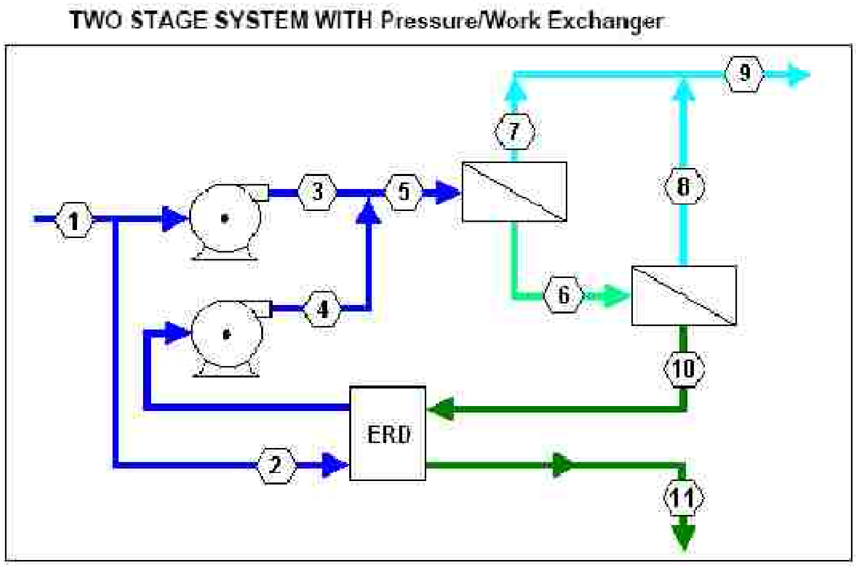
BASIC DESIGN WITH Pressure/Work Exchanger

RO program licensed					
Calculation created	Eleeja Shrestha				
Project name:	SWRO		Permeate flow:	60829.00	m3/d
HP Pump flow:	61347.2	m3/hr	Raw water flow:	112646.3	m3/d
Feed pressure:	65.6	bar	Permeate recovery:	54.0	%
Feedwater	21.0	C(70F)			
Feed water pH:	7.9		Element age:	5.0	years
Chem dose, ppm	0.0	H2SO4	Flux decline % per	6.9	
			Fouling factor:	0.70	
			Salt passage	10.0	
Average flux rate:	13.6	lm2hr	Feed type:	Seawater - open intake	

Stage	Perm. Flow m3/hr	Flow/Vessel		Flux	Beta	Conc.andThrot. Pressures		Element Type	Elem. No.	Array
		Feed m3/hr	Conc m3/hr	l/m2-hr		bar	bar			
1-1	2166.6	9.4	5.1	19.4	1.02	64.3	0.0	SWC5	3000	500x6
1-2	368.0	7.6	6.5	4.9	1.01	62.8	0.0	SWC5	2004	334x6

St	Ele no.	Fee pres bar	Pre drop bar	Perm flow m3/h	Perm Flux lm2h	Bet	Per sal TDS	Con osm pres	Concentrate saturation levels				
									CaSO	SrSO	BaSO	SiO	Lang
1-1	1	65.6	0.3	1.1	30.6	1.05	92.2	30.3	15	34	0	3	1.2
1-1	2	65.3	0.3	1.0	25.7	1.04	107.6	34.2	17	40	0	4	1.3
1-1	3	65.1	0.2	0.8	20.9	1.04	125.3	38.3	20	46	0	4	1.3
1-1	4	64.8	0.2	0.6	16.6	1.03	145.7	42.3	23	52	0	4	1.4
1-1	5	64.6	0.2	0.5	12.9	1.02	168.9	46.0	25	58	0	5	1.5
1-1	6	64.5	0.2	0.4	9.9	1.02	194.6	49.3	27	63	0	5	1.5
1-2	1	64.1	0.2	0.3	7.6	1.01	213.7	51.4	29	66	0	5	1.5
1-2	2	63.9	0.2	0.2	6.2	1.01	233.8	53.0	30	68	0	5	1.6
1-2	3	63.6	0.2	0.2	5.1	1.01	254.7	54.5	31	71	0	6	1.6
1-2	4	63.4	0.2	0.2	4.1	1.01	276.5	55.7	32	73	0	6	1.6
1-2	5	63.2	0.2	0.1	3.4	1.01	299.1	56.7	33	75	0	6	1.6
1-2	6	63.0	0.2	0.1	2.8	1.01	322.3	57.6	33	76	0	6	1.6

Stage	NDP bar
1-1	27.2
1-2	10.4



		1	2	3	4	5	6	7	8	9	10	11
Flow	m3/hr	4693.6	2137.5	2566.1	2137.5	4693.6	2534.5	2166.6	368.0	2534.5	2159.1	2159.1
Pressure	bar	0.0	0.0	65.6	65.6	65.6	64.3	0.0	0.0	0.0	62.8	0.0
TDS (ppm)		35409.8	35409.8	35409.8	38028.1	36602.4	67815.3	196.2	1066.1	322.5	79191.9	76591.2

Figure A2: Schematic of two stage RO system with pressure/work exchanger as ERD

Power Calculation for RO Design with using ERD

BASIC DESIGN WITH Pressure/Work Exchanger

RO program licensed					
Calculation created	Eleeja Shrestha				
Project name:	SWRO		Permeate flow:	60829.00	m3/d
HP Pump flow:	61347.2	m3/hr	Raw water flow:	112646.3	m3/d
Feed pressure:	65.6	bar	Permeate recovery:	54.0	%
Feedwater	21.0	C(70F)			
Feed water pH:	7.9		Element age:	5.0	years
Chem dose, ppm	0.0	H2SO4	Flux decline % per	6.9	
			Fouling factor:	0.70	
			Salt passage	10.0	
Average flux rate:	13.6	lm2hr	Feed type:	Seawater - open intake	

Stage	Perm. Flow	Flow/Vessel Feed	Flow/Vessel Conc	Flux	Beta	Conc.andThrot. Pressures		Element Type	Elem. No.	Array
	m3/hr	m3/hr	m3/hr	l/m2-hr		bar	bar			
1-1	2166.6	9.4	5.1	19.4	1.02	64.3	0.0	SWC5	3000	500x6
1-2	368.0	7.6	6.5	4.9	1.01	62.8	0.0	SWC5	2004	334x6

CALCULATION OF POWER REQUIREMENT

	Main Pump	ERD Boost
Feed pressure, bar	65.6	65.6
Concentrate pressure, bar	62.8	63.8
Permeate flow,m3/d	60829.0	60829.0
H.P. Differential of Pressure/Work Exchanger, Bar		0.5
Recovery ratio, %	54.0	
Pump efficiency, %	83.0	83.0
Motor efficiency, %	93.0	93.0
ERT efficiency, %	0.0	
ERT backpressure, bar	0.0	
Pumping energy, kwhr/m3	2.54	
Pumping power, kw	6445.9	
Recovered power, kw	0.0	
Power requirement, kw	6445.9	

H.P. Differential of Pressure/Work	0.5	bar	Pressure/Work Exchanger	1 %
Pressure/Work Exchanger Pump	1.8	bar	Volumetric Mixing:	6 %

Table A1: Cost of seawater desalination supply option using Net Present Value method

Capacity (m^3/y)	**Fiscal Year**	**Year**	**Total Capital Cost**	**No of Desalination Plant**	**Dismantling Cost**	**Salvage Value**	**Annual O & M Cost**				**NPV**
							Operating & Maintenance Cost/ Plant	**Yearly Operating & Maintenance Cost**	**Electrical cost for moving water in valley**	**Water treatment cost**	
	2011	0	$164,806,654	1							$164,796,699
	2012	1									
19,982,406	2013	2					$12,035,121	$12,035,121	$3,922,077	$378,463	$14,538,719
19,982,406	2014	3					$12,339,282	$12,339,282	$4,100,227	$395,653	$14,135,164
19,982,406	2015	4					$12,651,129	$12,651,129	$4,286,592	$413,637	$13,743,936
19,982,406	2016	5					$12,970,858	$12,970,858	$4,481,174	$432,413	$13,363,830
19,982,406	2017	6	$203,610,771	2			$13,298,667	$13,298,667	$4,684,711	$452,053	$156,534,115
19,982,406	2018	7					$13,634,760	$13,634,760	$4,897,502	$472,587	$12,639,367
39,964,812	2019	8					$13,979,348	$27,958,696	$10,282,372	$988,106	$24,612,972
39,964,812	2020	9					$14,332,644	$28,665,288	$10,749,620	$1,033,007	$23,941,153
39,964,812	2021	10					$14,694,869	$29,389,738	$11,237,694	$1,079,909	$23,288,694
39,964,812	2022	11	$241,569,661	3			$15,066,248	$30,132,497	$11,748,123	$1,128,960	$149,913,275
39,964,812	2023	12					$15,447,014	$30,894,027	$12,281,755	$1,180,240	$22,043,690
59,947,217	2024	13					$15,837,402	$47,512,205	$19,389,448	$1,850,775	$32,233,965
59,947,217	2025	14					$16,237,656	$48,712,968	$20,270,401	$1,934,865	$31,367,332
59,947,217	2026	15					$16,648,026	$49,944,078	$21,190,897	$2,022,728	$30,525,809
59,947,217	2027	16	$284,639,577	4			$17,068,767	$51,206,301	$22,153,423	$2,114,604	$141,757,972
59,947,217	2028	17					$17,500,141	$52,500,424	$23,159,692	$2,210,655	$28,918,556
79,929,623	2029	18					$17,942,418	$71,769,670	$32,582,512	$3,081,426	$37,638,844
79,929,623	2030	19					$18,395,871	$73,583,486	$34,062,742	$3,221,415	$36,643,329
79,929,623	2031	20					$18,860,785	$75,443,141	$35,609,709	$3,367,717	$35,676,652
79,929,623	2032	21	$332,820,517	5			$19,337,449	$77,349,795	$37,227,175	$3,520,685	$132,640,395

Capacity (m^3/y)	Fiscal Year	Year	Total Capital Cost	No of Desalination Plant	Dismantling Cost	Salvage Value	Annual O & M Cost				NPV
							Operating & Maintenance Cost/ Plant	Yearly Operating & Maintenance Cost	Electrical cost for moving water in valley	Water treatment cost	
79,929,623	2033	22					$19,826,159	$79,304,635	$38,918,133	$3,680,604	$33,828,920
99,912,029	2034	23					$20,327,220	$101,636,099	$51,456,769	$4,809,734	$41,338,594
99,912,029	2035	24					$20,840,944	$104,204,721	$53,794,333	$5,028,229	$40,264,353
99,912,029	2036	25					$21,367,652	$106,838,258	$56,237,539	$5,256,599	$39,221,065
99,912,029	2037	26	$386,112,482	5	$38,611,248		$21,907,671	$109,538,353	$58,791,995	$5,495,367	$131,567,468
99,912,029	2038	27					$22,461,337	$112,306,685	$61,462,480	$5,744,981	$37,225,557
99,912,029	2039	28					$23,028,996	$115,144,982	$64,254,264	$6,005,933	$36,270,909
99,912,029	2040	29					$23,611,002	$118,055,009	$67,173,060	$6,278,757	$35,343,934
99,912,029	2041	30					$24,207,716	$121,038,581	$70,224,021	$6,563,934	$34,443,520
99,912,029	2042	31	$444,515,472	5	$44,451,547		$24,819,511	$124,097,557	$73,413,774	$6,862,085	$113,884,676
99,912,029	2043	32					$25,446,768	$127,233,840	$76,748,414	$7,173,778	$32,720,229
99,912,029	2044	33					$26,089,877	$130,449,386	$80,234,520	$7,499,629	$31,895,462
99,912,029	2045	34					$26,749,240	$133,746,198	$83,879,129	$7,840,296	$31,094,340
99,912,029	2046	35					$27,425,266	$137,126,329	$87,688,967	$8,196,407	$30,315,992
99,912,029	2047	36	$508,029,486	5	$50,802,949		$28,118,377	$140,591,886	$91,672,020	$8,568,708	$98,151,582
99,912,029	2048	37					$28,829,005	$144,145,026	$95,835,991	$8,957,920	$28,825,452
99,912,029	2049	38					$29,557,593	$147,787,964	$100,189,100	$9,364,811	$28,111,748
99,912,029	2050	39					$30,304,594	$151,522,969	$104,740,056	$9,790,195	$27,418,268
99,912,029	2051	40					$31,070,474	$155,352,368	$109,497,486	$10,234,878	$26,744,314
99,912,029	2052	41	$576,654,525	5	$57,665,453		$31,855,709	$159,278,546	$114,471,132	$10,699,772	$84,268,692
99,912,029	2053	42					$32,660,790	$163,303,949	$119,670,694	$11,185,782	$25,452,947
99,912,029	2054	43					$33,486,217	$167,431,085	$125,106,432	$11,693,868	$24,834,302
99,912,029	2055	44					$34,332,505	$171,662,525	$130,789,163	$12,225,040	$24,232,973

Capacity (m^3/y)	**Fiscal Year**	**Year**	**Total Capital Cost**	**No of Desalination Plant**	**Dismantling Cost**	**Salvage Value**	**Annual O & M Cost**				**NPV**
							Operating & Maintenance Cost/ Plant	**Yearly Operating & Maintenance Cost**	**Electrical cost for moving water in valley**	**Water treatment cost**	
99,912,029	2056	45					$35,200,181	$176,000,905	$136,729,835	$12,780,323	$23,648,389
99,912,029	2057	46	$650,390,589	5	$65,039,059		$36,089,786	$180,448,928	$142,940,441	$13,360,836	$72,114,117
99,912,029	2058	47					$37,001,873	$185,009,365	$149,433,146	$13,967,718	$22,527,621
99,912,029	2059	48					$37,937,011	$189,685,056	$156,220,766	$14,602,167	$21,990,416
99,912,029	2060	49					$38,895,783	$194,478,915	$163,316,757	$15,265,438	$21,468,053
99,912,029	2061	50					$39,878,785	$199,393,927	$170,735,002	$15,958,832	$20,960,065
99,912,029	2062	51				$1,245,603,678	$40,886,631	$204,433,155	$178,490,156	$16,683,717	-$43,328,073
										Net Present Value	$2,201,382,511
										Total volume of water produced (m^3)	3,916,551,538
										Unit cost of water ($/$m^3$)	$0.56

Table A2: Cost of water conveyance supply option from distant location using Net Present Value method

Capacity (m^3/y)	**Fiscal Year**	**Year**	**Total Capital Costs**	**Operating & Maintenance Cost**	**NPV**
	2011	0	$2,683,455,453		$2,683,293,364
	2012	1			
	2013	2			
	2014	3			
	2015	4			
	2016	5			
	2017	6			
	2018	7			
	2019	8			
99,912,029	2020	9		$56,201,912	$33,265,957
99,912,029	2021	10		$57,622,287	$32,175,338
99,912,029	2022	11		$59,078,560	$31,121,948
99,912,029	2023	12		$60,571,636	$30,102,392
99,912,029	2024	13		$62,102,447	$29,116,180
99,912,029	2025	14		$63,671,945	$28,162,278
99,912,029	2026	15		$65,281,108	$27,239,219
99,912,029	2027	16		$66,930,940	$26,347,203
99,912,029	2028	17		$68,622,467	$25,484,051
99,912,029	2029	18		$70,356,744	$24,649,144
99,912,029	2030	19		$72,134,851	$23,841,591
99,912,029	2031	20		$73,957,896	$23,060,278
99,912,029	2032	21		$75,827,013	$22,304,989
99,912,029	2033	22		$77,743,369	$21,574,253
99,912,029	2034	23		$79,708,156	$20,867,440
99,912,029	2035	24		$81,722,598	$20,183,784
99,912,029	2036	25		$83,787,951	$19,522,402
99,912,029	2037	26		$85,905,501	$18,882,933
99,912,029	2038	27		$88,076,567	$18,264,295
99,912,029	2039	28		$90,302,503	$17,665,924
99,912,029	2040	29		$92,584,693	$17,087,157
99,912,029	2041	30		$94,924,561	$16,527,287
99,912,029	2042	31		$97,323,563	$15,985,888
99,912,029	2043	32		$99,783,195	$15,462,163
99,912,029	2044	33		$102,304,989	$14,955,596
99,912,029	2045	34		$104,890,515	$14,465,626

Capacity (m^3/y)	Fiscal Year	Year	Total Capital Costs	Operating & Maintenance Cost	NPV
99,912,029	2046	35		$107,541,384	$13,991,674
99,912,029	2047	36		$110,259,248	$13,533,316
99,912,029	2048	37		$113,045,800	$13,089,942
99,912,029	2049	38		$115,902,776	$12,661,094
99,912,029	2050	39		$118,831,955	$12,246,296
99,912,029	2051	40		$121,835,163	$11,845,070
99,912,029	2052	41		$124,914,269	$11,457,023
99,912,029	2053	42		$128,071,194	$11,081,672
99,912,029	2054	43		$131,307,902	$10,718,618
99,912,029	2055	44		$134,626,411	$10,367,459
99,912,029	2056	45		$138,028,787	$10,027,796
99,912,029	2057	46		$141,517,151	$9,699,278
99,912,029	2058	47		$145,093,676	$9,381,514
99,912,029	2059	48		$148,760,589	$9,074,160
99,912,029	2060	49		$152,520,174	$8,776,876
99,912,029	2061	50		$156,374,775	$8,489,328
99,912,029	2062	51		$160,326,792	$8,211,207
99,912,029	2063	52		$164,378,687	$7,942,194
99,912,029	2064	53		$168,532,985	$7,681,996
99,912,029	2065	54		$172,792,273	$7,430,321
99,912,029	2066	55		$177,159,205	$7,186,892
99,912,029	2067	56		$181,636,502	$6,951,438
99,912,029	2068	57		$186,226,951	$6,723,698
99,912,029	2069	58		$190,933,414	$6,503,419
Net Present Value					$3,330,562,719
Total volume of water produced (m^3)					4,895,689,423
Unit cost of water ($/m^3)					$0.68

VITA

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