THESIS

SUBSURFACE WATER STORAGE ASSESSMENT MODEL

Submitted by

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ABSTRACT

SUBSURFACE WATER STORAGE ASSESSEMENT MODEL

Water storage is an essential part of water resources management schemes. Due to the high cost and escalating risks of building new surface reservoirs, water managers are becoming interested in employing more effective alternatives. Subsurface water storage is getting attention as one of these alternatives. However, due to lack of experience and tools to estimate the cost and effectiveness of subsurface water storage, water managers are reluctant to adopt this alternative. Available tools/models are only case specific; hence in this study, we develop a general model for subsurface storage and recovery. The model estimates the cost of the subsurface water storage and recovery using wells in bedrock. The model takes monthly river flow, population, and per capita demand as inputs to determine capital cost and operation and maintenance costs for the lifespan of the proposed project. To account for uncertainty in the input parameters, the model has the capability to perform stochastic analyses as well. Furthermore, the model includes the option of modular expansion of infrastructure through time, potentially reducing total and operation and maintenance costs. An application of the model is advanced based on the conditions in the vicinity of Fort Collins, Colorado.

Critically, work presented herein should not be taken as a rigorous analysis of the issues faced by the city of Fort Collins. The application is simply a demonstration of what can be done with the tools developed in this thesis. The general premise of the application is creating new water storage in the Fountain Formation, north of Fort Collins.

This model uses either deterministic or stochastic inputs. Since the deterministic model's inputs and outputs are both fixed numbers, the model is relatively simple. However, this type of

input will yield specific results and does not consider the possibility of inputs varying through time. It misses a key challenge of water projects, the temporal variability in available water and demand. In Stochastic Analysis, inputs are varies from year to year and from month to month, allowing the system to accommodate wet or drought years, making the model more reliable for calculating the cost of system.

One hundred simulations were performed using the stochastic model to estimate the range of variability of outputs. Except total pumping and additional storage, other outputs have small coefficients of variation, which show that they are less sensitive to uncertainity in input variables. The coefficient of variation for cost variables are around 0.1 (i.e., costs are expected to vary within ±10% of the estimated mean cost). As different cost components estimated by deterministic model are within ±10% of estimated mean cost from stochastic model. Therefore, we conclude that the deterministic model estimates different cost components fairly well.

Both models, deterministic and stochastic, have been applied to a scenario predicted on conditions faced by the city of Fort Collins. At thirtieth year, the system can deliver 7.8×10^6 m^3/year of water (6.4×10^3acre-ft/year) in an average year and up to $15.7\times10^6 m^3$/year of water (12.7×10^3acre-ft /year) in a drought year. The estimated present value cost from deterministic and stochastic models of the entire project was $ 23.1 million U.S and **$** 22.5 million U.S., respectively. Not considered in the cost analysis is the value of the water saved due to reduced losses of evaporation and seepage losses, inherent with surface water storage.

The model shows high reliability in meeting demand through the lifespan of the project, with no failure anticipated. The deterministic model added 9.12 million m^3 to the aquifer, while the stochastic model shows an average addition of 16.8 million m^3 to the aquifer. Greater stored water with the stochastic model is attributed to less pumping of groundwater. Further study is needed to resolve the basis for the stochastic model pumping less groundwater.

The capital cost of the project is predicted to be approximately $ 6.0 million U.S. by both models. Both models estimated the need for 10 ASR wells and two alluvium inflow drain units through the the lifespan of the project. The case study of Fort Collins shows the potential of subsurface water storage as a viable and cost effective alternative to surface water storage.

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1. INTRODUCTION

1.1. Problem Statement

Water is vital part of life on earth. It is important for plants, animals, and people. In 1999, the world population was six billion people and is expected to reach eight billion people by 2024 (World population clock, 2014). This increase means that the demand for water will increase dramatically as the population rises. However, population growth is not the only the reason for the growing demand. The increase in quality of life and climate change also require new water resources (Mogelgaard, 2011). The limited resources and the rising demand require effective and creative water management to avoid any shortage in supplies (Bouwer, 1994).

The streamflow of rivers changes from year to year. In 2011, the mean runoff in the United States streams and rivers was higher than the long-term annual average (Harry Lins, 2012). The natural flow of streams differs significantly throughout the year because of weather changes. The flow is high in some seasons and lower in other seasons. This variation in supply and demand throughout the year requires efficient water storage. Water is currently stored in either surface water reservoirs or in aquifers through recharge.

The idea of surface water reservoirs is one of the oldest and most common methods for storing water. Surface water storage is most feasible where evaporative losses are low, seepage losses can be controlled, and affordable land is available. The high cost of construction, the huge land area it requires, potentially high losses, and the exposure to contaminants can constrain the efficiency of surface water storage. Also, the environmental concerns about surface storage and the difficulty in finding an appropriate site can make surface water storage a poor choice (Winter et al., 1998).

Artificial recharge is a method of storing water underground for later use. Infiltration ponds, injection wells, drainage pipes, and aquifer storage and recovery (ASR) are the most common techniques in aquifer artificial recharge. ASR has been introduced lately as a viable option to store and recover excess water at the same location, reducing the cost by using the same well for water pumping and injecting. The primary concerns regarding this technology are the quality of recovered water, formation plugging, and the potential that stored water could be lost (Malcom Pirnie Inc., 2011).

1.2. Research Objectives

The objective of this research is to develop a model that can estimate the cost of the subsurface water storage and recovery through ASR wells. This model is designed as a general tool that can be applied to a wide range of case studies. Critically, the models address the need to expand systems through time to meet future demands.

1.3. Contents

This thesis contains five chapters. The first chapter states the problem and clarifies the research objectives. The second chapter is a literature review of the work that has been previously conducted in this field and the theory of this work. The third chapter is a description of a model that has been used to calculate the cost of the aquifer storage and recovery system. The fourth chapter discusses model outputs based on specific inputs. The last chapter presents conclusions and recommendations for future work.

2. LITERATURE REVIEW

2.1. Artificial Recharge

2.1.1. Overview

Artificial recharge systems are systems that infiltrate surface water into soil which then moves to aquifers (Bouwer, 1994). The main idea of recharging aquifers is to store excess water to be pumped when needed. The excess water can be treated waste water or water from streams. Artificial recharge can reduce or stop a declining water table due to pumping. In some sites, it may increase the level of the water table (Asano, 1985). In Highlands Ranch, Colorado, where water injection has exceeded water pumping, artificial recharge has caused a rise in the water table level (Centennial Water and Sanitation, 2012). Moreover, artificial recharge could be used to prevent sea saltwater intrusion by increasing water pressure in fresh aquifers. Water that has been artificially recharged can be treated via interaction with aquifer solids, thus improving the quality of the water in a process called *Geopurification* (Bouwer, 1994). Finally, artificial recharge can reduce the cost of transmitting water from one point to another by using the aquifer as a water conveyance system (Pyne, 1995).

2.1.2. Artificial Recharge Methods

Artificial recharge can be performed using different methods, including:

Surface infiltration: There are two types of surface infiltration systems for artificial recharge: in-channel systems and off-channel systems. In-channel systems are systems that obstruct the flow of the stream and accumulate water behind it. The most common example of in-channel flow systems are dams. In dams, water accumulates behind the dam, infiltrates into the soil, and then moves to the aquifers. Off-channel systems are systems that store surface water but do not obstruct the flow of the stream. Infiltration basins and irrigation fields are clear examples of off-channel systems. Both systems require a large amount of available land to store water and permeable soil to infiltrate water (Bouwer, 2002).

Vadose-zone infiltration: Artificial recharge can be accomplished in the vadose zone by infiltration systems. These systems can be wells, trenches, or drains. Wells can be made at the vadose zone to infiltrate water. These wells can be 1×10^0 m in diameter and reach 60×10^0 m (196.9 ft) deep. Also, trenches of 1×10^0 m wide and 5×10^0 m (16.4ft) deep can be made to infiltrate water. Wells and trenches clog easily from suspended solids, making them less efficient. However, drains can inject the water into the vadose zone and extract it. By frequent injection and extraction, termed "backwash", drains are less likely to be plugged by suspended solids (Bouwer, 2002).

Wells: Water injection through deep wells to confined aquifers presents a practical opportunity to recharge aquifers. Unlike other methods, direct injection to confined aquifers can store water for a long period of time with almost infinite space. For operational reasons, water should be treated before injection to avoid clogging of wells (Pyne, 1995). In addition, water treatment is an important step in avoiding the contamination of native water that already exists in the aquifer. Water treatment levels depend on many factors. In most cases, water treatment should meet or exceed potable water drinking standards. Due to the plugging of single-purpose wells, some projects both inject and pump the water from the same well. This procedure will reduce clogging in the well due to successive pumping and injection (Pyne, 1995). Likewise, use of individual wells for both delivery and recovery of water can reduce the number of wells that operate in the same field. This process is called "aquifer storage and recovery".

2.1.3. Applications of Artificial Recharge

Although the main application of artificial recharge is to store surplus water for later use, many applications exist for artificial recharge. According to Pyne (1995), these applications include:

- Seasonal water storage
- Long-term water storage
- Emergency water storage
- Increasing water table level
- Preventing sea saltwater intrusion
- Soil and groundwater remediation
- Deferred expansion of water facilities
- Enhanced well field production

2.2. Subsurface Water Storage in Bedrock

Subsurface water storage in bedrock can be achieved via many methods. As Pyne (1995) explains, these methods are single-purpose recharge wells (injection wells) and dual-purpose recharge/production wells (aquifer storage and recovery wells).

2.2.1. Aquifer Storage and Recovery

Pyne (1995) defined ASR as the storage of water in an aquifer through a well that occurs when water is in surplus. The stored water can then be extracted when it is needed from the same well. ASR can be done in confined, semi-confined, or unconfined aquifers. Most often, ASR operates best in semi-confined aquifers that have been over pumped. ASR is less feasible with unconfined aquifers because of the high velocity of water in unconfined aquifers compared to water velocity in confined and semi-confined aquifers (Pyne, 1995).

2.2.2. Aquifer Storage and Recovery Advantages and Disadvantages

In addition to artificial recharge advantages, aquifer storage and recovery has supplementary advantages. These advantages include:

Cost effectiveness: In the last two decades, ASR wells have proven to be cost effective, a result of using the same well to inject and extract water, thereby reducing capital cost. Moreover, water injection and recovery through the same well decreases well clogging, in turn reducing maintenance cost (Topper et al., 2004).

Minimizing losses: ASR can sharply reduce evaporative losses from surface reservoirs. Water yield will increase by harvesting evaporative losses because water is stored in deep aquifers, which are distant from the surface (Weisheit, 2008),

Minimal surface impact: Land area requirements of the ASR system are far less than land required by surface reservoirs to store same amount of water.

Permitting: In some states, permitting ASR wells is cheaper and faster than permitting other water storage methods, thereby reducing cost and project time.

Some disadvantages may prevent the usage of ASR as a water storage tool. For example, in a survey sent to 22 water utilities in Texas asking them about their concerns about ASR projects (Malcolm Pirnie Inc et al., 2011). Their concerns include:

- Uncertainty of recovering injected water
- Recovered water quality

- ASR cost effectiveness

Other disadvantages that might be considered include:

- System complexity
- Local regulations
- Lack of experience

2.2.3. Aquifer Storage and Recovery Projects

Due to increasing need for water storage, cities have become interested in alternatives to current surface reservoirs. In 2009, there were more than 590 ASR wells operating in the United States. Most of these wells are in the Western and Southeastern states (EPA, 2012). The ASR technique is not common in the Northeastern and Midwest regions of the United States, probably due to the availability of abundant drinking water in the Northeastern region compared to the Western region (EPA, 2012).

2.2.3.1. Examples of ASR Projects in the United States

Las Vegas, Nevada: Las Vegas has the biggest ASR well field in the world with more than 42 ASR wells and 22 injection wells. The recharge capacity of the well field is more than 6.51×10^3 m^3/sec (455.2 acre-ft/day) with a recovery capacity of more than 9.92×10^3 m^3/sec (694.0 acre-ft/day) (NGWA, 2010).

San Antonio, Texas: The San Antonio Water System has the third largest ASR facility in the United States with more than 29 high-capacity ASR wells and three aquifer pumping wells. ASR wells recharge capacities range from 7.82×10^3 to 13.10×10^3 m^3/day (5.3–8.8 acre-ft/day) each (Pirnie, 2011). The Oaks aquifer stores more than 74.1×10^6 m^3 (60.0×10^3 acre-ft) of drinking water. The city recovered some of this stored water during an extreme drought between 2006 and 2009 (NGWA, 2010).

Highlands Ranch, Colorado: Centennial Water District has more than 25 ASR wells and injected more than 56.0×10^6 m^3 (14×10^3 acre-ft) of water through ASR wells. This amount of water is available to the city and can be recovered when needed (Centennial Water District, 2012).

2.2.3.2. Examples of International ASR Projects

Canada: Canada has many ASR projects around the country, one of them in Kitchener, Ontario. Kitchener has a water treatment plant that can treat 72.0×10^3 m^3 /day (58 acre-ft/day). This amount of treated water exceeds the demand for most of the year. The surplus water is injected through ASR wells to be recovered later when needed (Pyne, 1995).

Australia: There are many ASR well fields in South Australia that have been successful for many years. The City of Salisbury in northern Adelaide, for example, is catching storm water runoff and injecting it through ASR wells after treatment. The capacity of the system in 2009 was 13.7×10^3 m^3/day (11.1 acre-ft/day) (Hains, 2009).

England: In London, a private water company, Thames Water Utilities, t serves customers in London and Thames Valley. The surplus treated water during the winter months is injected for later use. The main purpose of the storage is to meet the demand during drought years (Pyne, 1995).

2.3. Models for Artificial Recharge

In the past few years, there were some models that simulated artificial recharge systems and conjunctive use of surface and groundwater to meet water demand (Almulla et al., 2004; Maurer, 2012; Bharati et al., 2008; Harou & Lund, 2008; Khan et al., 2008; Marques et al., 2006; Vieira et al., 2011). All but Maurer (2012) focused on hydraulic routing through the system and did not study the cost of the system in detail. Furthermore, most of the models were designed for a specific case study, which makes these models difficult to apply to other cases. For example, (Almulla et al., 2004) designed a model that can estimate the cost of aquifer storage and recovery as a strategic facility to balance water production and demand for Emirate of Sharjah, United Arab Emirates. Even though the model estimated the cost of ASR in most economic aspects, such as capital cost, operation, and maintenance cost, it did not account for the variation of water throughout the year. Since the main water supply in Sharjah is a desalination plant with consistent water levels, the Sharjah model did not need to accommodate water-level variation.

The model developed by Maurer (2012) routed water through a surface reservoir and an ASR well, with the total cost including the surface reservoir and subsurface storage, which is not the case in the model for this research. This model stores water only in the subsurface. The third example is from Marques et al. (2006), whose model simulated how water users make decisions in the market based on their reaction to their access to water and water cost. Furthermore, the Marques model simulates their decision to conserve, exchange, and select supplies of water. This model does not calculate the cost of storing water subsurface separately, so it can be used as a subsurface water storage estimation tool for multiple communities.

2.4. Stochastic vs Deterministic Model

This model uses either deterministic or stochastic inputs. Since the deterministic model's inputs and outputs are both fixed numbers, the model is relatively simple. However, this type of input will yield specific results and does not consider the possibility of inputs varying through time. It misses a key challenge of water projects, the temporal variability in available water and demand. In Stochastic Analysis, inputs are varies from year to year and from month to month, allowing the system to accommodate wet or drought years, making the model more reliable for calculating the cost of system. Stochastic inputs for this system are streamflow, annual population growth rate, and per capita demand.

3. MODEL DESCRIPTION

3.1. Overview

This chapter discusses the subsurface water storage model developed in this thesis. The model was developed using MATLAB R2013b. Matlab is a widely-used program for scientific and engineering calculations (MathWorks, 2014). The model uses two types of inputs, deterministic and stochastic. Figure 1 shows the schematic type of this model.

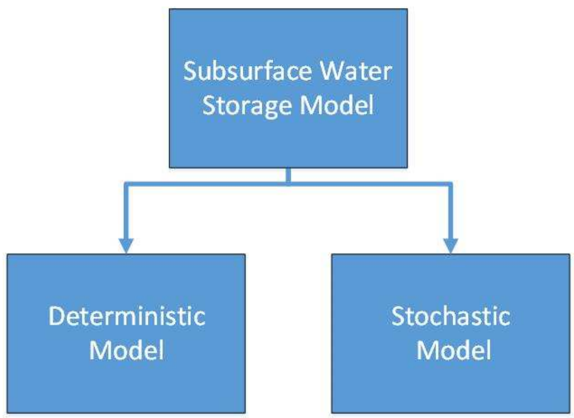

Figure 1: Schematic Type of Subsurface Water Storage.

To make the work more organized, the programming language (code) was divided into four files for the deterministic model and into five files for the stochastic model. These files are: input file, hydraulic calculations, cost calculations, output file, with the extra file in the stochastic model being the stochastic file. Figure 2 shows the code files for the deterministic model. Figure 3 shows the code files for the stochastic model.

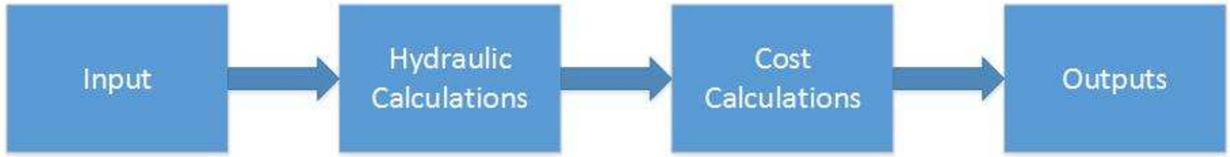

Figure 2: Code Files for the Deterministic Model.

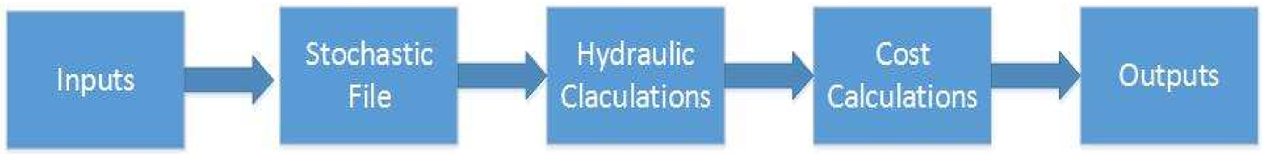

Figure 3: Code Files for the Stochastic Model.

3.2. Aquifer Storage and Recovery in Aquifers

This model estimates costs for subsurface water storage. Cost includes capital costs through-time, and operation and maintenance costs. To evaluate these costs, the model considers demand through time and variation in available raw water. The model has two different inputs, the deterministic and stochastic inputs, as discussed before. Figure 4 shows the key elements of the subsurface water storage model. The key elements as shown in the figure are:

- Raw water (river in this case).
- Alluvial inflow drains to divert water.
- Water treatment plant (treatment plant is treating surface and groundwater).
- Aquifer storage and recovery wells (ASR wells).
- Customers.

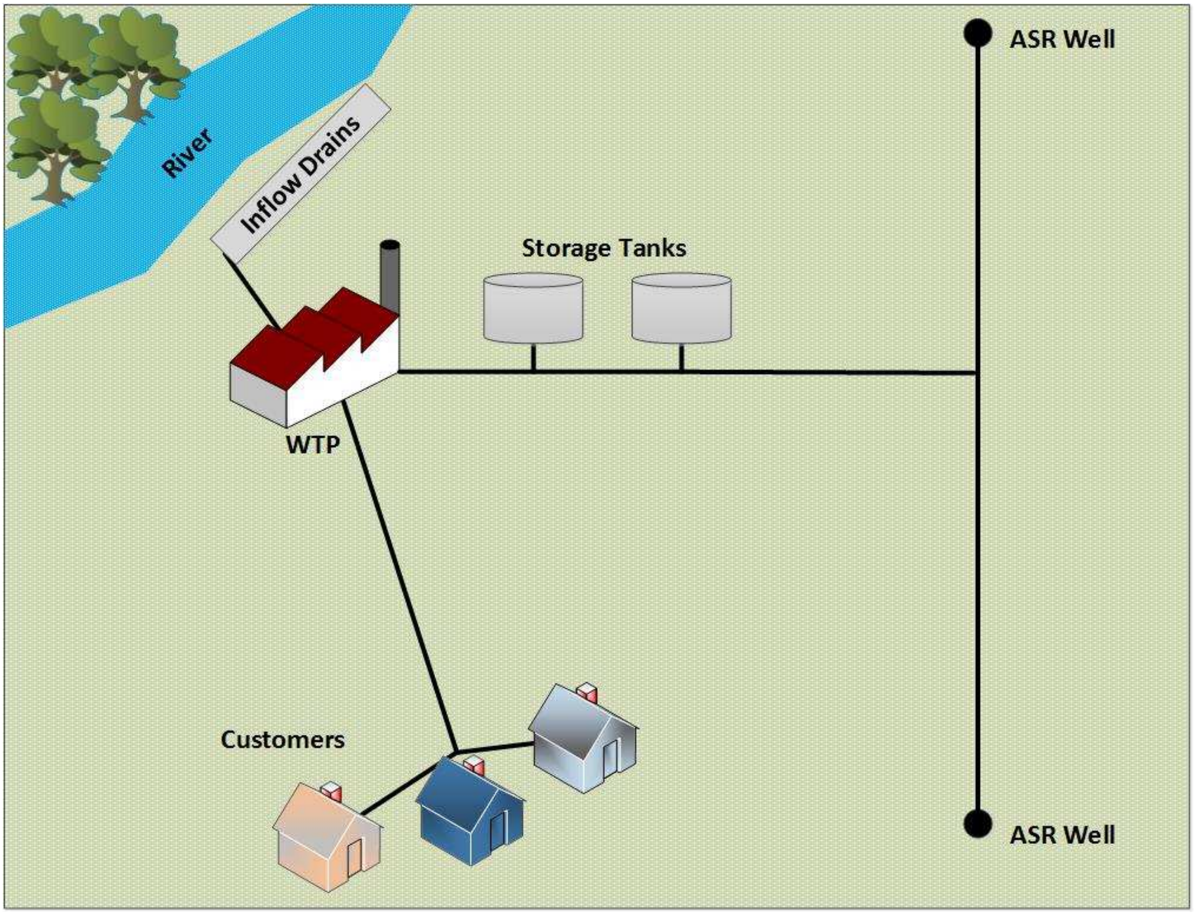

Figure 4: Key Elements of the Subsurface Water Storage Model.

3.2.1. Deterministic Model

The main advantage of deterministic inputs is simplicity. However, deterministic inputs generate fixed-result numbers that overlook the key variables of available water and demand from year to year. This section addresses the deterministic inputs, hydraulic and cost calculations, and the output files.

3.2.1.1. Inputs

The deterministic model inputs include hydraulic and cost parameters. The hydraulic inputs are:

Initial population: This input indicates the initial population for the city or the area under study.

Per capita demand: This input indicates monthly per capita (c) demand for the area under study, calculated by dividing the total water demand by the population. The unit used in this model is m^3/c/month.

Population growth rate: This input indicates the rate of population increase for a specific time. In this model, a percent/year unit is used. Equation 1 calculates this rate (Zender Environmental, 2006):

$$population\ growth\ rate = \frac{P(t_2) - P(t_1)}{P(t_1)} \qquad (1)$$

Where P (t_1) is population at time 1, P (t_2) is population at time 2.

Life span of project: This input indicates the lifespan of the project in years.

Monthly streamflow: This input indicates the average monthly flow of the stream that supplies the system with raw water. This input averages 12 months from January until December. The unit used in this model is m^3/month.

Inflow-drain capacity: This input indicates the capacity of inflow drains nearby the stream. A primary concept of this thesis is to use alluvial drains to divert water, low in total suspended solids (TSS), from surface water bodies. The unit used in this model is m^3/month/drain.

Aquifer capacity: This input indicates the capacity of the aquifer that the water will be injected into and extracted from. The unit of this input is m^3.

Aquifer storage: This input indicates the remaining volume of the aquifer that is initially available for water storage, calculated by subtracting the volume of water in the aquifer from the total capacity of aquifer. The unit of this input is m^3.

Water treatment plant initial capacity: This input indicates initial treatment plant capacity. This treatment plant will be used to treat water pumped from nearby the river. The unit of this input is m^3/month. In most cases, the primary goal of water treatment is to limit plugging of the storage zone due to TSS or inorganic precipitants.

Water-treatment-plant expansion increment: This input indicates the increment that water treatment plant can be expanded by. This process is to reduce capital cost and delay expansion of the system. The unit for the water treatment plant capacity is m^3/month.

Water-treatment-plant capacity limit: This input indicates the flow rate that the water-treatment-plant capacity cannot exceed without expansion. The unit used in this model is m^3/month.

Transmissivity: This input indicates the transmissivity of the aquifer that the system will inject into and pump the water from. The unit is m^2/sec.

Storativity: This input indicates the storativity of the aquifer that the system will inject into and pump the water from. This unit is dimensionless.

Drawdown: This input indicates the drawdown allowed at an ASR well. The unit is m.

Well spacing: This input indicates the distance between ASR wells. The unit is m.

Land required for ASR well: This input indicates the land that is required for each ASR well. The unit is m^2.

Land required for water treatment plant: This input indicates the amount of land required for the water treatment plant. The unit is m^2.

Distance from alluvium drains to water treatment plant: Distance between alluvium drains to water treatment plant. The unit is m.

Distance from water treatment plant to the first ASR well: Distance between water treatment plant and the first ASR well. The unit is m.

Distance from water treatment plant to the city: Distance between water treatment plant and the city pipe. The unit is m.

Total dynamic head in pumping: This input is for the total dynamic head during pumping. The unit is m.

Total dynamic head in injection: This input is for the total dynamic head during injection. The unit is m.

Labor: This input indicates number of people who operate the project.

Pump efficiency: This input is for pump efficiency. This input is in percentage (%).

Injection percentage: This input is the percentage that the system is allowed to pump from the river to the city's total demand. The main point of this restriction is to maintain a smooth the expansion of the system, avoiding sudden expansions. This input is in percentage (%).

Water rights from mid-October to mid-April: This input indicates water rights that the project owns between mid-October to mid-April. The unit is m^3/sec.

Water rights from mid-April to July: This input indicates water rights that the project owns between mid-April to the end of July. The unit is m^3/sec.

Water rights from August to mid-October: This input indicates water rights that the project owns between August 1st and mid-October. The unit of this input is m^3/sec.

The cost inputs are:

Water-treatment-plant initial cost: This input indicates the water-treatment-plant construction cost. The unit is $.

Diverted groundwater-water treatment plant operation and maintenance cost per m^3: This input indicates the cost of diverted groundwater-treatment plant operation and maintenance per m^3. This water is diverted by the inflow drains. The unit used is $/$m^3$.

Groundwater-treatment plant operation and maintenance cost per m^3: This input indicates the cost of groundwater treatment plant operation and maintenance per m^3. This water is pumped by ASR wells. The units used in this model is $/$m^3$.

ASR well cost: This input indicates the cost of each ASR well. The unit used in this model is $/well.The capacity of ASR wells will be discussed later.

ASR well operation and maintenance cost: This input indicates the cost of each ASR well's operation and maintenance. The unit used in this model is $/well.

Inflow drains units cost: This input indicates the cost of inflow drains nearby the stream. This input is for each drain. Each unit is 152.4m (500ft) long and has a capacity of 10,900 m^3/day (2000 gpm). The unit used in this model is $/unit.

Inflow drain operation and maintenance cost per unit: This input indicates the cost of operation and maintenance of one inflow drain. The unit used in this model is $/unit.

ASR well life: This input indicates the number of years that the ASR well is expected to work. The unit is years.

ASR well rehabilitation cost: This input indicates the repair cost of ASR wells. The unit used in this model is $/well.

ASR well rehabilitation frequency: This input indicates the frequency of ASR well rehabilitation. Wells usually need rehabilitation to maintain high efficiency. The unit used in this model is years.

Interest rate: This input indicates the interest rate that will be paid for a loan to fund the project. The unit used in this model is %.

Raw water cost per m^3: This input indicates the cost of raw water that will supply the system. This input includes water that is rented from other parties, water of which the city does not own water rights. The unit used in this model is $/$m^3$/year.

Design cost: This input indicates the design cost of the total project cost. The unit used in this model is % to the total cost.

Land cost: Land cost per meter. The unit used in this input is $/meter.

Labor cost: Labor annual total cost, including salary, benefits, overhead, etc. The unit used in this input is $/person.

Kilowatt-hour cost: This input indicates the cost per kilowatt-hour. The unit used in this input is $/kilowatt-hour.

Project contingency: This input indicates the percentage that can be added to the total cost to cover unanticipated expenses. This addition covers the uncertainty in calculating the actual cost of project. The unit used in this model is %.

3.2.1.2. Calculations

Section 3.2.1.2.1 presents calculations used in the deterministic model. Appendix C shows the deterministic model code.

3.2.1.2.1. Hydraulic Calculations

Hydraulic calculations include calculation of demand, expansion of current system if needed, pumping and injection from aquifers, and calculation of wells and drains. The first step of the hydraulic calculations is to calculate system capacities, as described in the following text.

Population: Calculation of monthly population based on growth rate is shown in Equation 2.

$$P(t_2) = P(t_1) * (1 + growth\ rate) \qquad (2)$$

Where P (t_1) is population at time 1, and P (t_2) is population at time 2.

Water demand: Demand can be calculated by multiplying per capita monthly demand by current population (both urban and irrigation demand). Population demand can be calculated by the following Equation 3.

$$population\ demand\ =\ population * per\ capita\ demand \qquad (3)$$

Water treatment expansion: Water treatment plants can be expanded with increasing demand and available raw water or a need for extra water storage.

Injection and pumping from aquifer: Pumping and injection from the aquifer is based on supply and demand. The model will meet demand first using available surface water. Surplus water will be injected up to the capacity of the well field. If available surface water does not meet demand, the model will extract groundwater to meet the difference between supply and demand. The model will run this algorithm on a monthly basis. The decision process for injection and production of groundwater is shown in Figure 5.

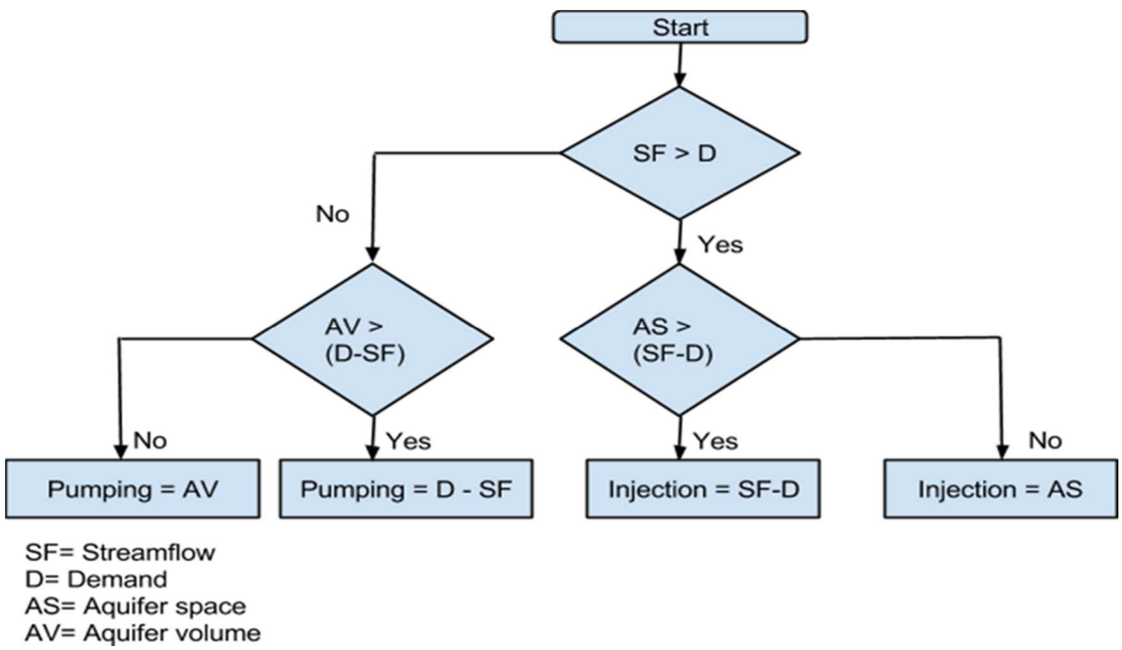

Figure 5: Algorithm Showing The Calculation Of Pumping And Injection.

Expanding the system to meet 100% of the demand might be too costly. To control cost, the system was restricted to inject no more than 10% of the maximum monthly demand of that year.

Inflow water drains calculation: The model calculates how many drains units are needed to divert water from the stream for injection into the aquifer. The model will divide the amount needed to be injected by the capacity of 1 alluvium drain.

ASR wells: The model will calculate how many wells are needed for the system. Injection capacity of ASR wells is at 0.8 pumping capacity. Injection is limited to a fraction of production to prevent irreversible plugging of wells by TSS. The number of ASR wells needed for pumping and injection can be calculated from Equations 4 and 5 respectively.

$$Pumping\ wells\ = \frac{Volume\ of\ water\ will\ be\ pumped}{capacity\ of\ ASR\ well} \qquad (4)$$

$$Injection\ wells\ = \frac{Volume\ of\ water\ will\ be\ injected}{0.8\ \ capacity\ of\ ASR\ well} \qquad (5)$$

The number of ASR wells needed for each month is the maximum of either pumping or injection wells. The model increases the number of ASR wells as needed based on the maximum number of ASR wells needed for 12 months.

Well capacity: Theis's (1935) method calculated the well capacity if the drawdown is known. To derive his equation, Theis (1935) made some assumptions. According to Sterret (2007), these assumptions include:

- The aquifer is confined with infinite extent and no vertical recharge or recharge.
- The aquifer is homogenous and isotropic with uniform thickness.
- The potentiometric surface prior to pumping is horizontal.
- The pumped well has an insignificantly small radius, fully penetrates the aquifer, and discharges at a constant rate.
- Flow in the aquifer is horizontal and laminar.
- Drawdown changes with time.

$$Q = \frac{4\ \pi Ts}{W(u)} \qquad (6)$$

Where Q is pumping rate (m^3/day), T is transmissivity (m^2/day), s is drawdown (m), and W (u) is the well function (dimensionless).

The model uses Equation 6 to estimate the pumping rate of ASR wells. Drawdown and storativity are user inputs.

3.2.1.2.2. Cost Calculations

The model calculates the cost of each element based on required capacities. Specifically, the model calculates capital cost, operation, and maintenance for each item. Additionally, the model calculates the total cost and the present value of future costs. Calculation of annual cost of the project is found by adding the cost of following items:

New ASR wells: Calculation of annual cost of new ASR wells is found by multiplying the number of wells needed each year by the cost of a single well.

Inflow drains: Calculation of annual cost of new inflow water drains is found by multiplying the number of units by the cost of one alluvium drain.

Water treatment plant operation cost: Calculation of water treatment plant cost is found by multiplying system capacity by the cost of treating 1 m^3 of water.

ASR well replacement: Because wells have a lifespan, they should be replaced to keep efficiency of the system high. This cost is calculated annually by dividing the cost by the lifespan of well. Calculation of well replacement is shown in Equation 7 (Maurer, 2012).

$$well\ replacement\ annual\ cost\ =\ total\ no.of\ wells\ \frac{well\ cost}{well\ life} \qquad (7)$$

ASR well operation and maintenance: Well operation and maintenance is calculated by multiplying the number of wells total by annual operation and maintenance cost for each well.

Inflow drains operation and maintenance: Inflow drain operation and maintenance is calculated by multiplying the number of units by the cost of operation and maintenance for one unit.

Project contingency: Project contingency is calculated by multiplying percentage of the total cost to the total cost. Project contingency can be calculated by the following Equation 8.

$$project\ contingency\ =\ project\ contingency\ percent *\ total\ cost \quad (8)$$

Design cost: Project design cost is calculated by multiplying the percentage of the total cost by the total cost. Project design cost can be calculated following Equation 9.

$$Project\ design\ cost\ =\ Project\ design\ cost\ percent *\ total\ cost \quad (9)$$

Land cost: Land needed is calculated by multiplying the number of ASR wells by the area required by each ASR well. This value will be added to the area needed by the water treatment plant which is defined by user. Land cost is the multiple of the area needed (m^2) by the cost of $1m^2$. Equation 10 shows the calculation of area needed by the model. Equation 11 shows the calculation of land cost.

$$Land\ needed = (ASR\ number * \frac{Area}{ASR\ well}) + WTP\ land \quad (10)$$

$$Land\ cost = Land\ needed * cost\ of\ 1m^2 \quad (11)$$

Pipes cost: The cost of pipes is the addition of the length of pipes multiplied by to the cost of pipes and their installation. The cost of pipes depends on the diameter. Table B1 shows the cost of ductile iron pipes per unit length (RSMeans, 2012). Equation 12 shows the calculation of pipes cost.

$$pipes\ cost = pipe\ length(m) * (\frac{cost\ of\ pipe\ and\ installation}{meter}) \quad (12)$$

Present value: The current worth of a future sum of money or stream of cash flows given a specified rate of return (Khan, 2004). Calculation of present value follows Equation 13.

$$PV = FV * \frac{1}{(1+r)^n} \qquad (13)$$

Where PV is present value, FV is future value, r is rate of return, and n is number of periods.

3.2.1.3. Outputs

The model generates graphs and tables. Results include monthly and annual values for key parameters. Monthly data include: water supply, water demand, and volume of pumping from aquifer, volume of injection to the aquifer, volume left in aquifer that the system can inject water into, capacity of the water treatment plant, number of ASR wells, and number of inflow drains. Annual data include costs for new ASR wells, inflow drains, water treatment plant capital, ASR well operation and maintenance, inflow drains, water treatment plant operation and maintenance, well replacement, pipes replacement, water treatment plant replacement. In addition, the model calculates total project cost in terms of present value and life cycle costs.

3.2.2. Stochastic Model

Stochastic inputs are inputs that vary through time. The empirical cumulative distribution function is used in the model to generate random data as inputs. Stochastic inputs make the model more reliable than the deterministic model because they account for the variability of key parameters. The stochastic model includes five programming files as discussed before. Appendix D shows the deterministic model code.

3.2.2.1. Empirical Cumulative Distribution Function

The empirical cumulative distribution function, known as empirical CDF, is the cumulative distribution function that is related to the empirical measure of a specific sample (Vaart, 1998). Empirical CDF is a function that steps by 1/n for each n until reaches 1 (n/n). Referring to the Glivenko–Cantelli theorem, Empirical CDF estimates the true underlying CDF of the data in a specific sample and converges with a probability of 1 (Vaart, 1998). Empirical CDF can be calculated following Equation 11.

$$F(t) = \frac{number\ of\ elements\ in\ the\ sample \leq t}{n} \quad (11)$$

Where F (t) is a function value evaluated at t, n is the total number of elements in the sample. In Matlab, the function "[f, x] = Empirical CDF(y) returns the empirical cumulative distribution function (CDF), f, evaluated at the points in x, using the data in the vector y" (Matlab, 2013). Figure 6 shows the January streamflow of the Cache La Poudre Valley Empirical CDF.

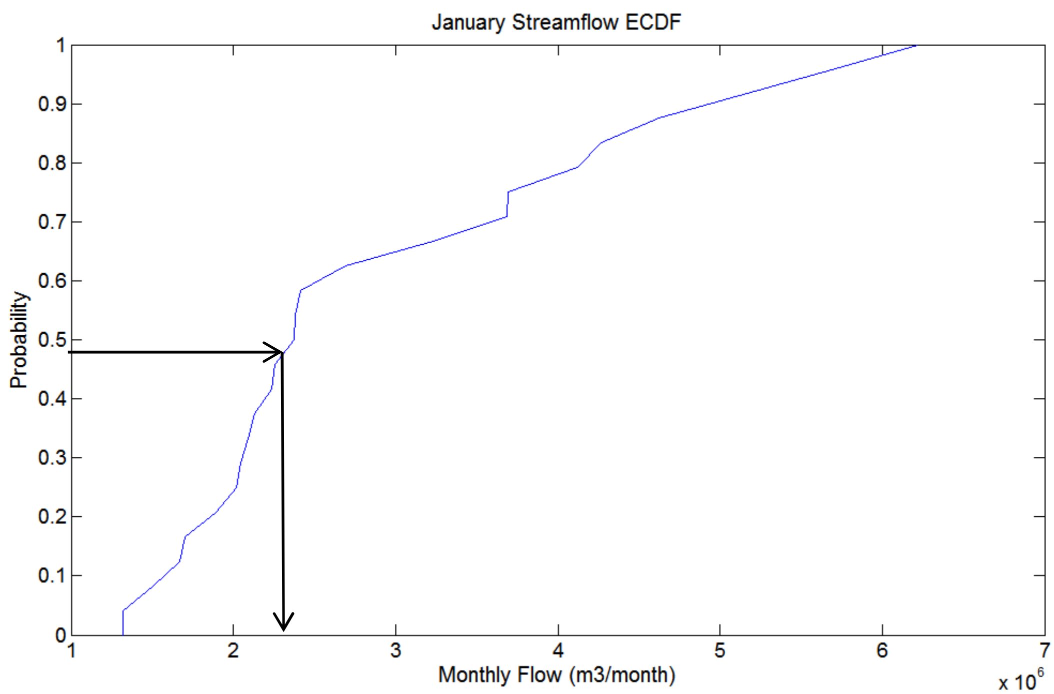

Figure 6: January Streamflow of Cache La Poudre Valley Empirical CDF.

3.2.2.2. Stochastic Inputs

The stochastic model generates some stochastic inputs and then runs the previously described deterministic model files. The three stochastic inputs in this model are per capita monthly water demand, annual growth rate, and monthly streamflow. All other inputs are the same inputs as the deterministic model.

3.2.2.2.1. Annual Growth Rate Input

Because annual growth rate varies, it should be considered as a stochastic input. This model will generate Empirical CDF based on the previous years' data available for the annual growth rate. After generating annual growth rate for the Empirical CDF, the model generate a random number from zero to 1. The model then evaluates annual growth rate, from the x-axis, based on the random number in y-axis. This process will be repeated every year throughout the project lifespan.

3.2.2.2.2. Streamflow Stochastic Input

Based on last years' monthly streamflow, the model generates empirical CDFs for each month's streamflow throughout the year. After generating the 12 Empirical CDFs, the model generates a random number between 0 and 1 and then evaluates the streamflow of January based on the random number. The same random number will be used to get the streamflow for the next 11 monthly streamflow Empirical CDFs. This process prevents the program from calculating high flows in winter and low flows in summer. This means that there is one random number that will be used to generate streamflow throughout the year. This number changes from year to year, resulting in the whole year to be dry, wet, or an average year.

3.2.2.2.3. Per Capita Demand Input

Per capita demand varies throughout the year. Demand in the summer is usually much greater than demand in the winter. Most of this increase is due to urban irrigation. Because indoor use of water rarely changes seasonally, the model considers indoor daily use of water to be constant through the year. Stochastic per capita demand applies to irrigation use only. Irrigation demand varies depending on annual rain or snow fall. To account for wet and dry years, the model considers the level of streamflow that year. Equations 12 and 13 explain the relationship between the level of streamflow and per capita demand that year.

$$Y = 1 - X \qquad X > 0.1 \qquad (12)$$

$$Y = 0 \qquad X \leq 0.1 \qquad (13)$$

Where Y is the random number that generates per capita demand from ECDFs. X is the random number used to generate the streamflow from its ECDFs. The model will ban irrigation if the streamflow of that year is 10% or less than historical data.

3.2.2.3. Calculations

Stochastic model calculation includes hydraulic and cost calculations.

3.2.2.3.1. Hydraulic Calculations

Hydraulic calculations in the stochastic model are the same as in the deterministic model.

3.2.2.3.2. Cost Calculations

Cost calculations in the stochastic model are the same as in the deterministic model.

3.2.2.3.3. Outputs

Outputs are the same as in the deterministic model.

3.2.3. System Water Balance

A water balance is performed as a means of testing the computational method in both models (deterministic and stochastic). When the water balance is zero, inputs are equal to outputs and the system is running correctly. If the water balance is not zero, the model code should be revised. Mass balance of the system follows Equation 14.

$$water\ balance = Inflow + pumping - Injection - metDemand \qquad (14)$$

4. MODEL APPLICATION

The main goal of this thesis is to design a model that can assess the feasibility of subsurface water storage for a specific place. The city of Fort Collins, Colorado was chosen as a case study for this model to demonstrate the effectiveness and working capabilities of the model. However, in no way should this work be viewed as having direct applicability to the city of Fort Collins. Due to the complexity of the water system in Fort Collins, no direct conclusion should be drawn with respect to the future actions by the city of Fort Collins. The area chosen to store the water is centered about Ted's Place, north of Fort Collins, Colorado, USA (Figure 7).

Figure 7: The Location of Ted's Place.

Following Hogan (2013), outcrops of the Fountain Formation in Northern Colorado and stratigraphic sections are illustrated in Figures 8 and 9. The Fountain Formation is an arkosic conglomeratic sandstone that was deposited in fluvial environments along the eastern flanks of the ancestral Rocky Mountains (Hogan, 2013). The total thickness of the Formation in northern Colorado is about 250m (Braddock et al., 1988). Unfortunately, little is known about the transmissivity of the Fountain Formation in northern Colorado. Figure 10 shows the key elements of the envisioned subsurface water storage system.

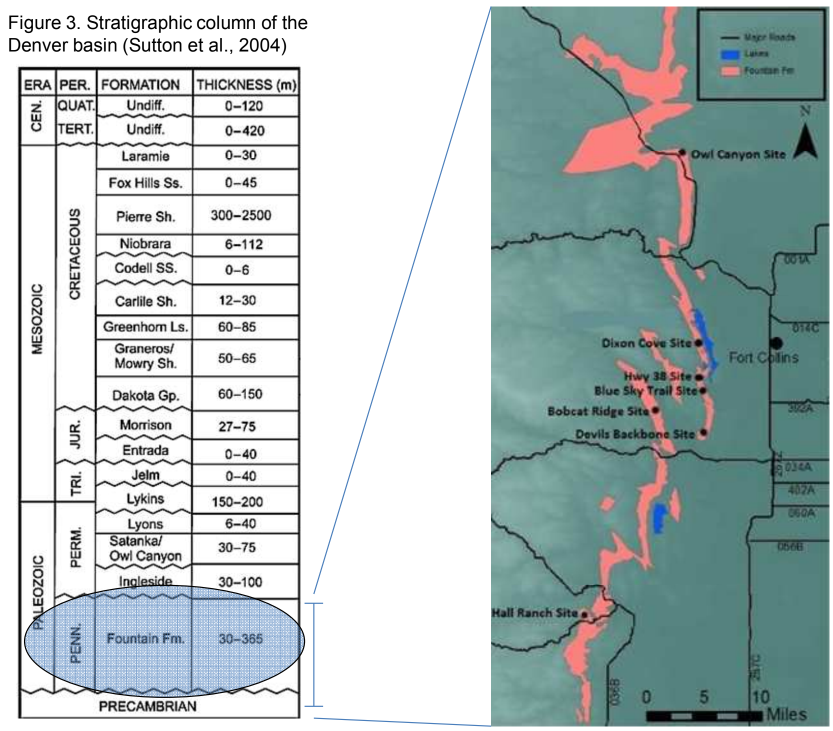

Figure 8: Outcrops of the Fountain Formation in Northern Colorado (Hogan, 2013)

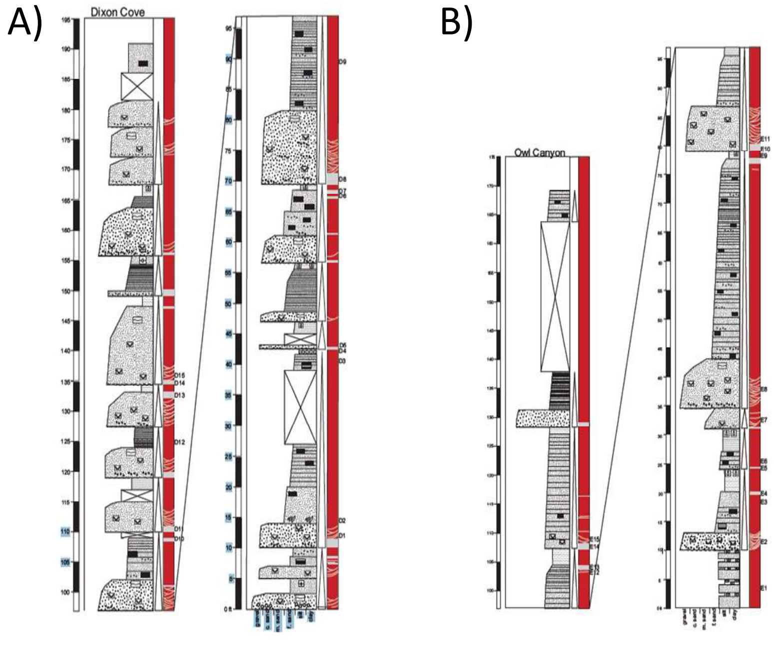

Figure 9: Fountain Formation Stratigraphic Sections Hogan (2013). a) Dixon Cove and b) Owl Creek Canyon.

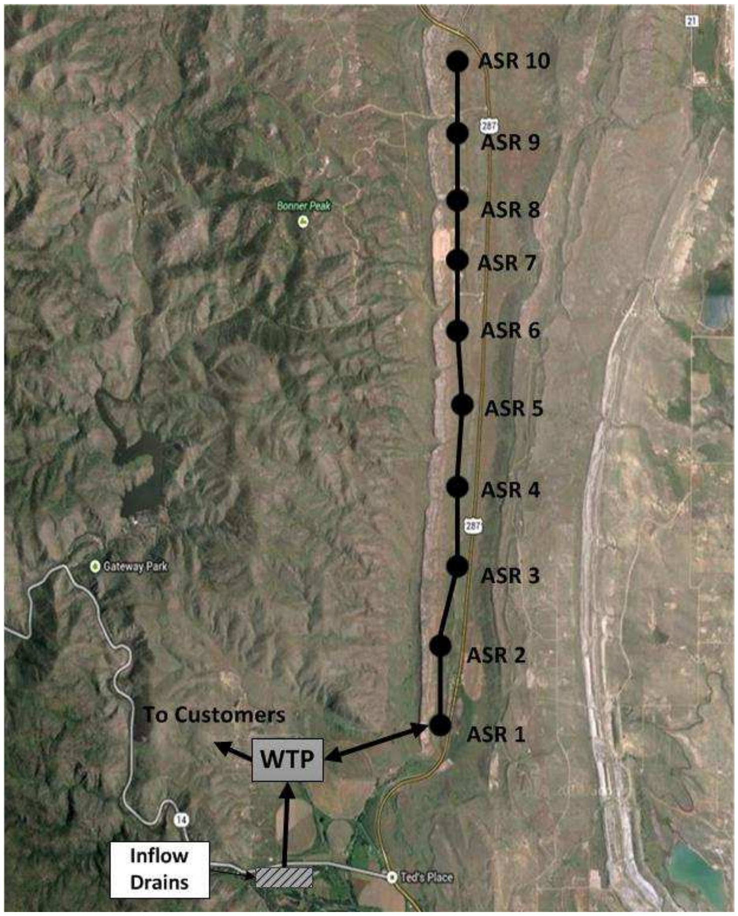

Figure 10: Key Elements Location on the Map.

ASR wells are screened at Fountain Formation for pumping and injection. The casing of these wells is about 120 m and screened for about 240m. ASR wells contain Baski valves to allow water to be pumped and injected to the aquifer. Figure 11 shows the cross section of ASR wells used in this project.

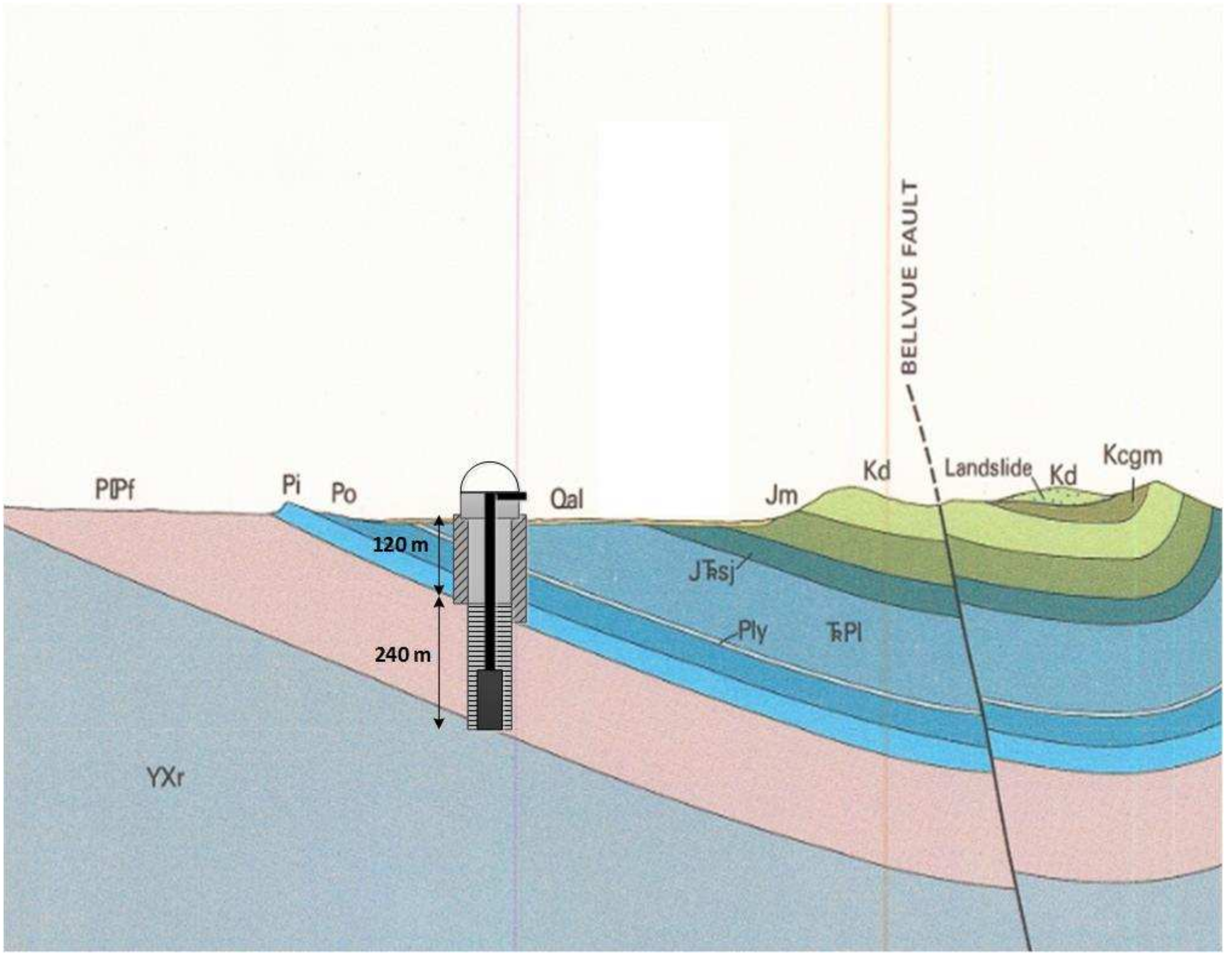

Figure 11: Cross Section of ASR Wells Used In This Project (Geology based on Braddock et al., 1988).

Inflow drains are composed of 150m of subsurface drains that divert water. The water diverted will be pumped by a pump installed near the drains to lift water. The depth of inflow drains is about 45m from surface ground. Figure 12 shows a cross section of inflow drains used in this model.

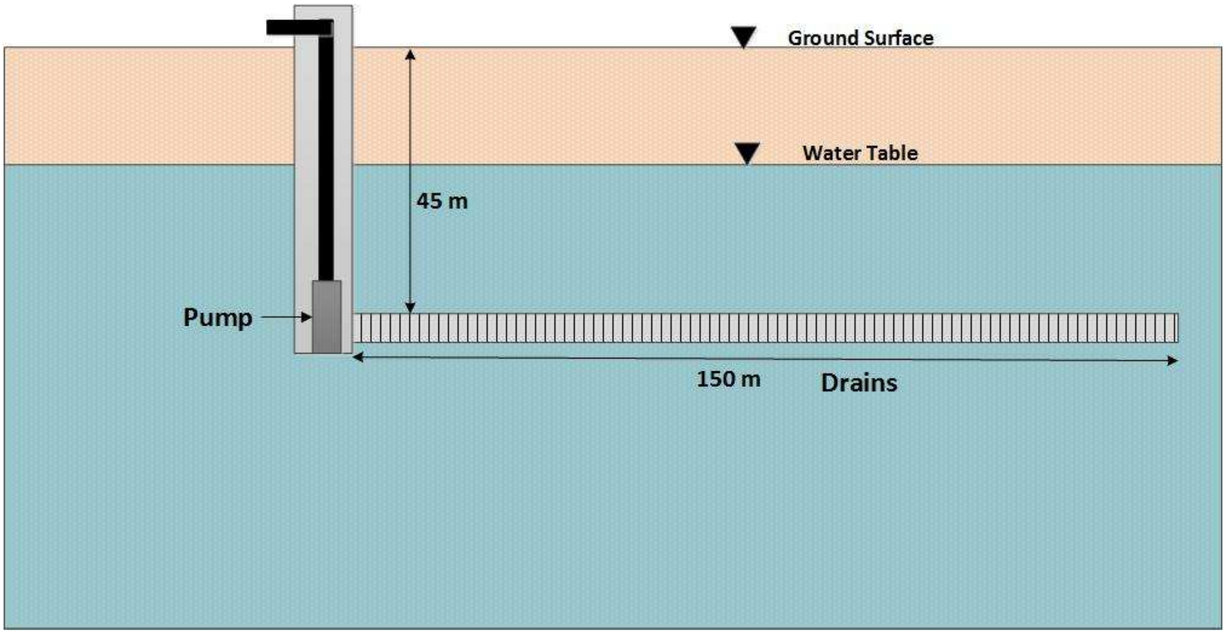

Figure 12: Cross Section of Inflow Drains Used In This Model.

4.1. City of Fort Collins

The city of Fort Collins is located in the northern Colorado. Fort Collins is home to Colorado State University. The population of Fort Collins was 152,061 in 2013 (U.S. Census Bureau, 2014). Table 1 shows the population of Fort Collins and the annual growth percentage between 1990 and 2013.

Table 1: Population of the City Of Fort Collins and the Annual Growth Percentage between 1990 and 2013.

Year	Population	Growth %
1990	89333	
1991	91979	2.88
1992	94991	3.17
1993	98203	3.27
1994	101619	3.36
1995	103764	2.07
1996	105667	1.80
1997	107712	1.90
1998	110505	2.53
1999	113432	2.58
2000	120062	5.52
2001	123241	2.58
2002	125512	1.81
2003	127020	1.19
2004	128333	1.02
2005	129497	0.90
2006	131487	1.51
2007	133373	1.41
2008	135870	1.84
2009	138733	2.06
2010	144509	4.00
2011	145959	0.99
2012	148938	2.00
2013	152061	2.05

4.1.1. Water Demand and Supply

The volume of water needed in Fort Collins continue to increase. This demand includes indoor and outdoor use. The demand on water depends on population growth and the rate of economic and industrial development (Fort Collins Final Report, 2014). To meet the demand, the city draws water from the Poudre River Basin, and the Colorado-Big Thompson (CBT) Project. The city's access to CBT water is through Horsetooth Reservoir. The city owns senior water rights including converted agriculture water rights, CBT units, supplies from the Michigan ditch, and from Joe Wright Reservoir (City of Fort Collins Utilities, 2014). The city owns senior direct water rights for the Poudre River. Specifically, the city owns 0.43 m^3/sec (15 ft^3/sec) from mid-October to mid-April and owns 0.56 m^3/sec (19.93 ft^3/sec) from mid-April to mid-October. These water rights are reliable because they are senior. However, the city owns water rights that allow it to access up to 3.96 m^3/sec (140 ft^3/sec) in some months during wet years. Figure 13 shows the average demand of the city per capita for 2004 to 2013. Figure 14 shows the monthly demand of the city of Fort Collins between 2004 and 2013.

The city of Fort Collins diverts water from Horsetooth Reservoir and Poudre River. The city diverts water from either resource based on many factors. For example, the city diverted almost nothing from Poudre River in summer 2012 because of the nearby wildfires. Figure 15: Poudre River monthly water flow at Mouth Canyon. Figure 16: City of Fort Collins monthly supply and demand.

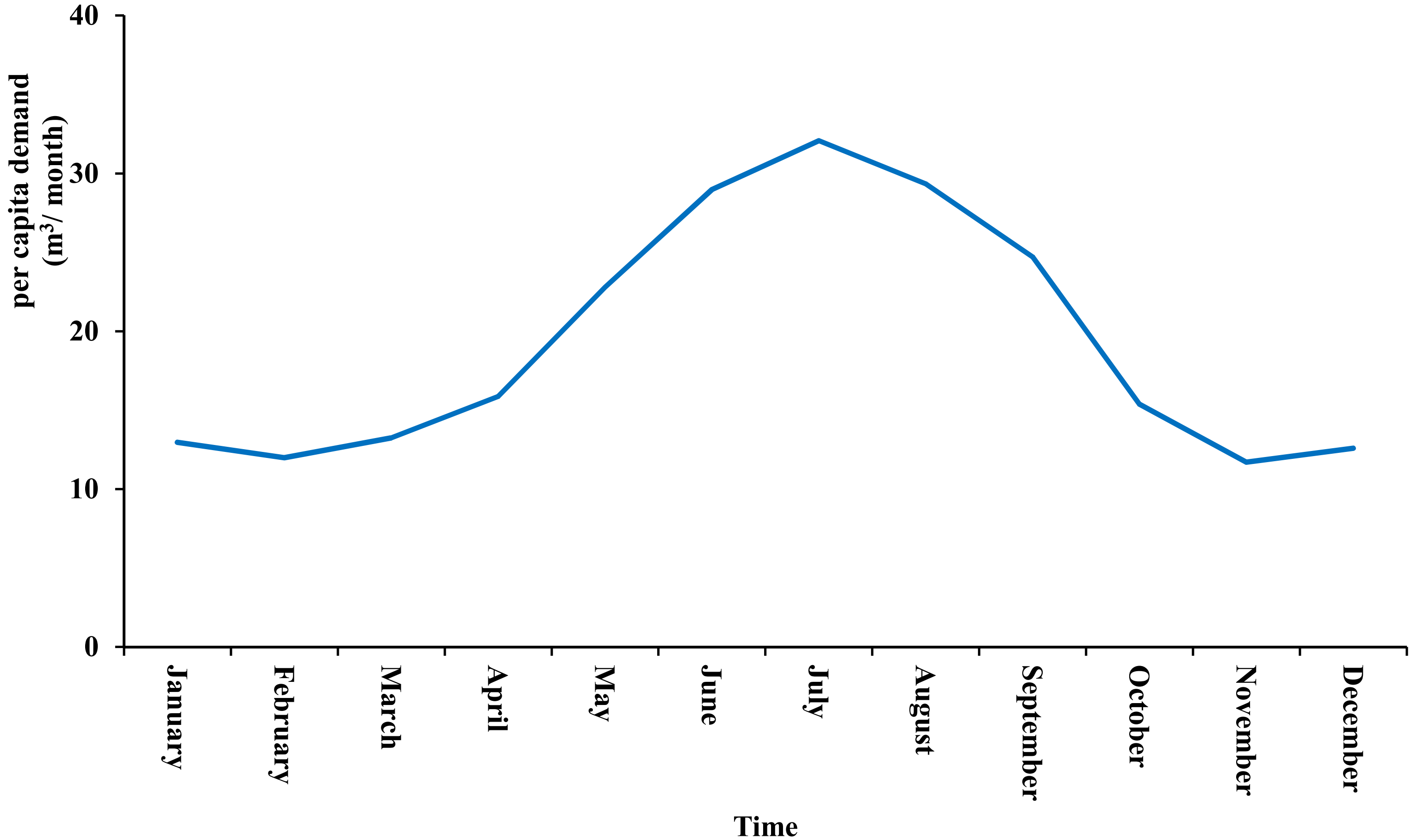

Figure 13: The Average of the City per Capita Demand for the Time (2004-2013).

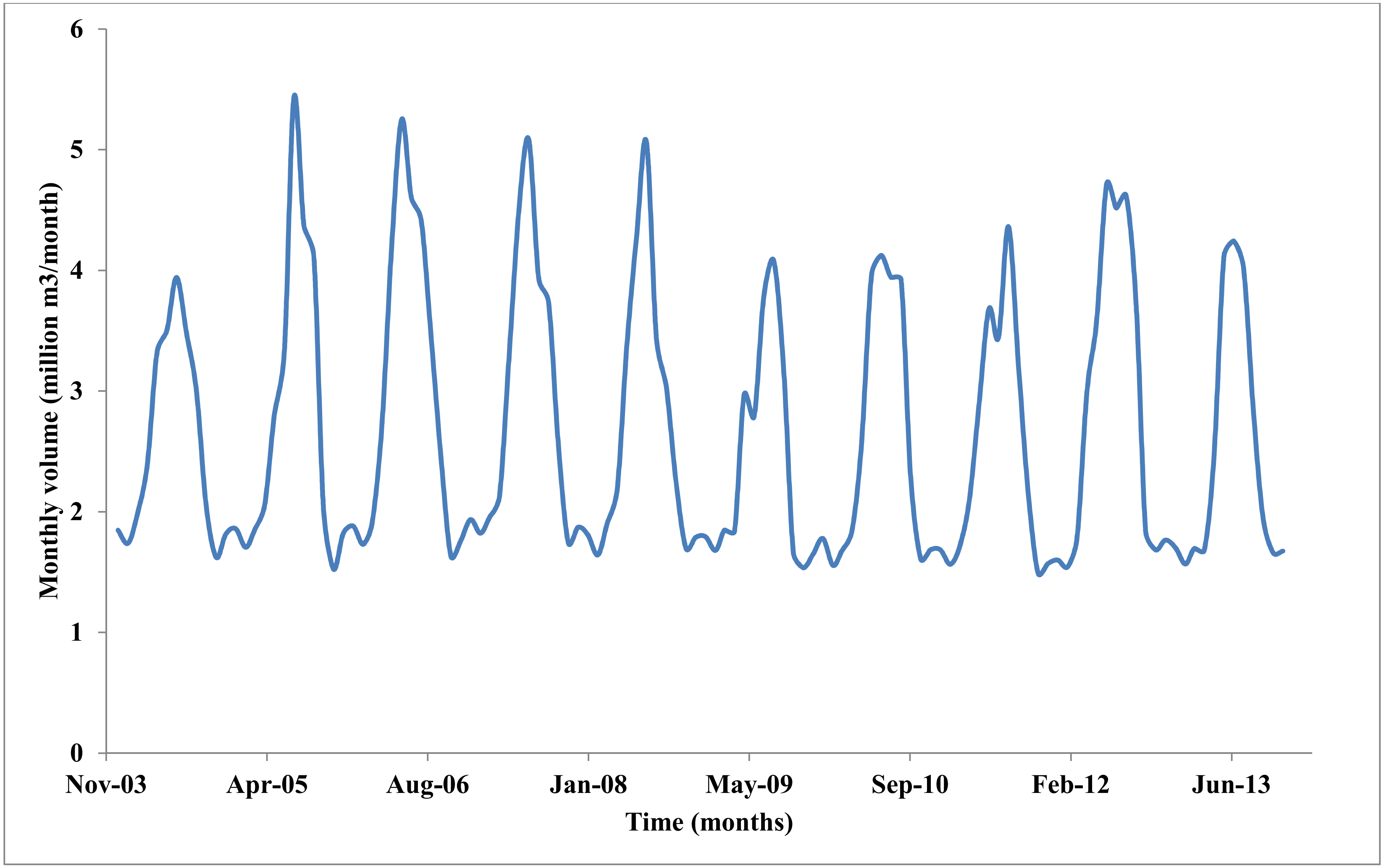

Figure 14: Monthly demand of the City of Fort Collins between 2004 and 2013.

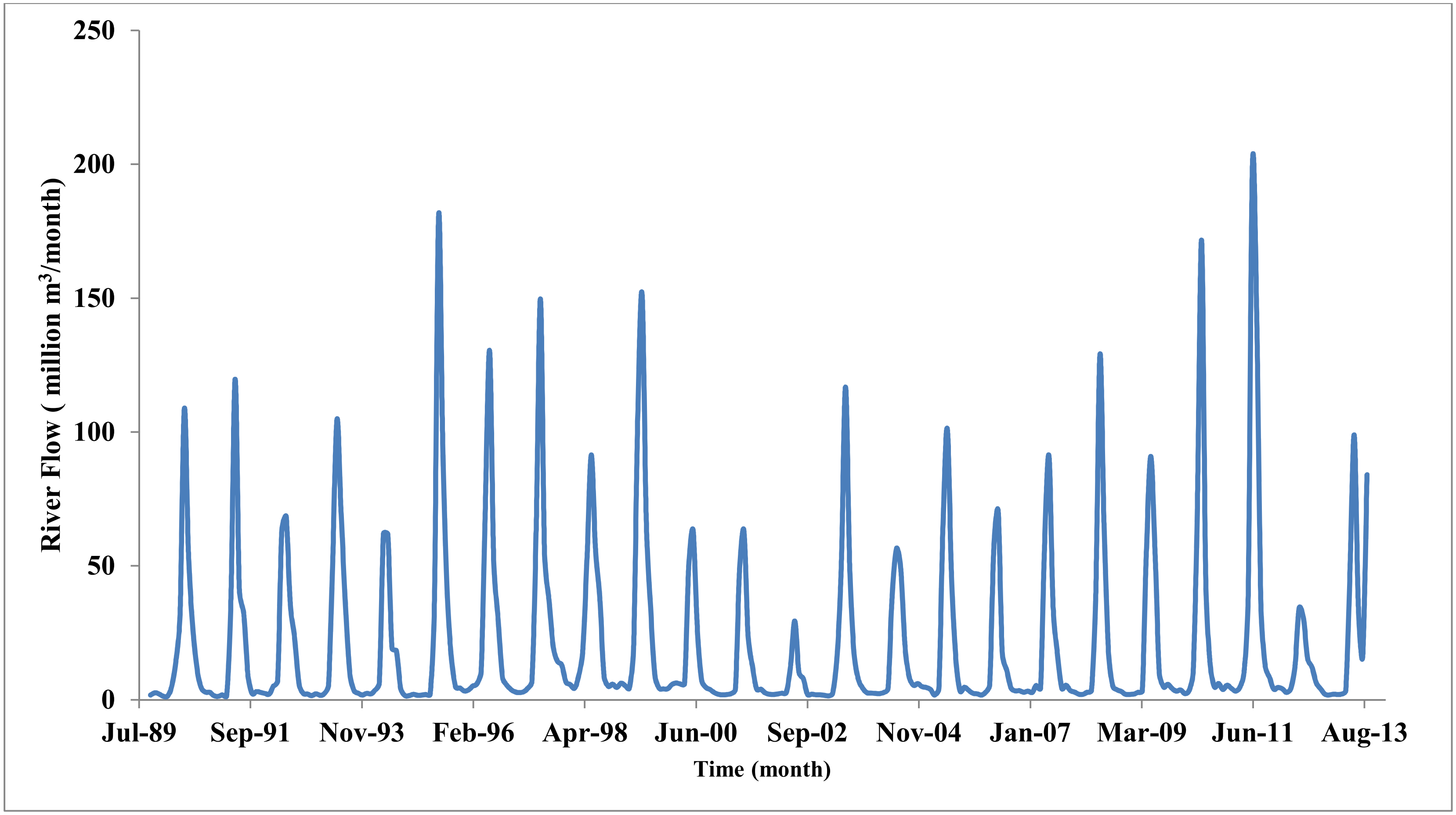

Figure 15: Poudre River monthly water flow at Mouth Canyon

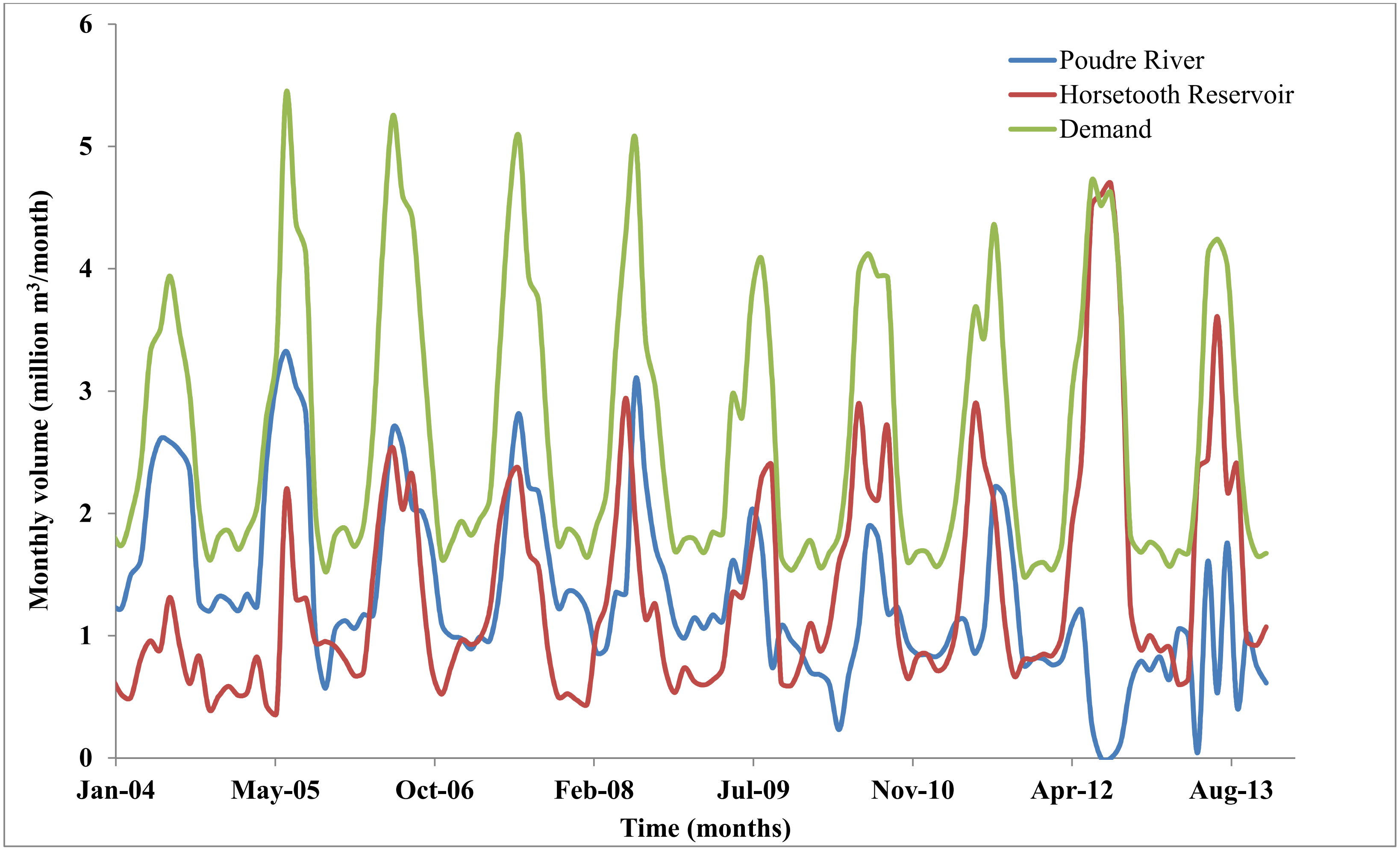

Figure 16: City of Fort Collins monthly supply and demand

4.1.2. Water Storage

The flow of the Poudre River varies throughout the year. Historically, flow in summer has been greater than the city's demand and the flow in winter has been lower than the city's demand. To account for that variation of water supply and demand, the city requires water storage for surplus water in the summer to compensate for the shortage of water in the winter. Figure 14 shows 1986 Poudre River flows and the city's 2008 water demands. Figure 17 (1) shows the direct flow rights that city can pump from the river. From mid-October to mid-April, the city can divert only 0.42 m^3/sec. However, during the summer, the city can pump up to 4 m^3/sec. This happened if there is surplus water in the river such as 1986 flow. Figure 17 (2) shows that the city requires storage to meet its municipal demand in winter. Figure 17 (3) shows that the flow in 1989 was 130% of the flow average.

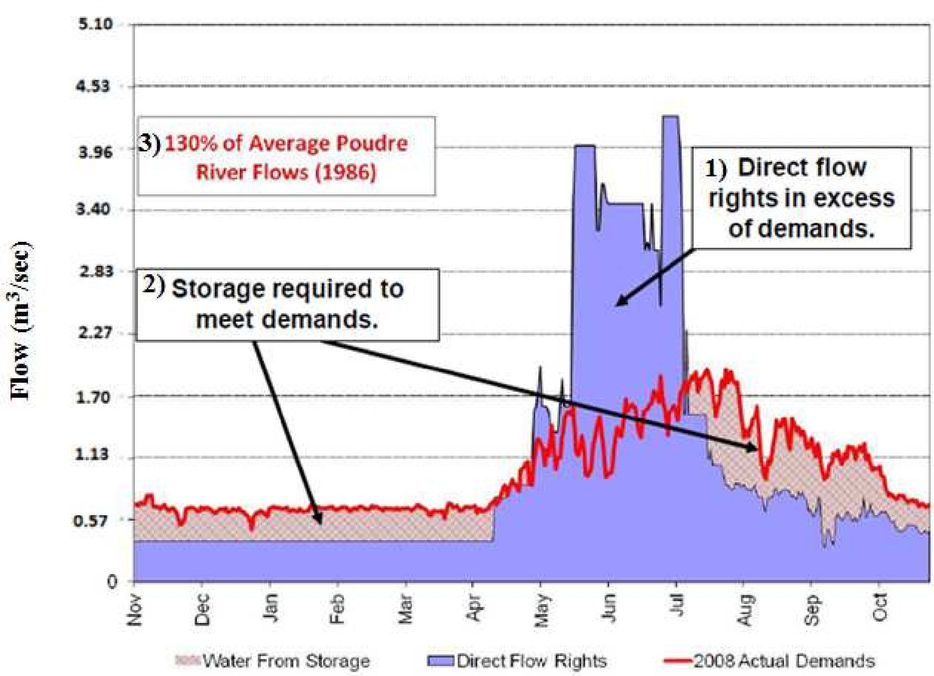

Figure 17: 1986 Poudre River Flows and the City's 2008 Water Demands (City Of Fort Collins Utilities, 2014).

4.2. Deterministic Model

4.2.1. Inputs

Deterministic inputs for the city of Fort Collins are listed in Table 2, and 3. Hydraulic inputs except streamflow and per capita demand are listed in Table 2. Streamflow and per capita demand for the 12 months of the year are listed in Table 3. Cost inputs are listed in Table 4.

Table 2: Hydraulic Inputs for Deterministic Model

Input	Description	Value	Source
Population	Population at the start of the project	60,824 people (40 % of Fort Collins population)	United States Census Bureau
Pop_Growth_rate	The average growth rate of the model user	2.28 % (Average of 20 years growth rate)	City of Fort Collins Utilities
N_years	Years of project	30 years	User Input
WTP_capacity	Water treatment plant initial capacity	0.35×10^6 m^3/month (9.2 acre-ft/day)	User Input
WTP_expansion_increment	Water treatment plant expansion increment	0.35×10^6 m^3/month (9.2 acre-ft/day)	User Input
WTP_expansion_limit	Water treatment plant maximum expansion limit	1.70×10^6 m^3/month (46 acre-ft/day)	User Input
Transmissivity	Transmissivity of the aquifer	$2.50*10^{-3}$ m^2/day	Estimated based on typical sandstone hydraulic conductivities and the thickness of Fountain Formation near Fort Collins. (Freeze and Cherry,1979)
Storativity	Storativity of the aquifer	0.1×10^{-3}	Estimate based on typical sandstone storativity
Drawdown	The drawdown allowed at the ASR well	0.1×10^3 m	1/3 of the thickness of Fountain Formation
well_spacing	The space between ASR wells	1×10^3 m	User Input
Storage_needed	Aquifer capacity	74.0×10^6 m^3	User Input

		(60×10^3 acre-ft)	
Aquifer_volume	Aquifer current water volume	37.0×10^6 m^3 (30×10^3 acre-ft)	User Input
Distance_Drains_WTP	Distance between Alluvium drains and water treatment plant	0.45×10^3 m	User Input
Distance_WTP_ASR	Distance between water treatment plant and First ASR well	2.1×10^3 m	User Input
Distance_WTP_city	Distance between water treatment plant and the pipe of the city's raw water distribution system	1×10^3 m	User Input
Injection_percentage	Water injection percentage that the system allowed to inject to the total demand	10 % to the total demand	User Input
TDH_pumping	Total dynamic head in pumping	0.152×10^3 m	User Input
TDH_injection	Total dynamic head in injection	30×10^0 m	User Input
Well_land	The land required by each well	20.0×10^3 m^2 per well (5 Acres per well)	User Input
WTP_land	The land required by the water treatment plant	80.0×10^3 m^2 (20 Acres)	User Input
Labor	Workers number	2 people	User Input
pump_efficiency	The efficiency of pumps used in ASR wells	0.80 (80%)	User Input
Water_rights_Oct_Apr	Water right at the river from mid-October to mid-April	0.43 m^3/sec (15 ft^3/sec)	User Input
Water_rights_Apr_Aug	Water right at the river from mid-April to July	3.40 m^3/sec (120 ft^3/sec)	User Input
Water_rights_Aug_Oct	Water right at the river from August to mid-October	0.85 m^3/sec (30 ft^3/sec)	User Input

Table 3: Poudre River Flow and City Of Fort Collins per Capita Demand. (Colorado Division of Water Resources,2015)

Month	Flow ($\times 10^6$ m^3/month)	Per capita demand (m^3/month)
January	3	12.96
February	2.7	11.98
March	3.7	13.25
April	7.5	15.87
May	51.5	22.79
June	103.3	28.98
July	486.9	32.07
August	22.1	29.33
September	10.8	24.70
October	4.7	15.38
November	3.7	11.7
December	3.0	12.58

Table 4: Cost Inputs for Deterministic Model

Input	Description	Value	Source
WTP_Initial_cost	Water treatment plant initial cost	0.73×10^6 USD per 346×10^3 m^3/month (9.2 acre-ft/day)	User Input
WTP_expansion_cost	Water treatment plant expansion cost	0.51×10^6 USD per 346×10^3 m^3/month (9.2 acre-ft/day)	User Input
DGWTP_OM_cost	Diverted ground water treatment plant annual operation and maintenance cost	$.01\times10^0$ USD per m^3	User Input
GWTP_OM_cost	ground water treatment plant annual operation and maintenance cost	$.01\times10^0$ USD per m^3	User Input
ASR_Well_Cost	ASR well cost	1×10^6 USD per ASR well	(Hemenway, 2015)
ASR_OM_Cost	ASR annual operation and maintenance cost	15×10^3 USD per ASR well	User Input
well_life	Well life	30 years	User Input
WTP_life	Water treatment plant life	30 years	User Input
Pipes_life	Pipes' life	50 years	User Input
ASR_rehabilitation_cost	ASR rehabilitation cost	50×10^3 USD per well	User Input
Rehabilitation_frequency	ASR rehabilitation frequency	Every 11 years	User Input
New_Inflow_drains_cost	inflow alluvium drains cost	100×10^3 USD per unit	(Hemenway, 2015)
New_Inflow_drains_OM	Inflow alluvium annual operation and maintenance cost	10×10^3 USD per unit	(Hemenway, 2015)
Interest Rate	Interest rate	.03 (3%)	User Input
RawWaterPricem3	Raw water cost per cubic meter	0 USD	User Input
project_contingency	Contingency of the project	25 % of the life cycle total cost	User Input
Design_cost	Design cost percentage to the total cost	5 % to the life cycle total cost	User Input
Land_cost	Land cost per m^2	\$1.24 per m^2 (5×10^3 USD per acre)	User Input
Labor_cost	Labor annual total cost	50×10^3 USD per person	User Input
kW_cost	kilowatt hour cost	0.04 USD per kW-hr	User Input

4.2.2. Outputs

The population at the beginning of the project is 60,824 people (40% of total population) and increases through time by an average growth rate of 2.35% (the average of Fort Collins growth between 1990 and 2013). The 40% was chosen because the city gets a large fraction of its water from Horsetooth Reservoir. The population is projected to be 122×10^3 by the 30th year of the project, an increase by 100.74% from the beginning of the project. Figure 18 shows the population through time.

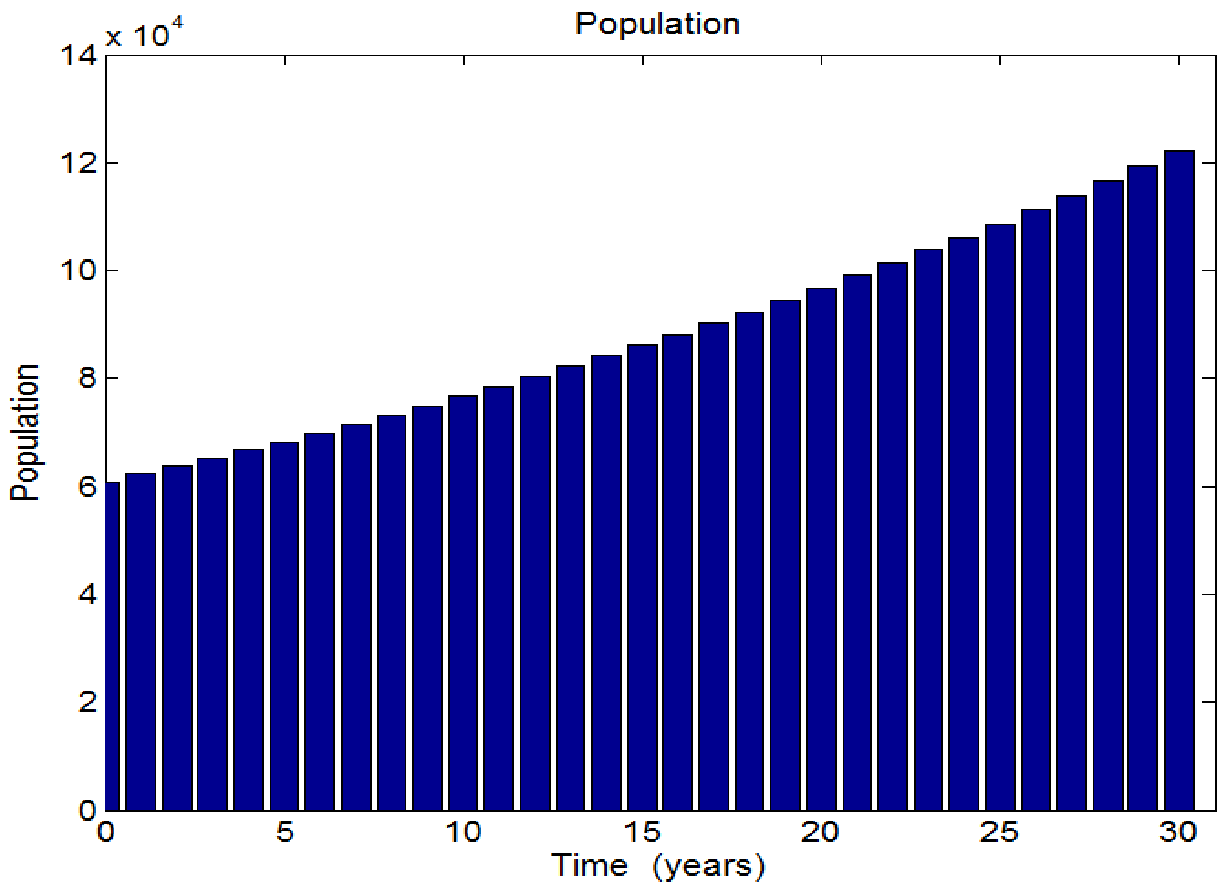

Figure 18: Population through Lifespan of the Project.

Monthly total demand is calculated based on population each month and monthly per capita demand of that month for that year. Population is changing from month to month and from year to year as discussed before. However, monthly per capita demand is an input for each month and repeated every year. Table 3 shows per capita demand variation through the year. The maximum demand is 3.90 $\times 10^9$ m^3/month on the 30th year of the project. The lowest demand was 727 $\times 10^3$ m^3/month in the beginning of the project. Figure 19 shows the forecasted demand of the city of Fort Collins through time.

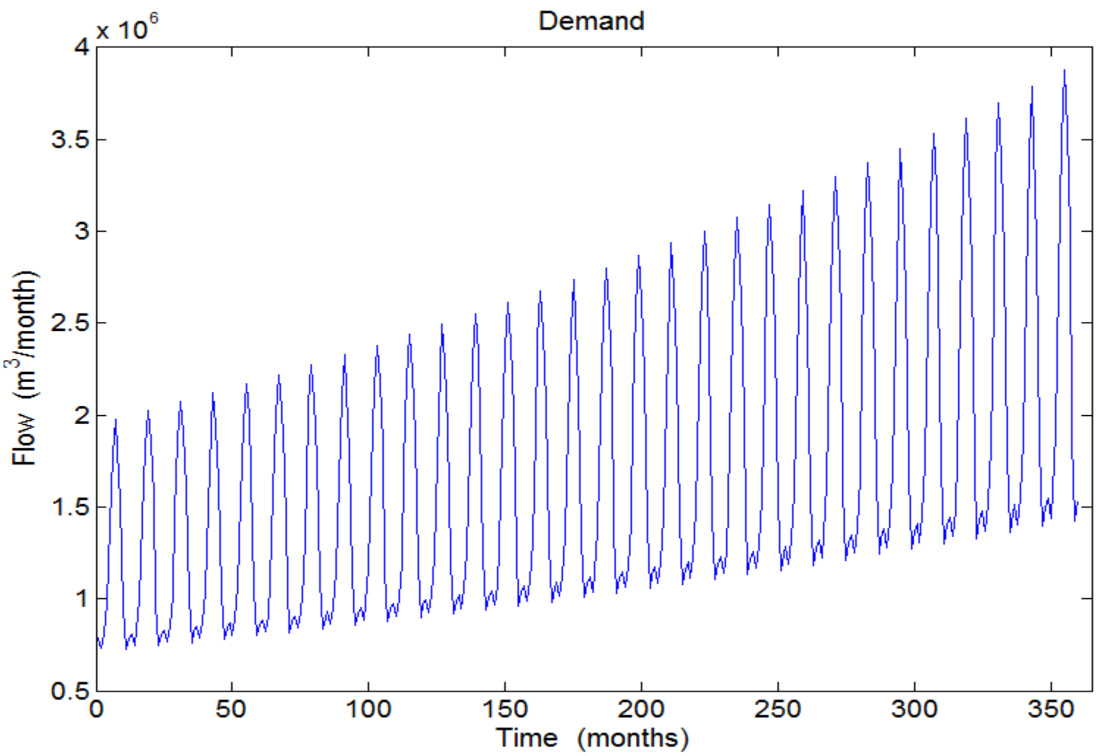

Figure 19: Forecasted Demand Of Fort Collins Through Time.

Each well has a capacity of 4.28$\times 10^3$ m^3/day (785 gpm) for pumping and 3.43 $\times 10^3$ m^3/day (628 gpm) for injection based on Equation 6.

Pumping and injection to the aquifer varies every month based on supply, demand, and system restrictions. The system will pump water from the aquifer if there is shortage in supply. The system will meet the demand first by diverting water directly from the river. If the supply cannot meet demand, the system will pump water to cover the shortages. The maximum volume of pumping was 1.3×10^6 m^3/month in the last year of the project. The maximum injection volume was 388×10^3 m^3/month in the last year of the project. Figure 20(a) shows pumping through time. Figure 20(b) shows injection through time.

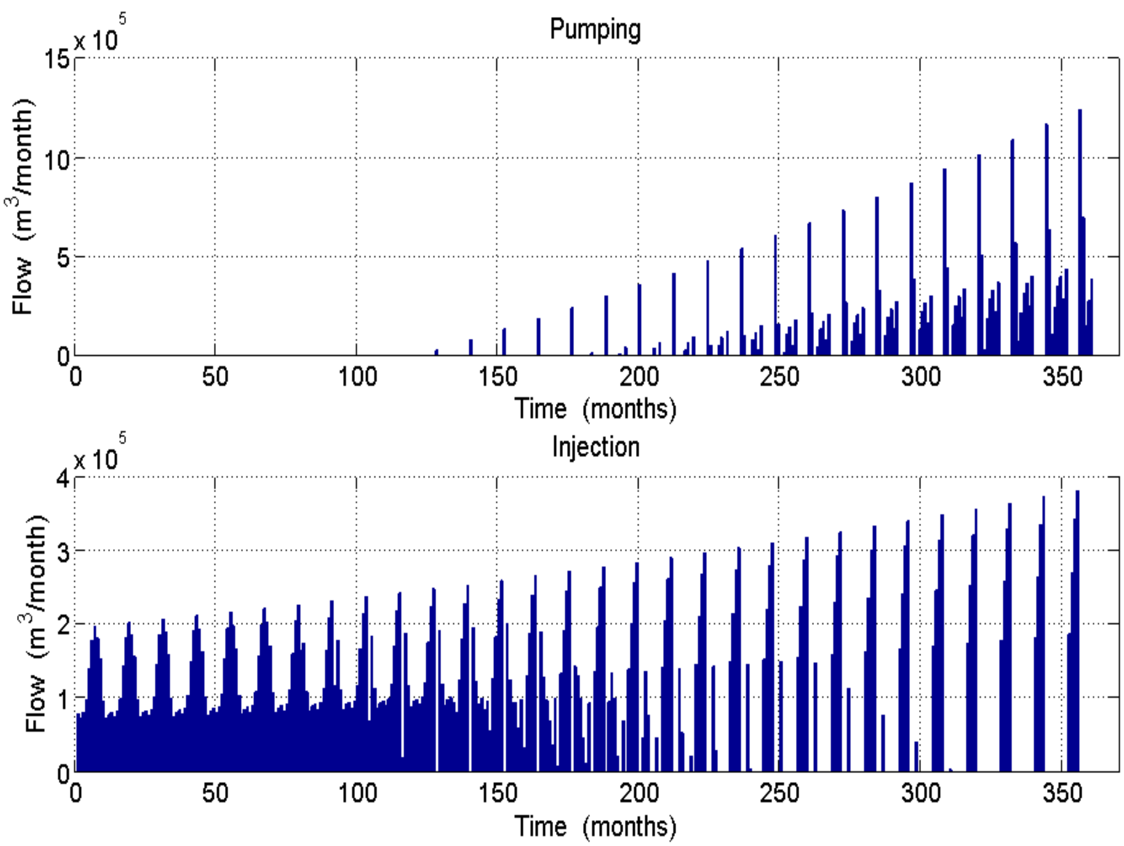

Figure 20: (a) Pumping Through Time (b) Injection through Time.

The system requires two wells in the first year of project. After that, the system requires installation of one ASR well in the fourth year of the project. By the end of the project, the system requires 10 ASR wells to inject and recover water from aquifer. The system increases the number of ASR wells gradually to keep cost as low as possible. Figure 21(a) shows the number of ASR wells needed by the system to inject and recover water from aquifer.

The system requires one alluvium subsurface drain unit at the beginning of the project and will require another unit by the 25th year of the project. The capacity of each unit is $10.9\times10^3 m^3/$ day (2000 gpm). Figure 21 (b) shows alluvium subsurface drains that are required by the system to inject water to the aquifer.

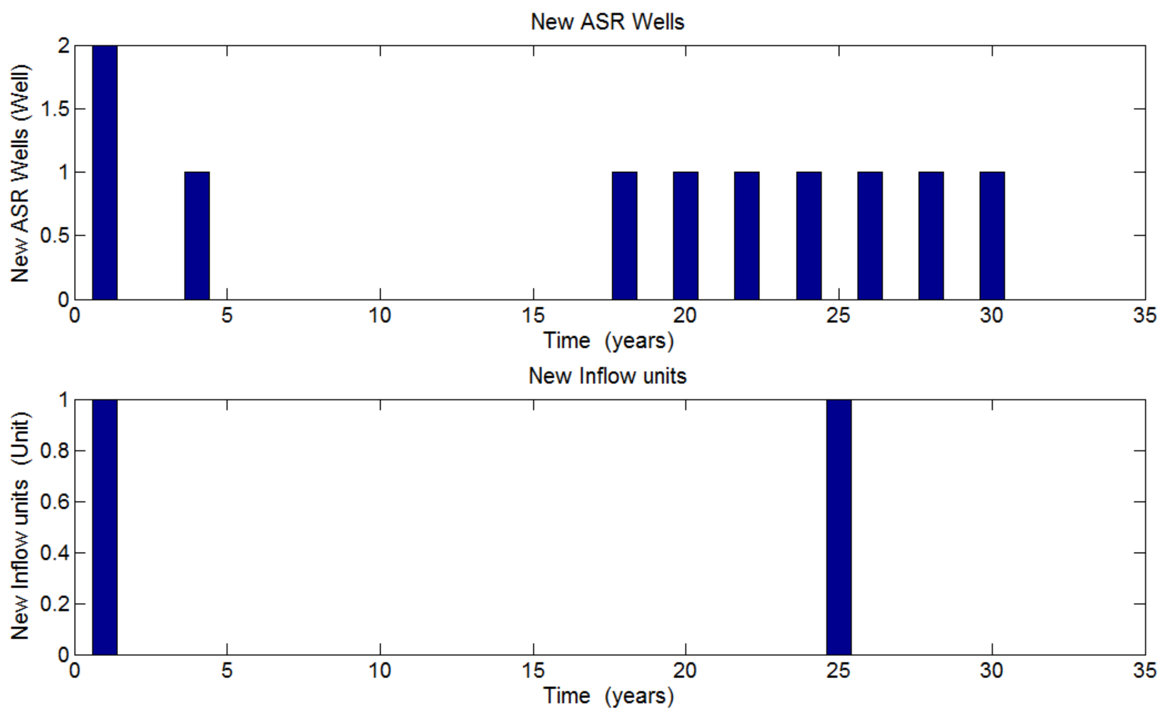

Figure 21: (a) Number of ASR Wells Needed By the System (b) Number of Alluvium Inflow Drains Needed By the System.

Withdrawing water from the river has three restrictions. Three restrictions limit withdrawing water from the river: availabilty of water in the river, city water rights, and 10% of the city total demand. In the first 10 years of the project, the main restriction on the system was the 10% of the total demand. However, by increasing demand through time, water rights started to restrict water withdraw from river. Water availabilty in the river did not restrict water in the river through the time of project. Figure 22 shows the three restrictions on water withdraw from the river. Figure 23 shows the lower part of Figure 22.

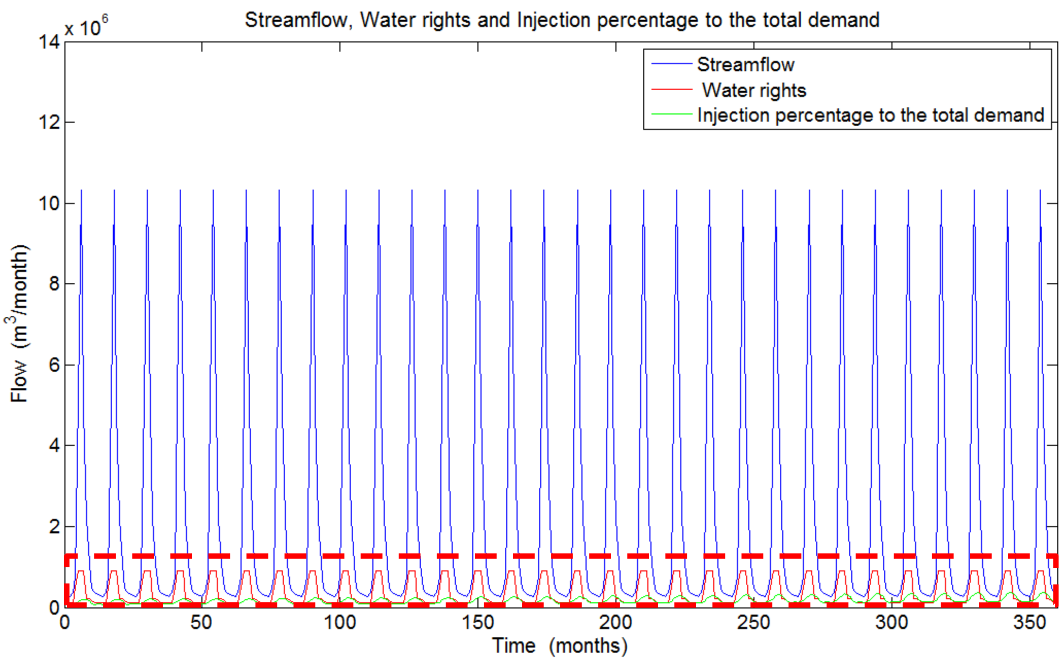

Figure 22: Streamflow, Water Rights, and the Injection Percentage to the Total Demand

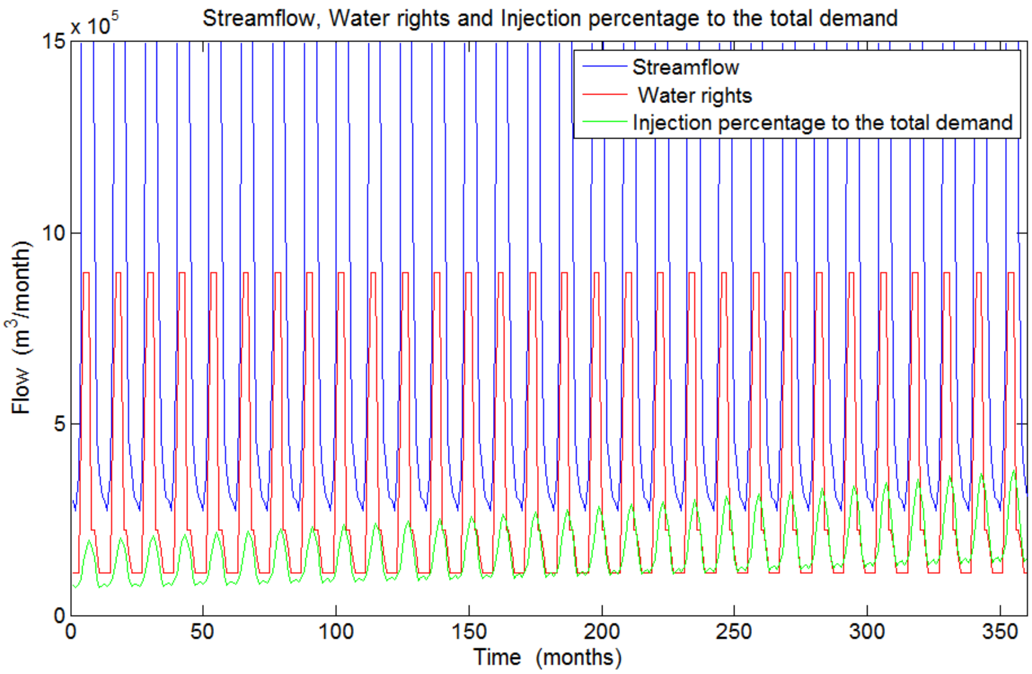

Figure 23: Lower Part of Figure 22.

The aquifer started half full with a volume of 37.0×10^6 m^3 (30×10^3 acre-ft) with the storage at the end of the project being 46.0×10^6 m^3 (37.4 ×10^3 acre-ft). The system added 9.1×10^6 m^3 (7.4 acre-ft) to the aquifer. The system injected 39.9 ×10^6 m^3 (32.3 ×10^3 acre-ft) and pumped from the aquifer 31×10^6 m^3 (25.3×10^3 acre-ft) during the project life. On average, the system injected 1.3×10^6 m^3 (1×10^3 acre-ft) and pumped 1×10^6 m^3 (844 acre-ft) yearly. Figure 24 (a) shows aquifer volume through time. Figure 24(b) shows the aquifer capacity available for water injection. If the capacity is zero, the aquifer is full and the system no longer inject water to the aquifer. likewise, if the capacity is the same as the original aquifer capacity, system is empty and cannot pump water from the aquifer.

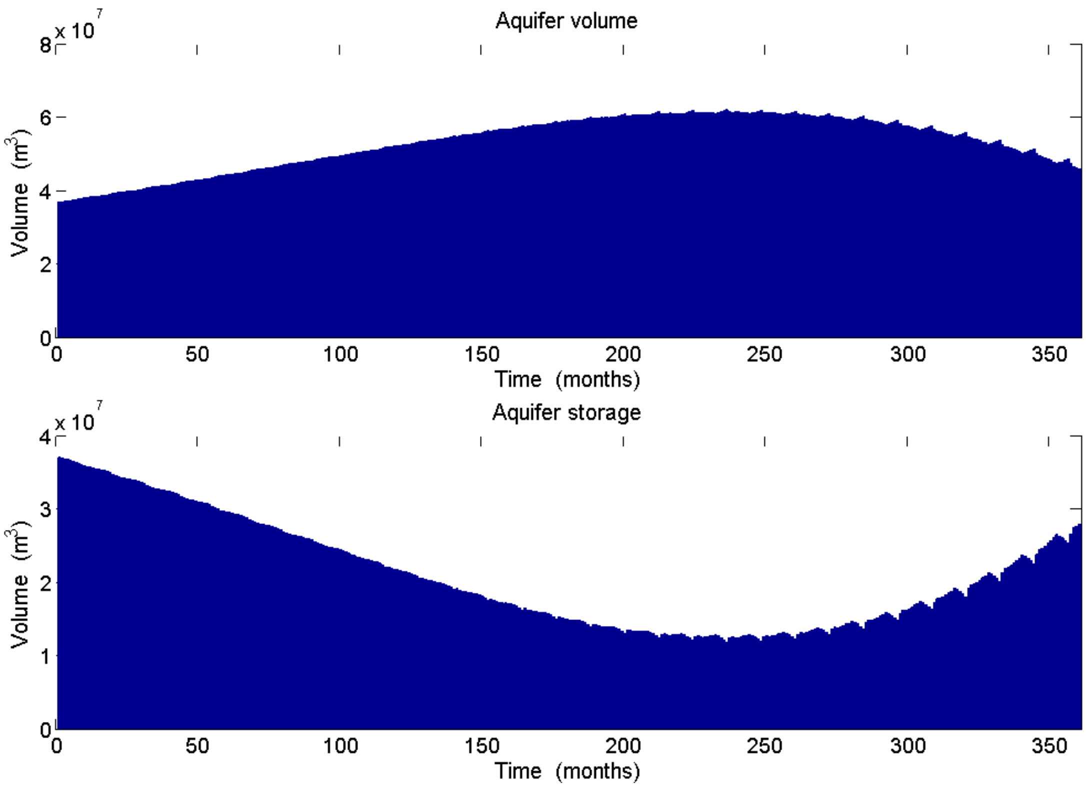

Figure 24: (a) Aquifer Storage through Time (b) Aquifer Capacity through Time

Water treatement plant capacity at the beginning of the project was 0.35×10^6 m^3/month (9.2 acre-ft/day). The water treatment plant treats both groundwater from ASR and from drains, meaning the system will expand based on the higher volume of either. The system expanded the water treatment plant because of the increasing groundwater pumping needed. The system expanded the water treatment plant the initially after 200 months (16.67 years) from the beginning of project. The water treament plant expanded three times during the lifespan of the project to reach a final capacity of 1.40×10^6 m^3/month (36.8 acre-ft/day). Most of system expansion is due water pumping from aquifer. Figure 25 shows the water treatment plant capacity, injection, and pumping through the time of the project.

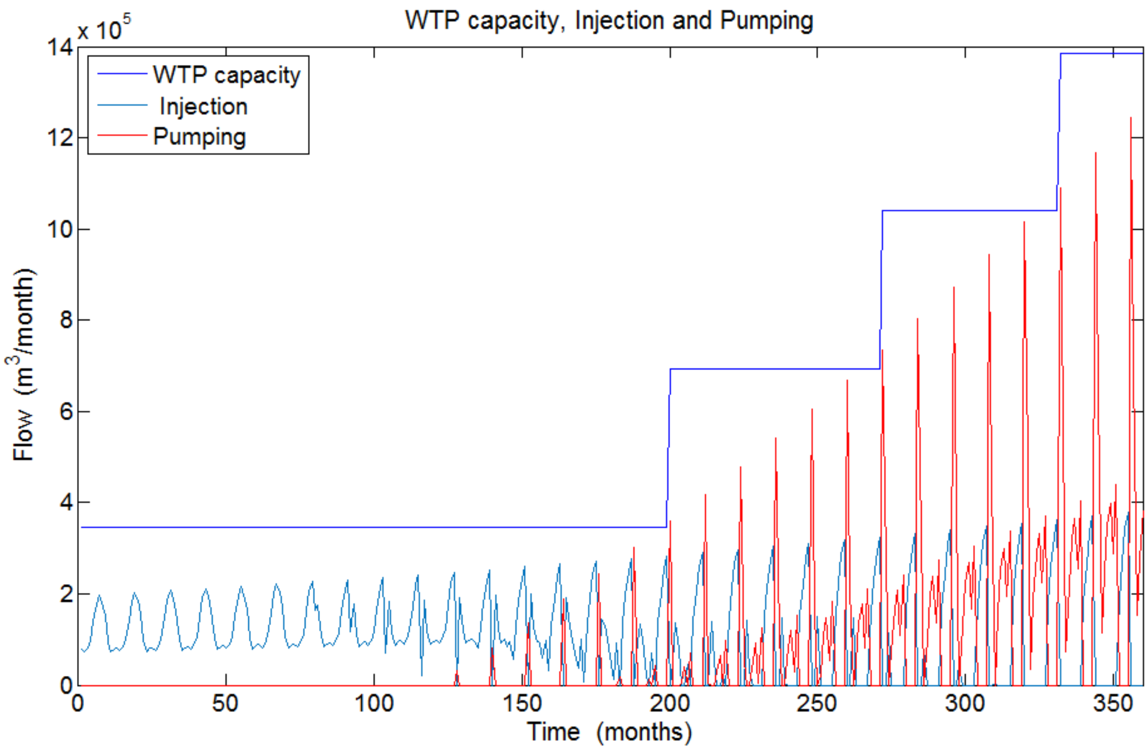

Figure 25: Water Treatment Plant Capacity, Injection, and Pumping Through the Time of the Project.

The deterministic model predicted no shortage in supply through the lifespan of the project. In the beginning, the model did not pump from the aquifer because of the available water in the river was more than the demand. However, the model started pumping after 130 months (10.8 years). Because of the constant streamflow and water rights and decreasing demand, the system started pumping from the aquifer to meet demand. However, the system was reliable 100% of the time and did not fail to meet the total demand. Figure 26 shows demand through time, the amount of shortage that was covered by pumping, and the failure to meet demand.

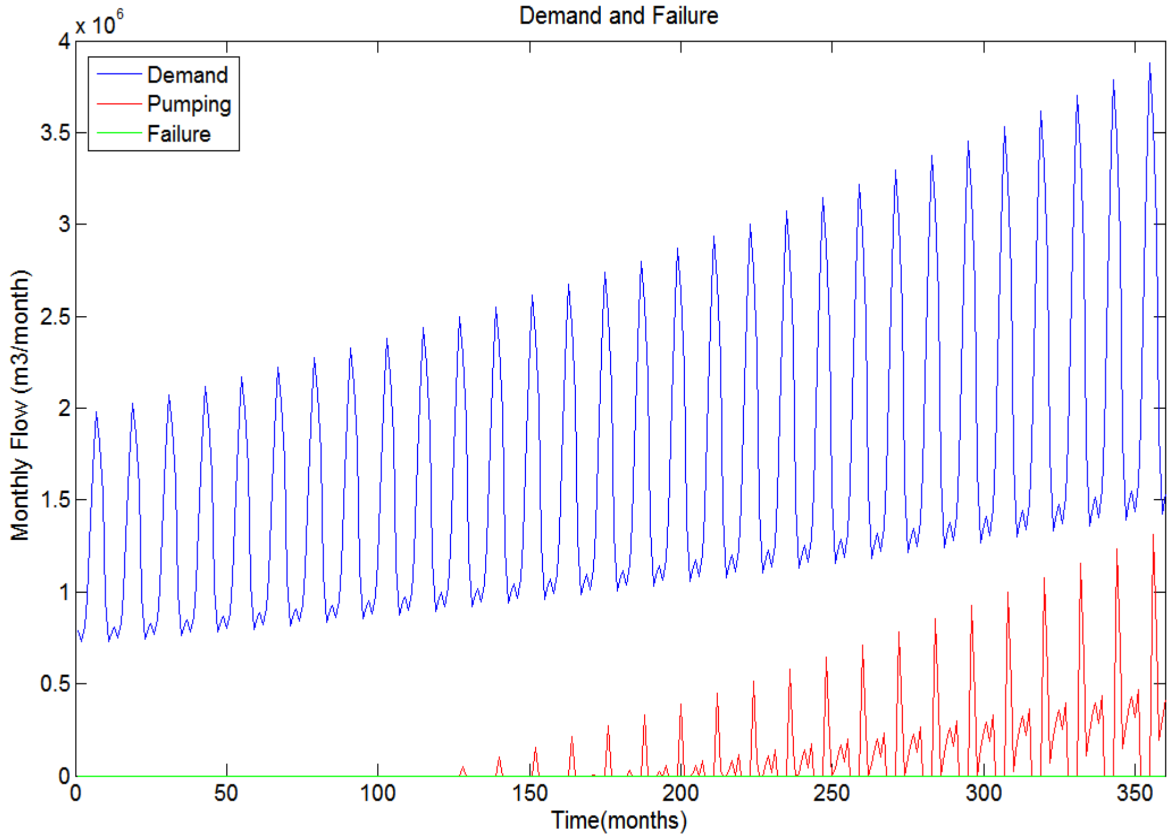

Figure 26: Demand, Pumping, and Failing to Supply System through Time.

The most pumping occurs in the final year of project by 4.2×10^6 m^3/year (3.4×10^3 acre-ft/year). The maximum injected volume of water was in the 6th year of project by injecting 1.6 $\times10^6$ m^3/year (1.3×10^3 acre-ft/year). Figure 27 shows the annual volume of pumping and injection from the aquifer.

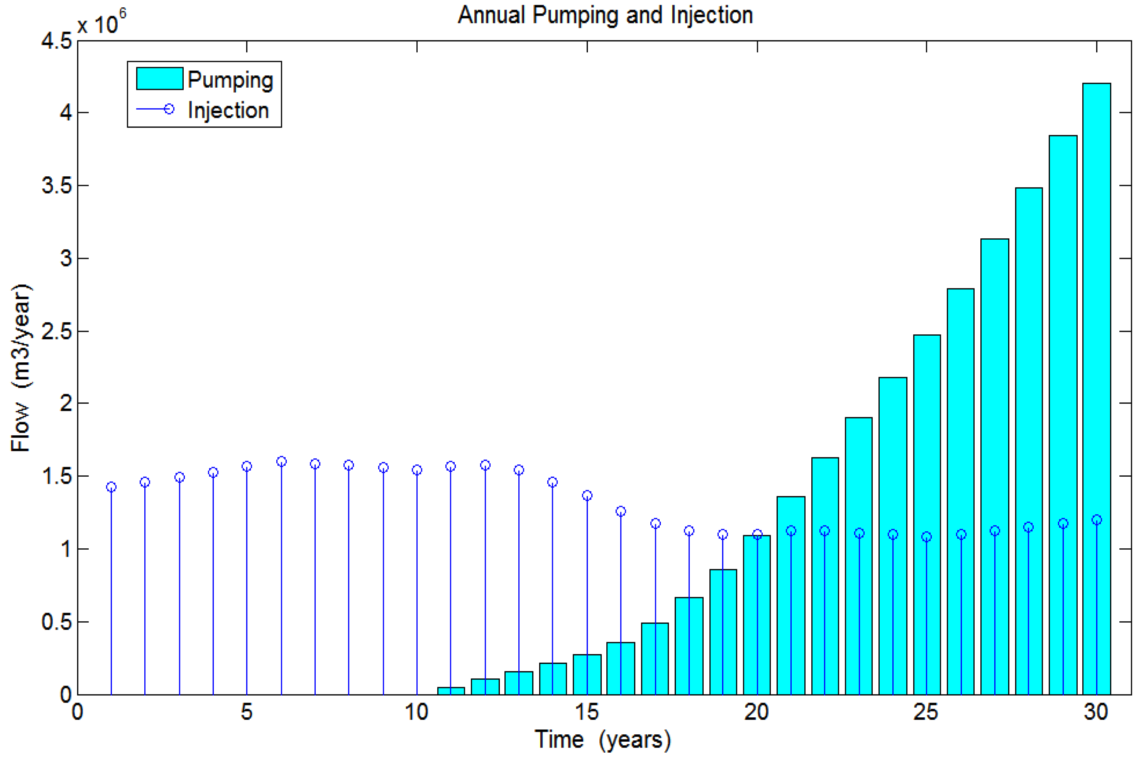

Figure 27: Annual Pumping and Injection Volume

The system is capable of pumping up to 17.8 $\times 10^6$ m^3/year (14.4 $\times 10^3$ acre-ft/year) in in the last year of the project in drought conditions, in which system pump continuously for 12 months without injection into the aquifer. The purpose of Figure 28 is to show the capacity of the system in case of drought or emergency. Figure 29 shows the system capacity for an average year, in which the system can pump continuously for 6 months. The system can pump up to 0.88 $\times 10^6$ m^3/year (713.4 acre-ft/year) in the last year of the project.

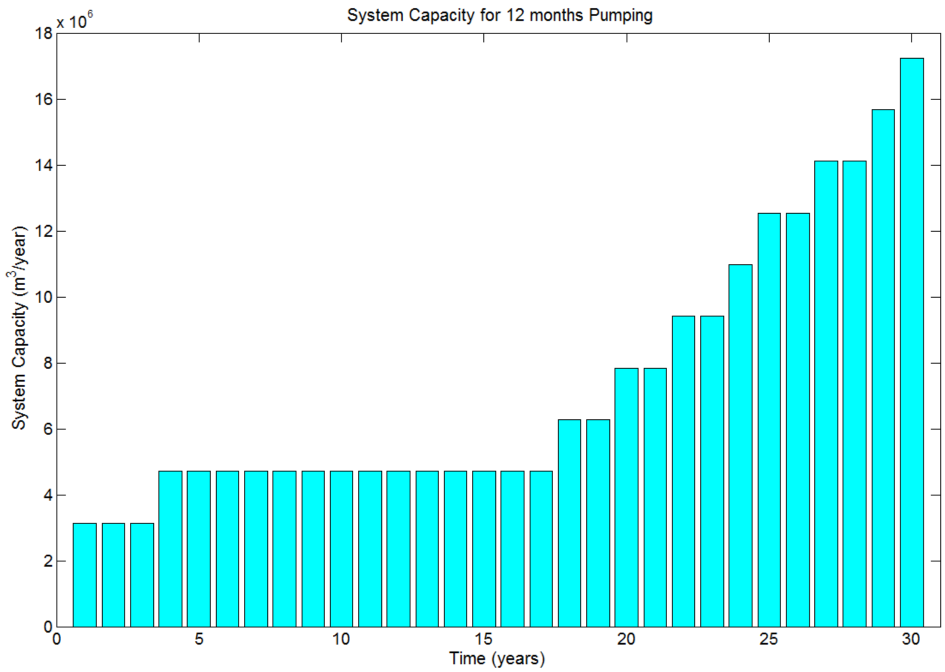

Figure 28: System Capacity in Drought Years.

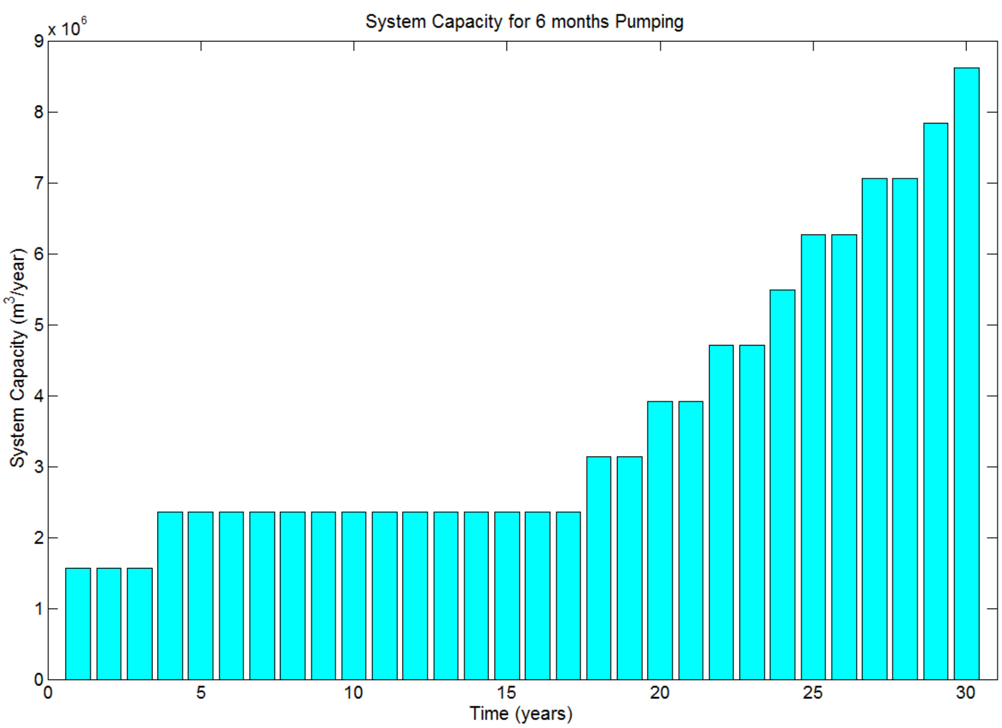

Figure 29: System Capacity in Average Years.

In the first year, the cost would be $\$5.8\times10^{6}$ U.S. including construction of water treatment plant, two ASR wells, pipe installation, alluvium subsurface drains, and other expenditures. The total cost of the project including all expansions, operation, maintinace, total replacement cost, power, labor, and other expenditures for the lifespan of the project is $\$35.6\times10^{6}$ U.S. The present value of the project is $\$ 23.1\times10^{6}$ U.S. Figure 30 shows the cost for each element for the duration of the project. Figure 31 shows the present and future value of each year for the duration of the project. Figure 32 shows the cost of key project elements on a percentage basis.

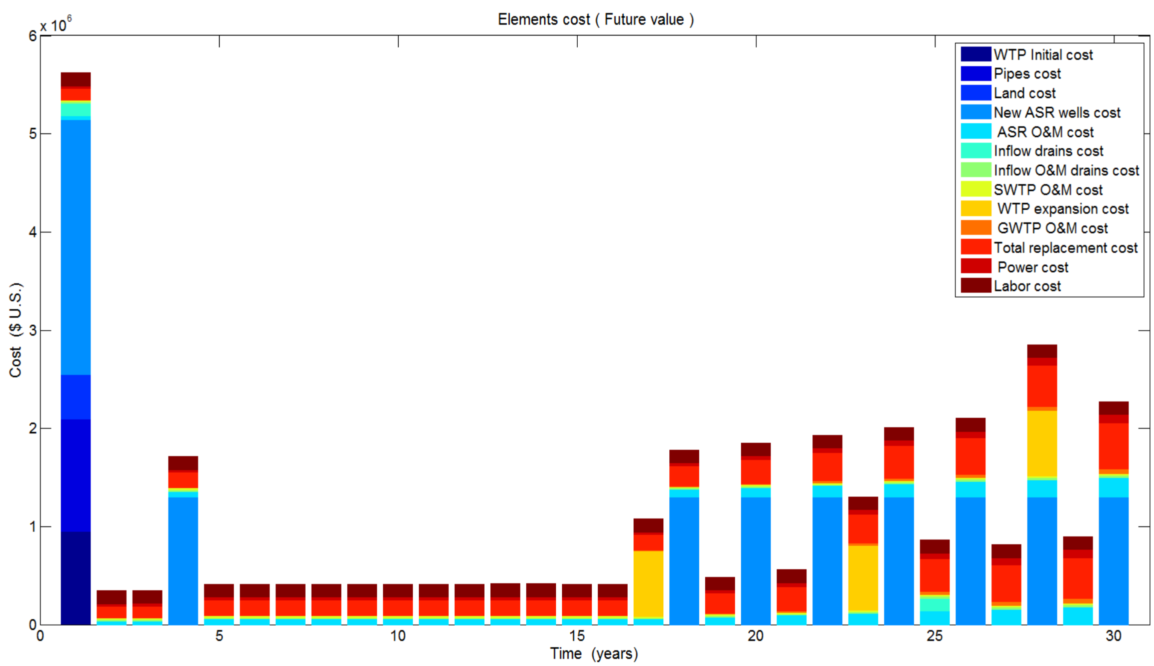

Figure 30: Cost for Each Element for the Duration of the Project.

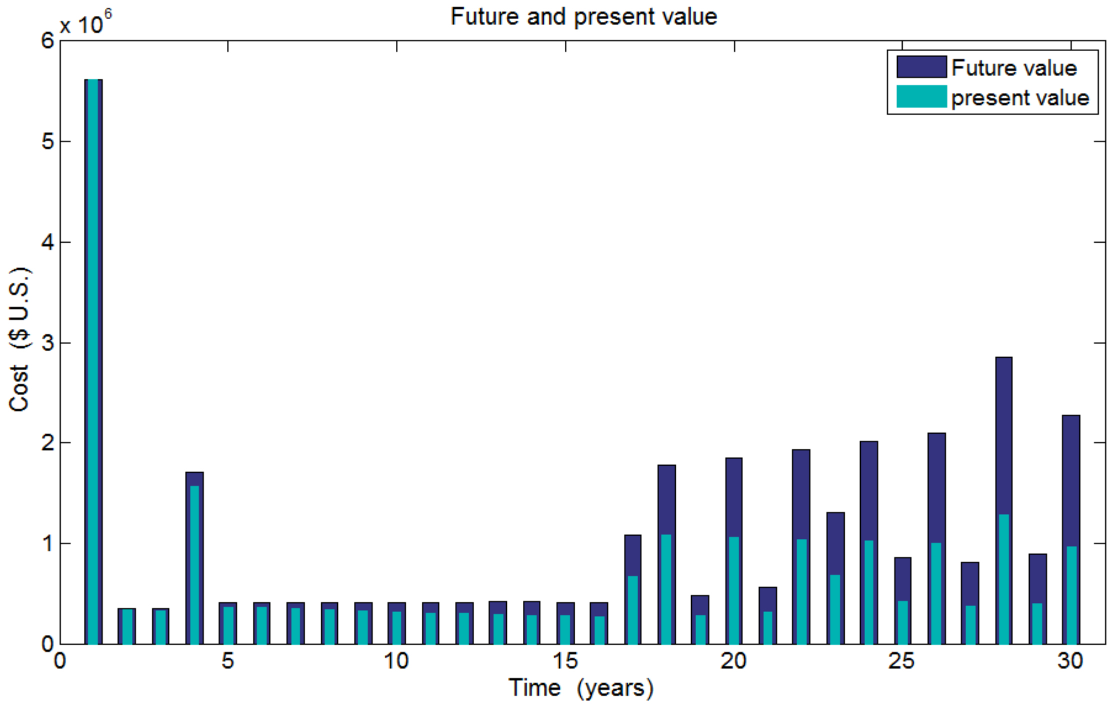

Figure 31: Present and Future Value of Each Year for the Duration of the Project.

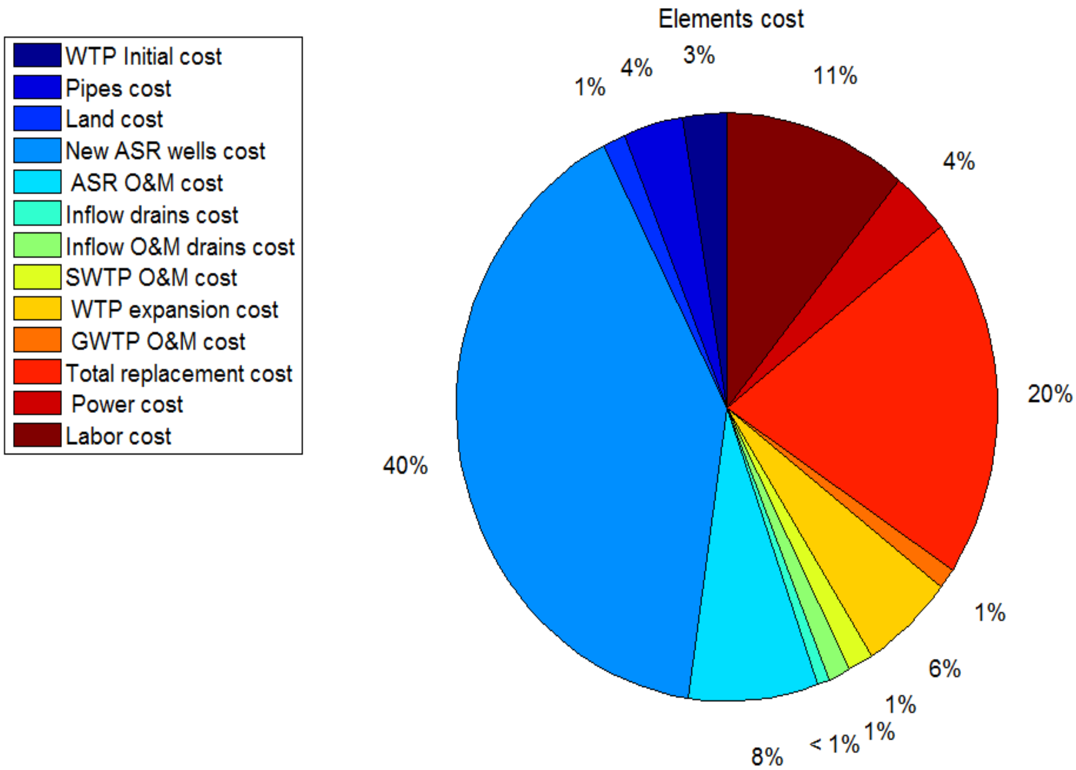

Figure 32: Cost of Key Project Elements on a Percentage Bas

4.3. Stochastic Model

Stochastic simulations for the case study were performed 100 times. One random simulation is introduced in this section for demonstration. Statistics for these 100 runs will follow at the end of the chapter. Inputs and outputs for the model are described in the following subsections.

4.3.1. Inputs

Most of the hydraulic and cost inputs in the stochastic model are the same as the inputs in the deterministic model. Additional inputs include monthly per capita demand, annual growth rate, and Poudre River streamflow. Table 1 shows the population growth rate in the city of Fort Collins. Table 5 shows the monthly per capita demand between 2004 and 2013. Table 6 shows Streamflow of Poudre River at Mouth Canyon between 1989 and 2013.

Table 5 : Monthly per Capita Demand for the City of Fort Collins (m^3/month). (City of Fort Collins Utilities,2014)

	January	February	March	April	May	June	July	August	September	October	November	December
2004	14.39	13.54	15.42	18.64	25.84	27.30	30.71	27.10	23.32	15.98	12.64	14.13
2005	14.35	13.17	14.30	15.88	21.62	25.62	41.95	33.77	31.73	15.63	11.76	14.03
2006	14.31	13.15	14.47	20.79	31.96	39.93	35.01	33.55	26.11	18.68	12.42	13.34
2007	14.51	13.66	14.64	15.94	24.66	33.87	38.13	29.51	27.97	19.22	13.07	14.03
2008	13.31	12.08	14.00	16.05	24.76	31.63	37.28	25.37	22.33	16.57	12.49	13.15
2009	12.92	12.10	13.32	13.24	21.39	20.10	27.24	29.41	22.89	11.97	11.06	11.87
2010	12.31	10.76	11.60	12.72	17.76	27.41	28.54	27.27	27.14	15.81	11.13	11.65
2011	11.54	10.71	11.65	14.33	19.71	25.20	23.59	29.88	22.05	14.85	10.21	10.75
2012	10.74	10.36	11.94	20.09	24.02	31.63	30.32	31.00	24.96	12.29	11.30	11.85
2013	11.20	10.30	11.15	11.05	16.15	27.07	27.90	26.43	18.53	12.76	10.91	11.01

Table 6: Streamflow of Poudre River at Mouth Canyon (m^3/month) (Colorado Division of Water Resources,2015)

	January	February	March	April	May	June	July	August	September	October	November	December
1989										1447	2146	1796
1990	1070	1133	3921	11633	25770	88178	43935	21850	9075	3576	2313	2273
1991	1220	1083	1500	1158	29891	97041	33287	26337	7275	1902	2505	2262
1992	1930	1747	4136	5722	51392	55522	28759	18677	4869	1960	1761	1273
1993	1829	1339	1878	4374	41935	84910	56210	28763	7888	2825	1995	1439
1994	1958	1811	2910	5078	50311	50145	15616	14924	3499	1335	1265	1664
1995	1381	1450	1630	1636	27652	146660	77646	32521	12603	3866	3602	2688
1996	2989	4179	4804	8596	57976	105685	42469	24391	6916	4522	3156	2401
1997	2184	2464	3459	5595	50512	121331	44129	30375	16094	11709	10513	5417
1998	4631	3509	6990	14866	42278	74125	46210	30818	7081	4086	4731	3769
1999	5044	4243	3477	15449	86116	122799	54628	27791	7383	3517	3312	3316
2000	4631	5086	4828	4818	40416	51381	22336	6042	3773	3114	2200	1660
2001	1535	1621	1880	3148	39638	51311	19567	10213	3191	3225	2101	1686
2002	1638	1789	2009	2192	9810	23873	8398	6478	1626	1732	1529	1507
2003	1353	1192	2037	13119	39789	94672	40446	14170	6222	3598	2162	2077
2004	1926	1884	2229	3384	31665	45859	40009	16380	6780	4409	4901	4009
2005	3749	3102	1440	3330	53057	81978	37427	12500	2616	3804	2868	1991
2006	1811	1450	2225	4510	45970	57083	13964	8991	3622	2719	2763	2291
2007	2618	2247	4340	3437	47779	73760	28267	13730	3431	4437	2815	2370
2008	1696	1670	2299	2850	30012	104511	52527	14573	4135	3074	2533	1660
2009	1656	1755	2293	2674	45831	73701	45523	8192	3902	4705	3429	2628
2010	2995	1884	2626	8263	57857	139004	36163	10868	3935	4943	3126	4433
2011	3461	2646	3646	8105	30322	162072	119278	28785	10169	6835	3255	3735
2012	3342	2241	3301	9955	27704	24808	12569	9969	5183	3410	1751	1462
2013	1726	1628	1720	2771	38369	80122	27932	13268	68133			

4.3.2. ECDFs

The model generates the annual population growth ECDF, which is the basis for forecasting the population growth for the lifespan of the project. Similarly, the model generates monthly streamflow and per capita demand for forecasting supply and demand for every month. Appendix A shows the ECDFs used in this model.

4.3.3. Outputs

For every month, there is a specific ECDF that reflects the streamflow data provided for the flow in the river. The model generates a random number and reflects it through the curve to get the flow for that month. Figure 33 shows the stochastic streamflow of the Poudre River that was generated by the streamflow ECDFs.

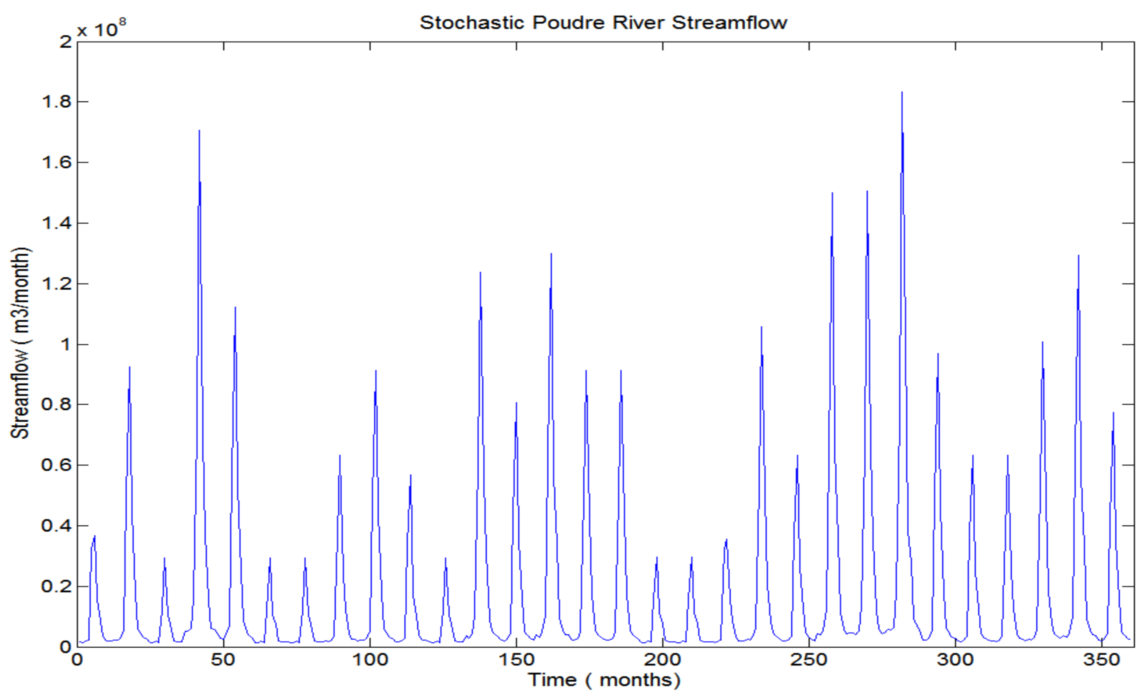

Figure 33: Stochastic Poudre River Streamflow

The model pumps the least of restricted by streamflow, water rights, and injection percentage to total demand. The main point of restricting the system to a specific percentage of the total demand is to keep the expansion of the system smooth. Figure 34 shows the stochastic streamflow of Poudre River, water rights the city owns, and the injection percentage to the total demand. Figure 35 shows a small part of Figure 34.

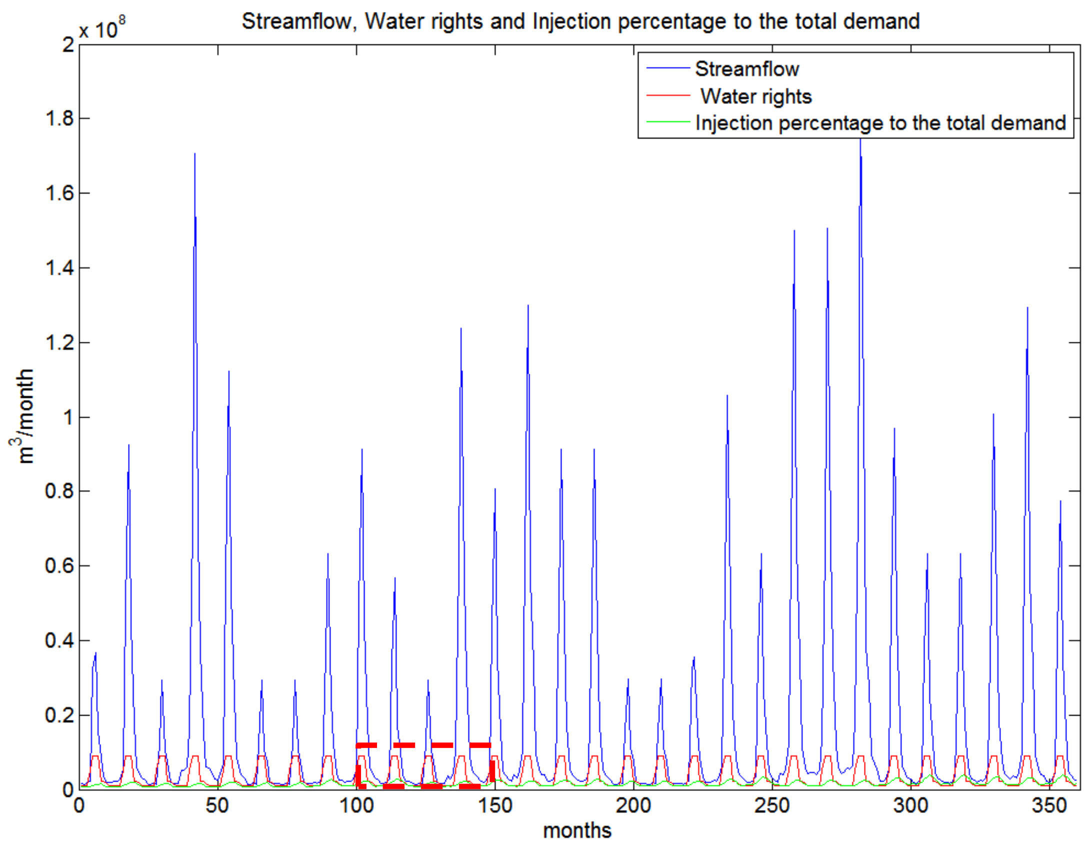

Figure 34: Streamflow, Water Rights, and Injection Percentage to the Total Demand

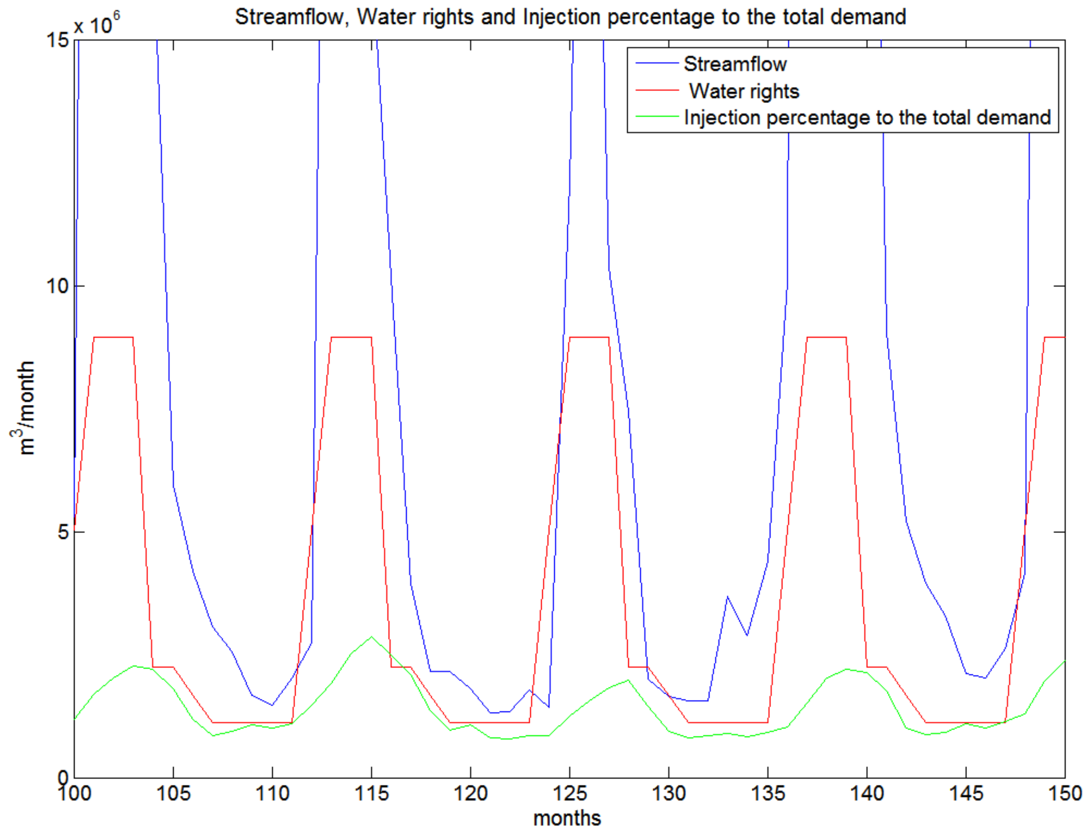

Figure 35: Lower Part of Figure 34.

Population at the beginning of project is 60,824 people and increases through time by taking the random average growth rate from average growth rate ECDF. The population will be 119.9×10^3 at the 30^{th} year of the project. This increases by 97.13% from the beginning of the project, a value similar to the deterministic model's. Figure 36 shows population through time.

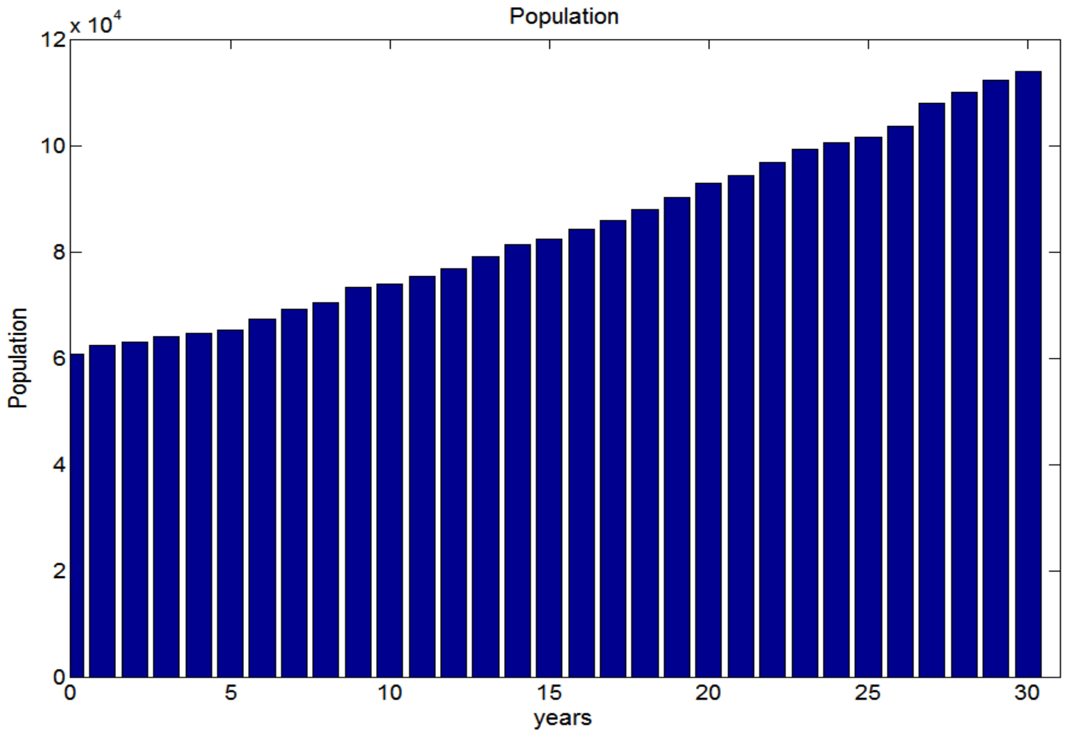

Figure 36: Population through Time.

The maximum growth rate was during the 6th year by 4.27% . The lowest growth rate was in the 8th year of the project by 1.07 %. The average growth rate through the lifespan of project is 2.29%. Figure 37 shows the stochastic growth rate for every year of the lifespan of the project.

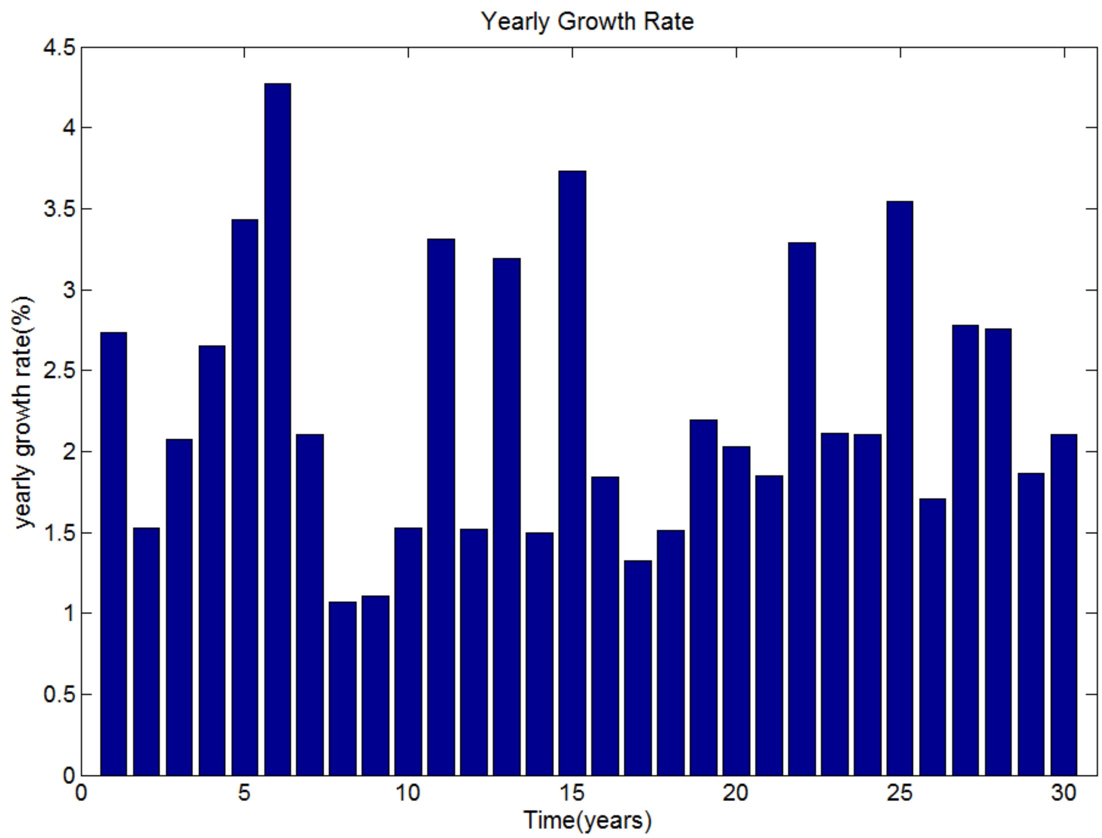

Figure 37: Stochastic Growth Rate for Every Year of the Lifespan of the Project.

A relationship exists between the streamflow and water per capita demand. If the year is considered a wet year, the demand will be less. If the year is dry, the water demand will be higher. To account for this relationship, the system uses the random number (y) to generate per capita demand (Equations 12 and 13). Figure 38 shows the monthly per capita demand for the lifespan of the project.

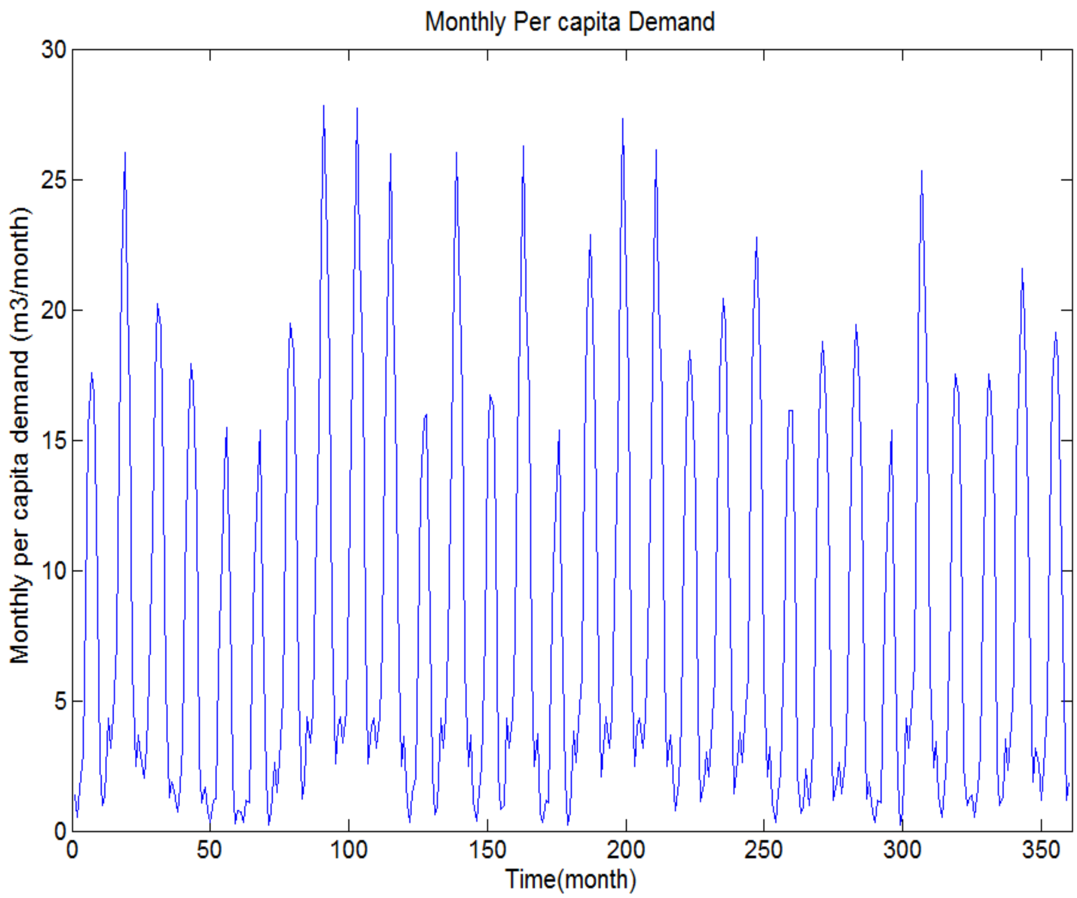

Figure 38: Monthly Per Capita Irrigation Demand for the Lifespan of the Project.

Monthly total demand are calculated based on population each month and monthly per capita demand of that month for the year. Population changes from month to month and year to year as discussed before. Similarly, per capita demand changes from month to month and year to year, unlike the deterministic model. With the deterministic model, urban irrigation was fixed as 10 m^3/month.The stochastic model will stochastically calculate the irrigation demand from the ECDFs. The maximum demand is 3.9 $\times 10^6$ m^3/month (3.1$\times 10^3$ acre-ft/month) on the 30th year of the project. The lowest demand was 726$\times 10^3$ m^3/month (589 acre-ft/month) in the beginning of the project. Figure 39 shows the forecasted monthly total demand for the city of Fort Collins.

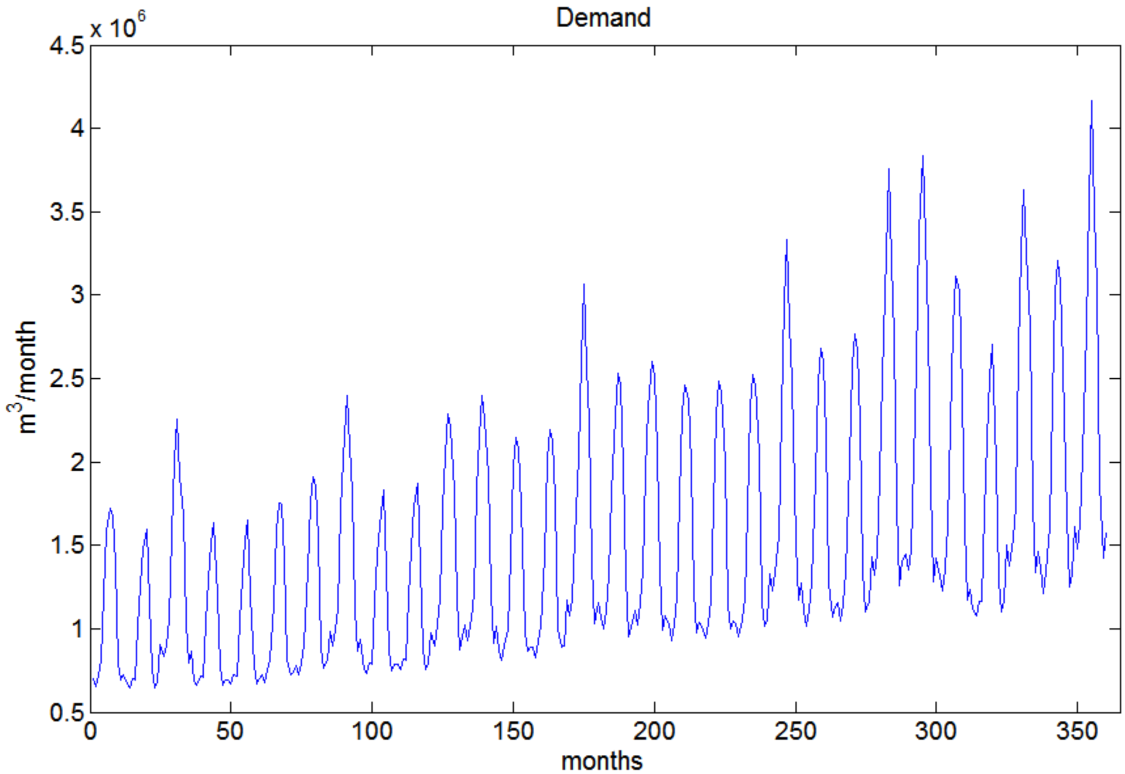

Figure 39: Forecasted Monthly Total Demand for the City Of Fort Collins

Each well has a capacity of 4.28×10^3 m^3/day (785 gpm) for pumping and 3.43×10^3 m^3/day (628 gpm) for injection based on equation 6.

Pumping and injection to the aquifer varies each month based on the supply and demand and the restrictions on the system. The system pumps water from the aquifer if there a shortage exists in the supply. The system will meet the demand first by diverting water directly from the river. If the supply could not meet the demand, the system pumps water to cover the shortage. The maximum volume of pumping was 1.3×10^6 m^3/month (1×10^3 acre-ft/month) in the last year of the project. The maximum injection volume was 407×10^3 m^3/month (330 acre-ft/month) in the 27th year of the project. Figure 40(a) shows pumping through time. Figure 40(b) shows injection through time.

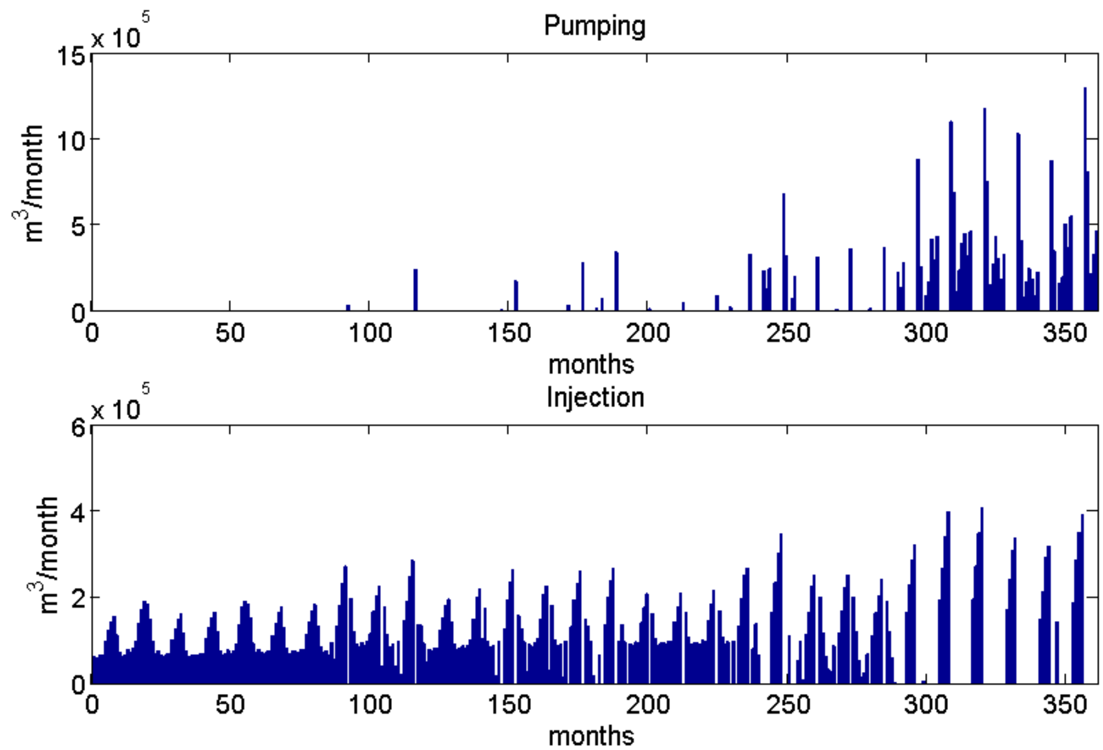

Figure 40: (a) Pumping Through Time, (b) Injection through Time.

The aquifer started half full with a volume of 37×10^6 m^3 (30×10^3 acre-ft), and the storage at the end of the project was 52.5×10^6 m^3 (42.6×10^3 acre-ft), an addition of 15.5×10^6 m^3 (12.6×10^3 acre-ft) to the aquifer. The system injected 39×10^6 m^3 (31.7×10^3 acre-ft) and pumped from the aquifer 24×10^6 m^3 (19.4×10^3 acre-ft) during the project life. The system injected 1.3×10^6 m^3/year (1×10^3 acre-ft/year) and pumped 800×10^3 m^3/year (648 acre-ft/year) on average. Figure 41(a) shows aquifer volume through time. Figure 41(b) shows the aquifer capacity available for water injection. If the capacity is zero, the aquifer is full and the system cannot inject more water into the aquifer. If the capacity is the same as aquifer original capacity,the system is empty and cannot pump water from the aquifer.

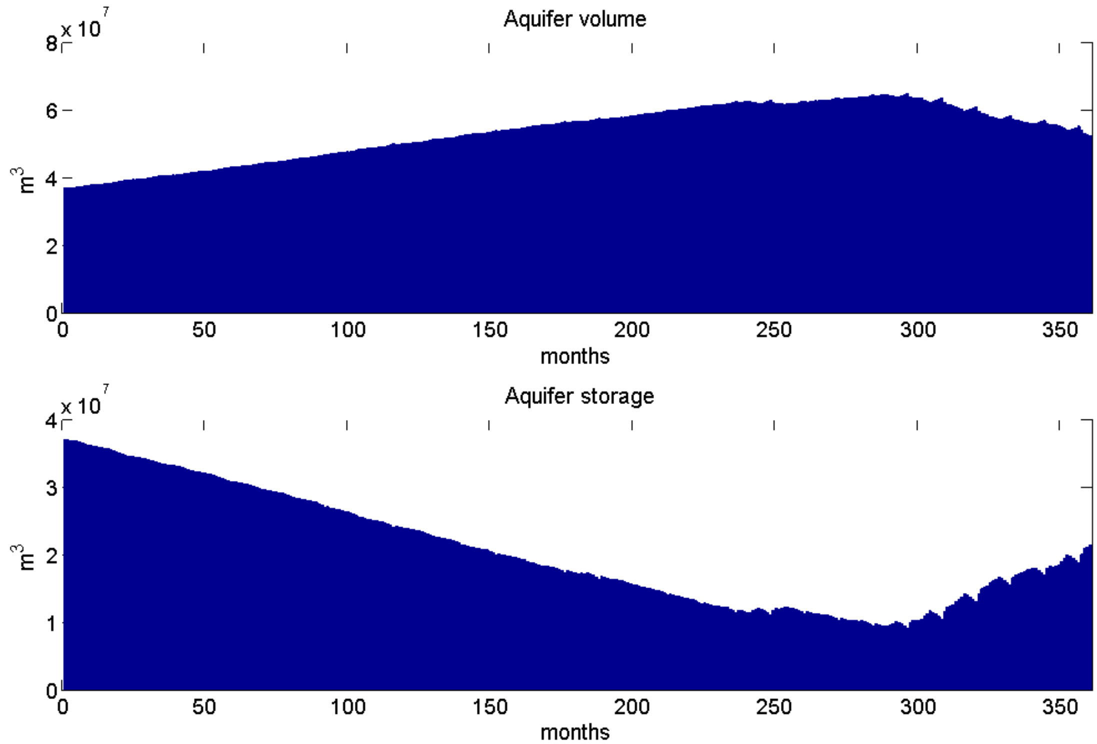

Figure 41: (a) Aquifer Storage through Time, (b) Aquifer Capacity through Time.

Water treatment plant capacity at the beginning of project was 346×10^3 m^3/month (9 acre-ft/day). The water treatment plant treats both groundwater from ASR and from drains, meaning the system will expand based on the higher volume of either. The system expanded water treatment plant because of the incraesing groundwater pumping that is needed. The system expanded the water treatment plant initially after 250 months (20.8 years) from the beginning of project. The water treament plant was expanded three times in the lifespan of the project, reaching a capacity of 1.4×10^6 m^3/month (37 acre-ft/day) at the end of project. Figure 42 shows water treatment plant capacity, injection, and pumping throughout the time of the project.

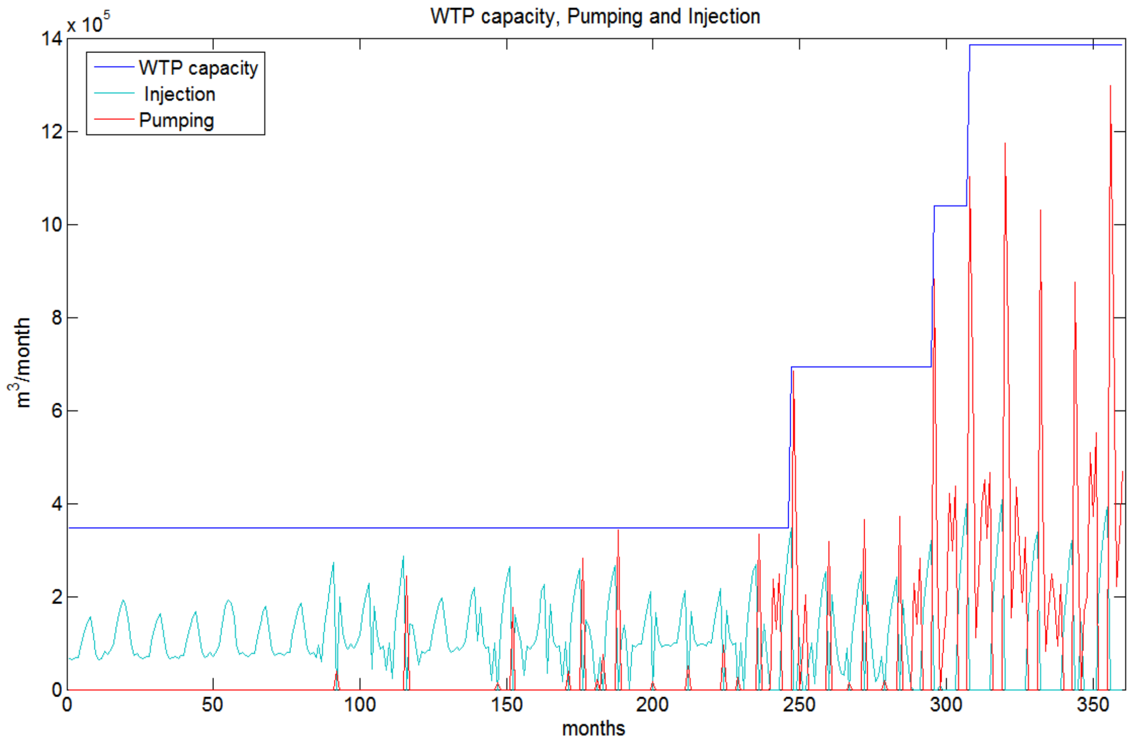

Figure 42: Water Treatment Plant Capacity, Injection, and Pumping Throughout the Time of the Project.

The system needs two ASR wells in the first year of project. The system requires additional ASR well in the third year of the project. By the end of the project, the system will require 10 ASR wells to inject and recover water from aquifer. The system will increase the number of ASR wells gradually to keep cost as low as possible. Figure 43(a) shows the number of ASR wells needed by the system to inject and recover water from aquifer. The system requires one alluvium subsurface drain unit at the beginning of the project and will require another unit at the 21st year of the project. The capacity of each unit is 10.9×10^3 m^3/ day (8.84 acre-ft/day). Figure 43(b) shows alluvium subsurface drains that are required by the system to inject water to the aquifer.

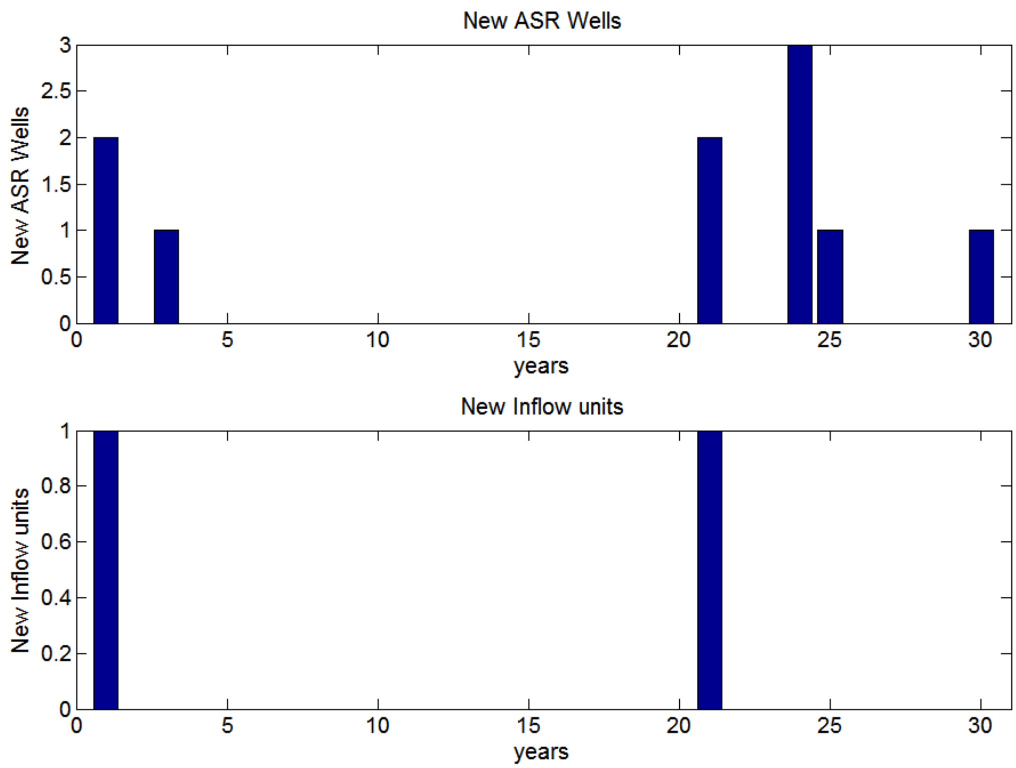

Figure 43: (a) New ASR Wells Needed Through Time (b) New Inflow Units Needed Through Time.

The stochastic model shows no shortage in supply through the lifespan of the project. In the beginning, the model did not pump from the aquifer because of the avaialble water in the river was more than the demand. However, the model started pumping after 90 months (7.5 years), which means that the amount of water in the river was not enough to meet the demand. Thus, the system pumped from the aquifer to meet the demand. The system was reliable 100% of the time and did not fail to meet the total demand. Figure 44 shows demand through time, the amount of shortage that was covered by pumping, and the failure to meet demand.

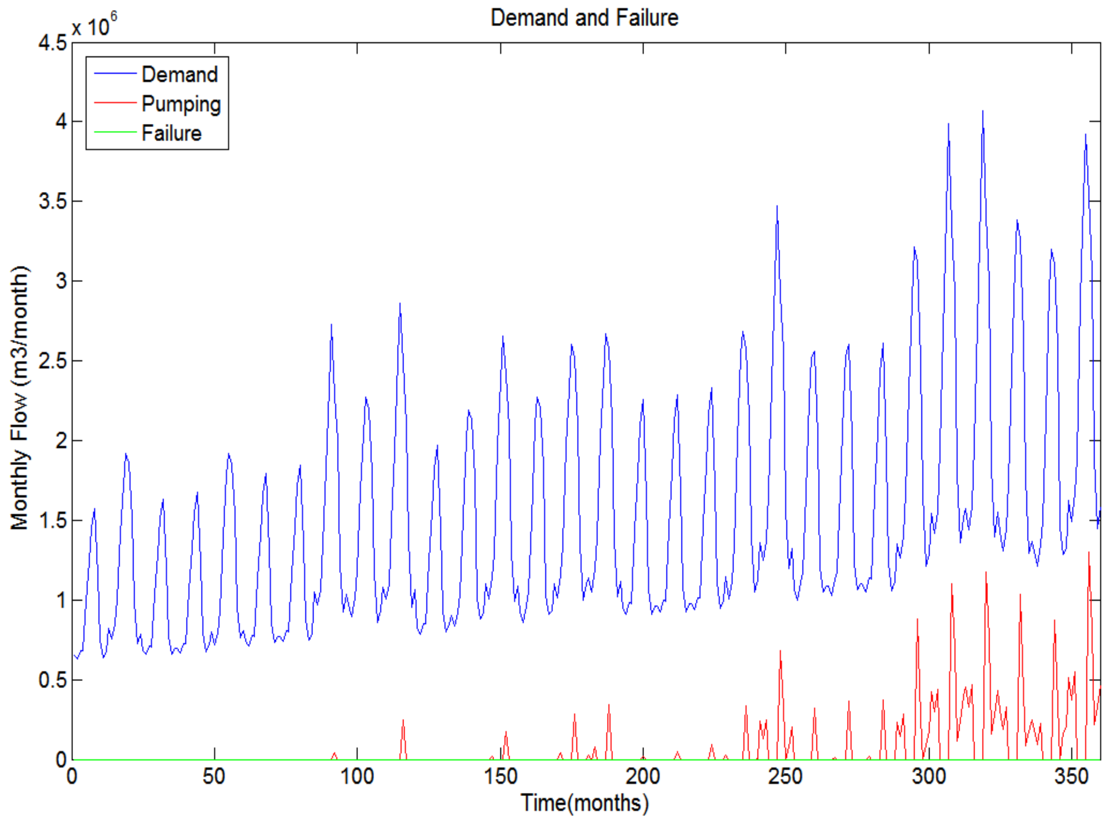

Figure 44: : Demand through Time, the Amount of Shortage Covered By Pumping, and the Failure to Meet Demand.

Most pumping occurs in the last year of project, 46×10^6 m^3/year (3.7×10^3 acre-ft/year). For first eleven years, no pumping from the aquifer occurred because it was unnecessary. The maximum injected volume of water was in the 8th year of project by injecting 1.5×10^6 m^3/year (1.3×10^3acre-ft/year). Figure 45 shows the annual volume of pumping and injection from the aquifer.

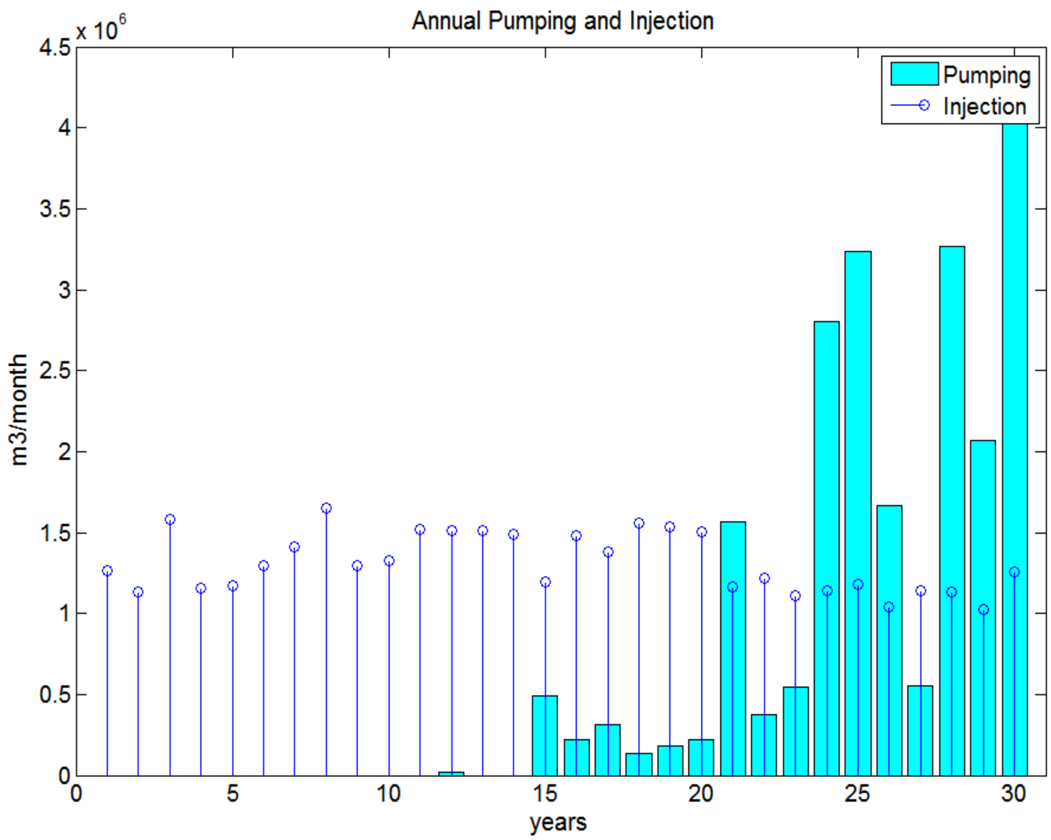

Figure 45: Annual Volume of Pumping and Injection from the Aquifer.

The system can pump up to 15.9 $\times 10^6$ m^3/year (12.9×10^3 acre-ft/year) in the last year of the project in the event of drought year, in which system pump continuously for 12 months without injection into the aquifer. Figure 46 shows the capacity of the system in case of drought or emergency. Figure 47 shows the system capacity for average year. For an average year, system can pump continuously for 6 months up to 0.88 $\times 10^6$ m^3/year in the last year of the project. Summary of system capacity shown in Table 8 at the end of this chapter.

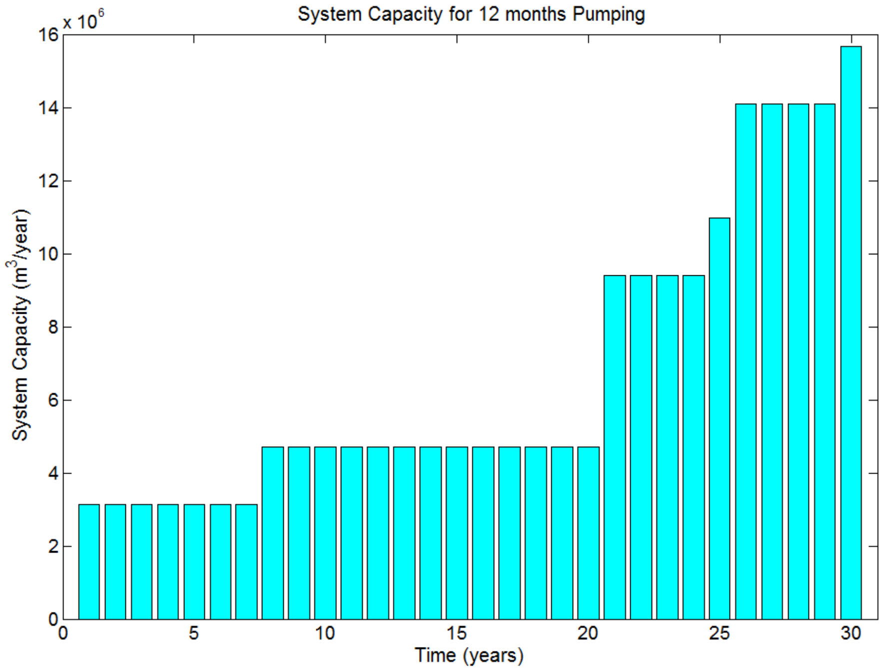

Figure 46: System Capacity in Drought Years.

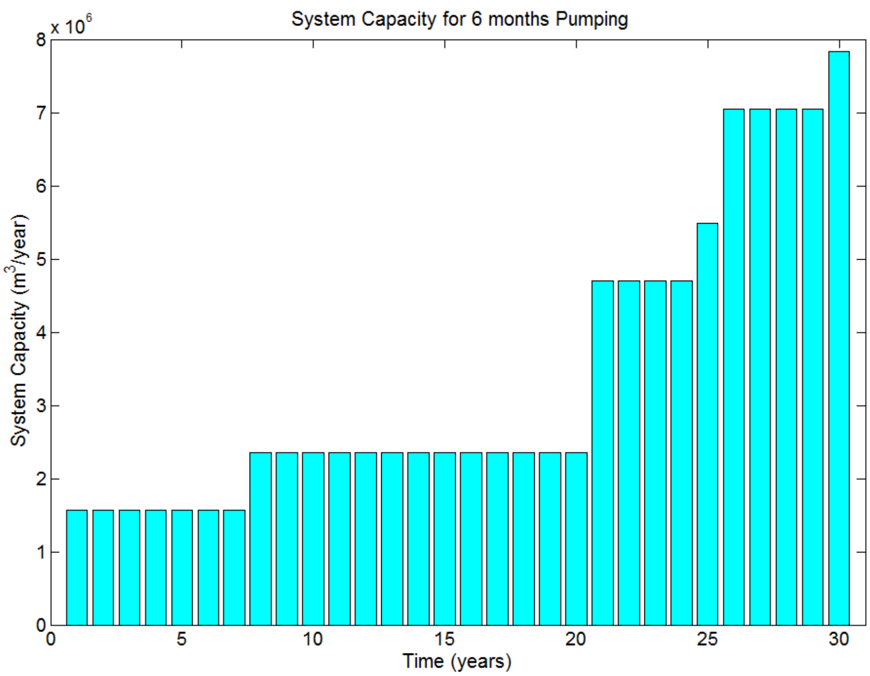

Figure 47: System Capacity in Average Years.

In the first year, the cost would be $\$5.8\times10^{6}$ U.S. including construction water treatment plant, two ASR wells, installation of pipes, alluvium subsurface drains, and other expenditures. The total cost of the project including all expansions, operation, maintainence, total replacement cost, power, labor, and other expenditures for the lifespan of the project is $\$ 33 \times10^{6}$ U.S. The summation value of the present cost for every year will be $\$21.4\times10^{6}$ U.S. Figure 48 shows the cost for each element during the lifespan of the project. Figure 49 shows the present and future value of each year for the lifespan of the project. Figure 50 shows the cost of key project elements on a percentage basis. Summary of system costs shown in Table 9 at the end of this chapter.

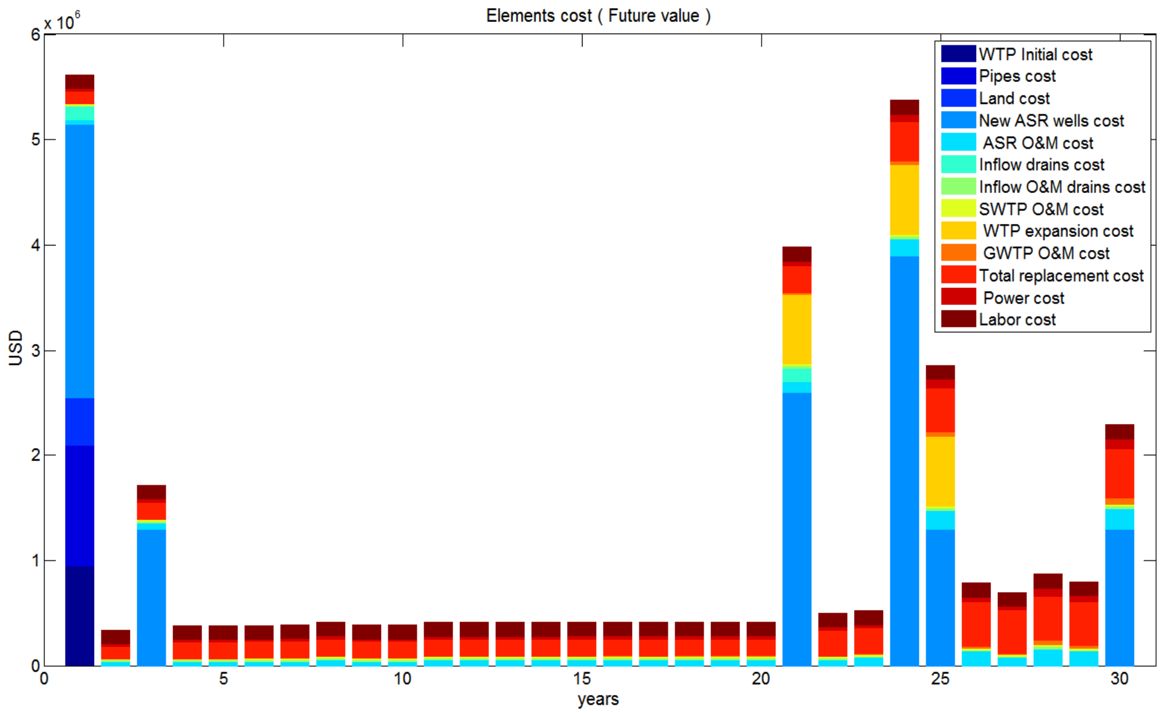

Figure 48: Cost for Each Element during the Lifespan of the Project.

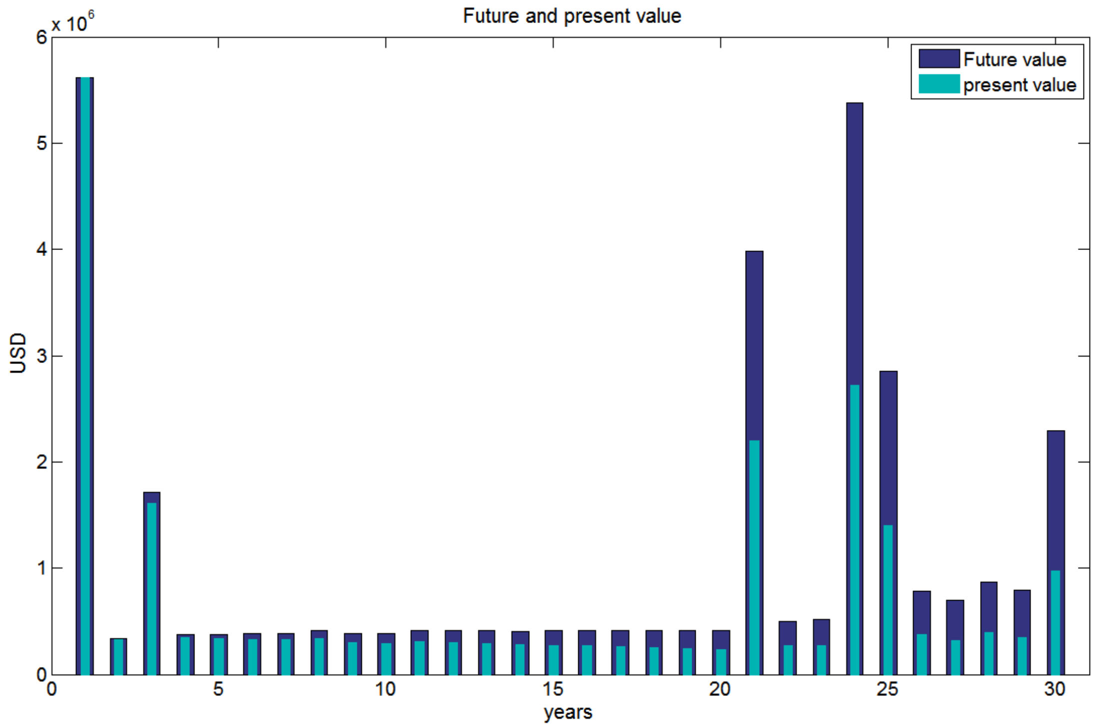

Figure 49: Present and Future Value of Each Year in the Lifespan of the Project.

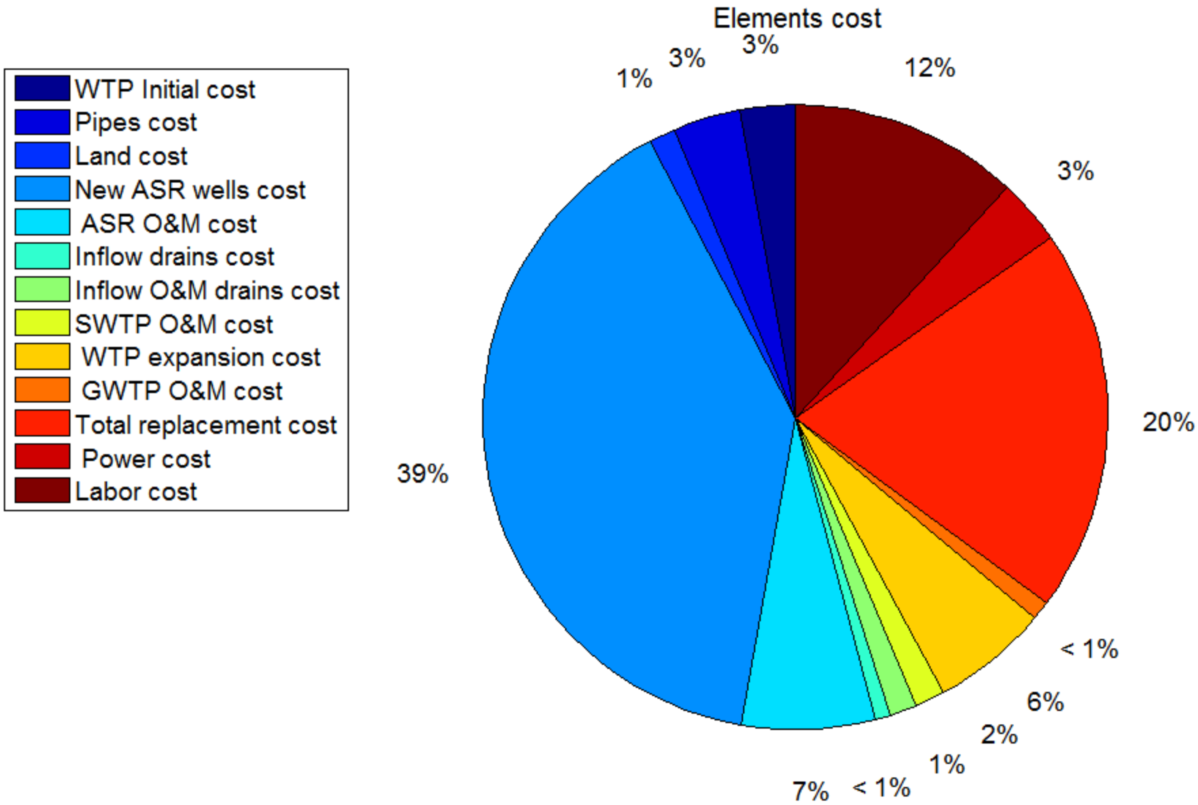

Figure 50: Cost of Key Project Elements on a Percentage Basis.

Table 7: Statistics for 100 Stochastic Runs.

	Mean	Median	Standard Deviation	Coefficient of Variation	Maximum	Minimum
Max. population (thousands)	117.9	117.0	6.5	0.055	132.6	102.4
Total pumping (million m^3/month)	22.6	21.9	7.4	0.330	50.9	8.7
Total injection (million m^3/month)	39.4	39.4	1.0	0.024	42.2	37.2
Additional Storage (million m^3)	16.8	17.8	7.9	0.468	33.4	-11.8
Final WTP Capacity (million m^3/month)	1.4	1.4	0.2	0.163	1.7	1.0
ASR wells	10.4	10.0	1.9	0.179	14.0	6.0
Inflow units	2.0	2.0	0.0	0.000	2.0	2.0
Capital cost (million $U.S.)	5.9	5.8	0.6	0.099	7.5	5.1
Total Present Value (million $U.S.)	22.5	22.3	2.3	0.102	28.7	17.6
Life cycle cost (million $U.S.)	34.1	33.5	4.1	0.121	44.2	25.0

Table 8:Summary of System Capacity.

model	**Deterministic**		**Stochastic**	
	Year 30 (m^3/year)	Year 30 (acre-ft/year)	Year 30 (m^3/year)	Year 30 (acre-ft/year)
6 Months of Pumping	8.6×10^6	7×10^3	7.8×10^6	6.4×10^3
12 Months of Pumping	17.2×10^6	14×10^3	15.7×10^6	12.7×10^3

Table 9:Summary of System Cost.

Project Cost (USD)	**Deterministic**	**Stochastic**
Capital Cost	5.8×10^{6}	5.8×10^{6}
Present Value	23.1×10^{6}	21.4×10^{6}
Life Cycle	35.6×10^{6}	33×10^{6}

5. CONCLUSION AND RECOMMENDATION

5.1. Conclusions

The goal of this thesis was to design a general model that can assess a variety of subsurface water storage projects feasibility. The model forecasts water demand and supply to calculate the amount of storage needed and means of handling supply shortages. The model was applied to a scenario based on conditions in the vicinity of Fort Collins, Colorado to prove its capability. The results are not directly applied to the city of Fort Collins. Two types of the inputs were applied, deterministic and stochastic. 100 simulations were performed using stochastic model to estimate the range of variability of outputs.

One of the main advantages of this subsurface water storage project that it would minimize water losses due to evaporation and infiltration, creating a great opportunity to increase water yield from these projects compared to surface reservoirs projects, where a huge amount of water evaporates. The harvested losses can be sold or rented to decrease the total cost of the project.

The estimated present value cost from deterministic and stochastic models of the entire project was \$23.1 million U.S and \$22.5 million U.S., respectively. The capital cost of the project is predicted to be around \$6.0 million U.S. by both models. The model shows high reliabilty in meeting demand through the lifespan of the project with no expected failure. The deterministic model added 9.1 million m^3 to the aquifer, while the stochastic model shows average addition of 16.8 million m^3 to the aquifer. Both models estimated the need for 10 ASR wells and two alluvium inflow drain units through the the lifespan of the project. However, the timing of ASR wells installation was different for each models. Population were estimated almost the same from both models. Both models yielded similar results, while using different inputs.

We found that deterministic model would give very reasonable results compared to the output of mutliple stochastic analysis when the average of available data is used as input to deterministic model. However, if the deterministic inputs used is the same as the available data, we expect the outputs to be within the range that were produced from large number runs of the stochastic model.

Except total pumping and additional storage, other outputs have a small coefficient of variation (Table 7),which shows that they are less sensitive to uncertainity in input variables. Coefficient of variation for cost variables are around 0.1(i.e., costs are expected to vary within ±10% of the estimated mean cost). Since different cost components estimated by deterministic model is within ±10% of the estimated mean cost from stochastic model, we conclude that deterministic model estimates different cost components fairly well.

The model shows that the ASR wells construction is almost 40% of the total cost of the project. Also, total replacement cost for ASR wells, water treatment plant, and pipes cost almost 20% of the total cost of the eproject. Labor and ASR operation and maintinance compose 12% and 7% of the total cost respectively. These four elements are 80% of the total project, and the rest of elements compose the rest 20% of the total cost of the project.

The model includes the option of modular expansion of the infrastructure through time, potentially reducing the total and operation and maintenance costs. In this case, the model has decreased the cost by almost 35% because of modular expansion.

5.2. Recommendations

Recommendations for future work include:

- Optimization in some of the calculations is needed in order to generate more accurate results. Optimization can be applied to calculation, such as the injection percentage to the total demand, the calculation of demand, and water treatment plant capacity expansion.
- Linking this model to other models to improve results. Models that can be linked to this model include MODFLOW, where the calculations of water table and groundwater flow will help estimating the volume of water in aquifer and the system ability to pump and inject.
- Conducting field tests would help estimating aquifer parameters to develop more accurate measurements of the capacity of the aquifer, transmissivity, storativity, and water table drawdown.
- Improving the model itself by adding more functions and tools. Similarly, adding an interface to the program that will make running the program easier for users.
- Comparison with other water storage options-addition of environmental effects within the model operations
- Using other stochastic methods to make prediction more accurate.
- The model should be modified for situations using other sources for fresh water. For example, Saudi Arabia where treated waste water can be injected to the aquifers and used later.

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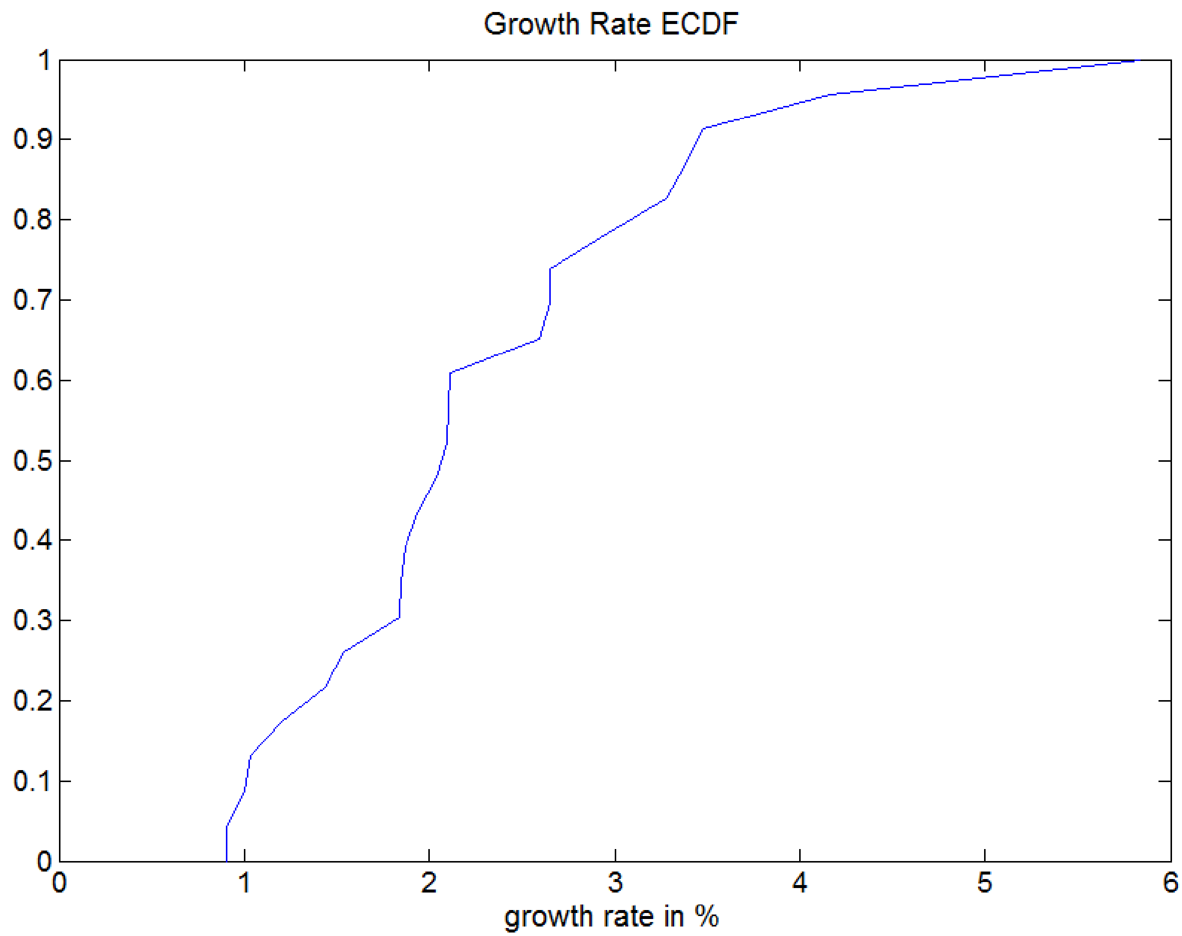
APPENDIX A: ECDF for Growth Rate, Streamflow, and Per Capita Demand



FigureA1: Growth rate ECDF based on the data of Fort Collins growth rate between 1990 and 2013.

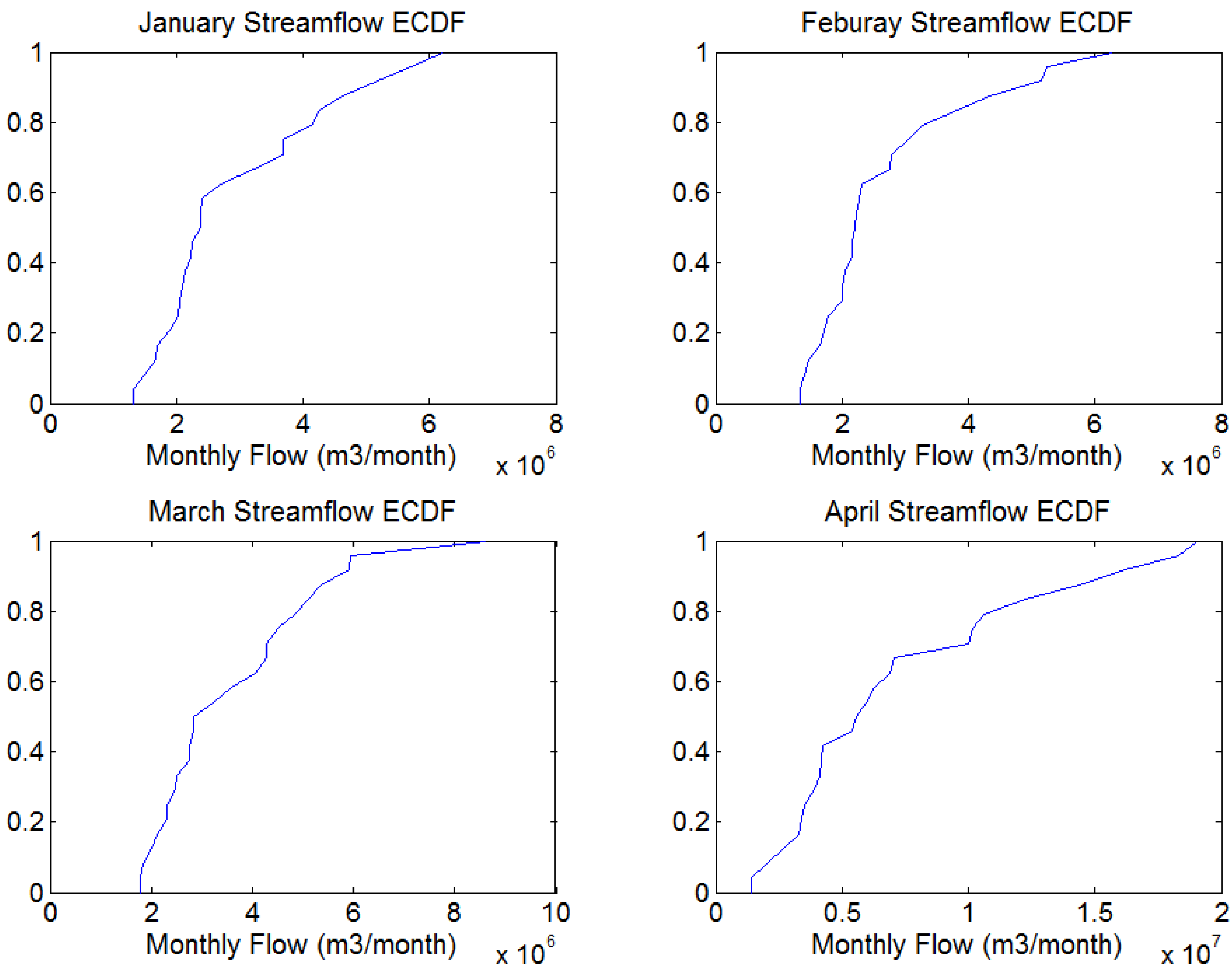


Figure A2: Podre River Stochastic streamflow ECDFs from January to April.

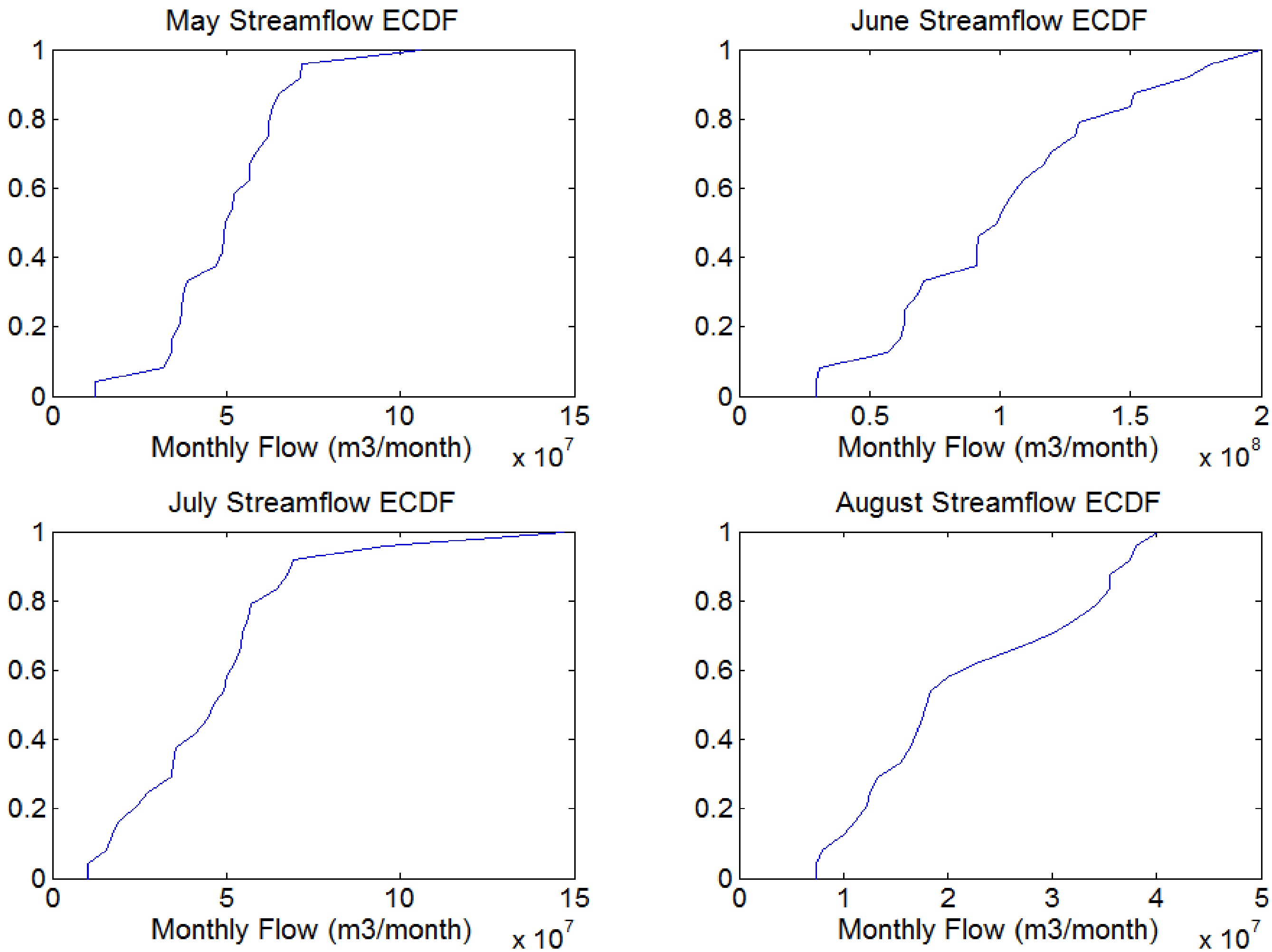


Figure A3: Podre River Stochastic streamflow ECDFs from May to August.

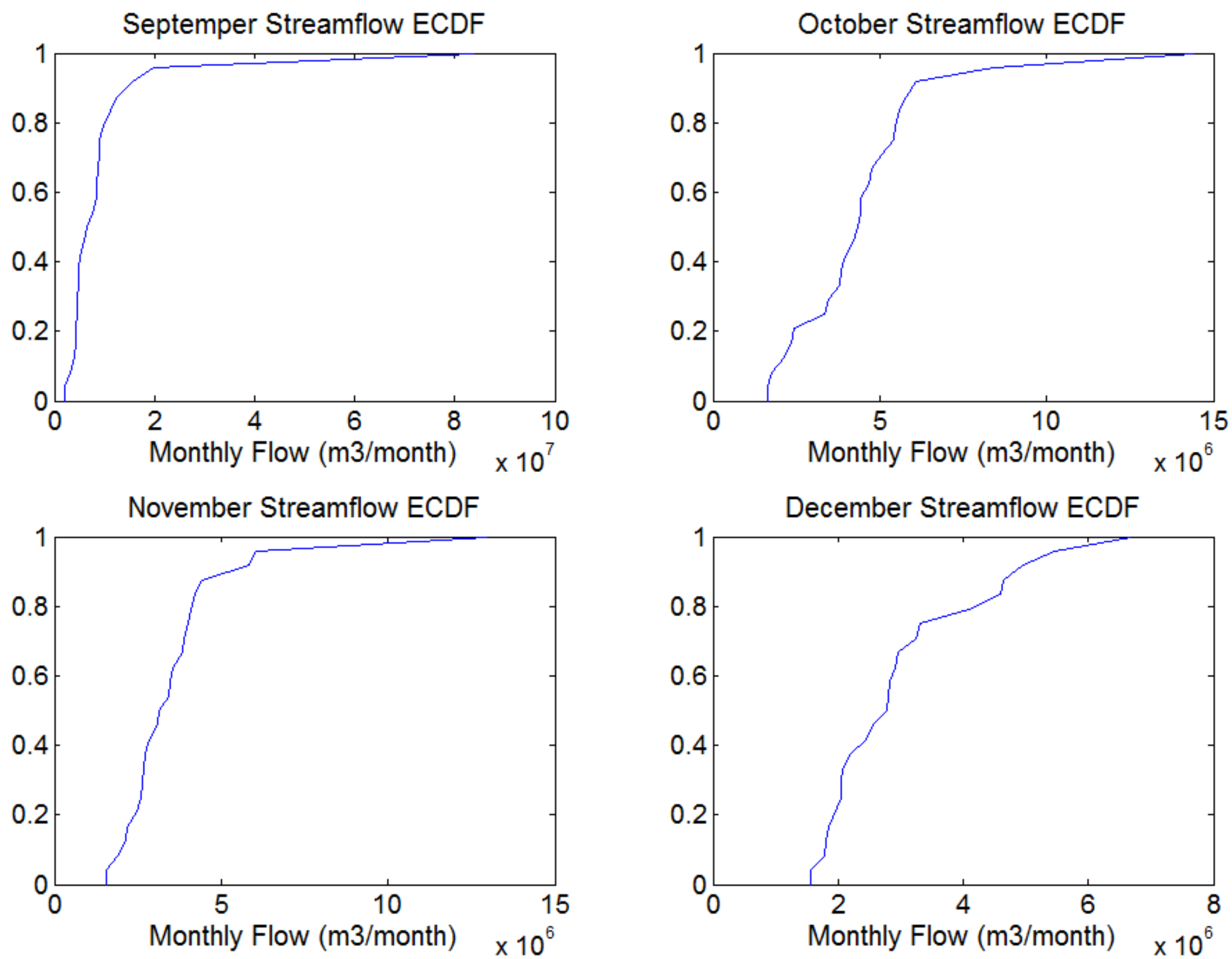


Figure A4: Podre River Stochastic streamflow ECDFs from September to December.

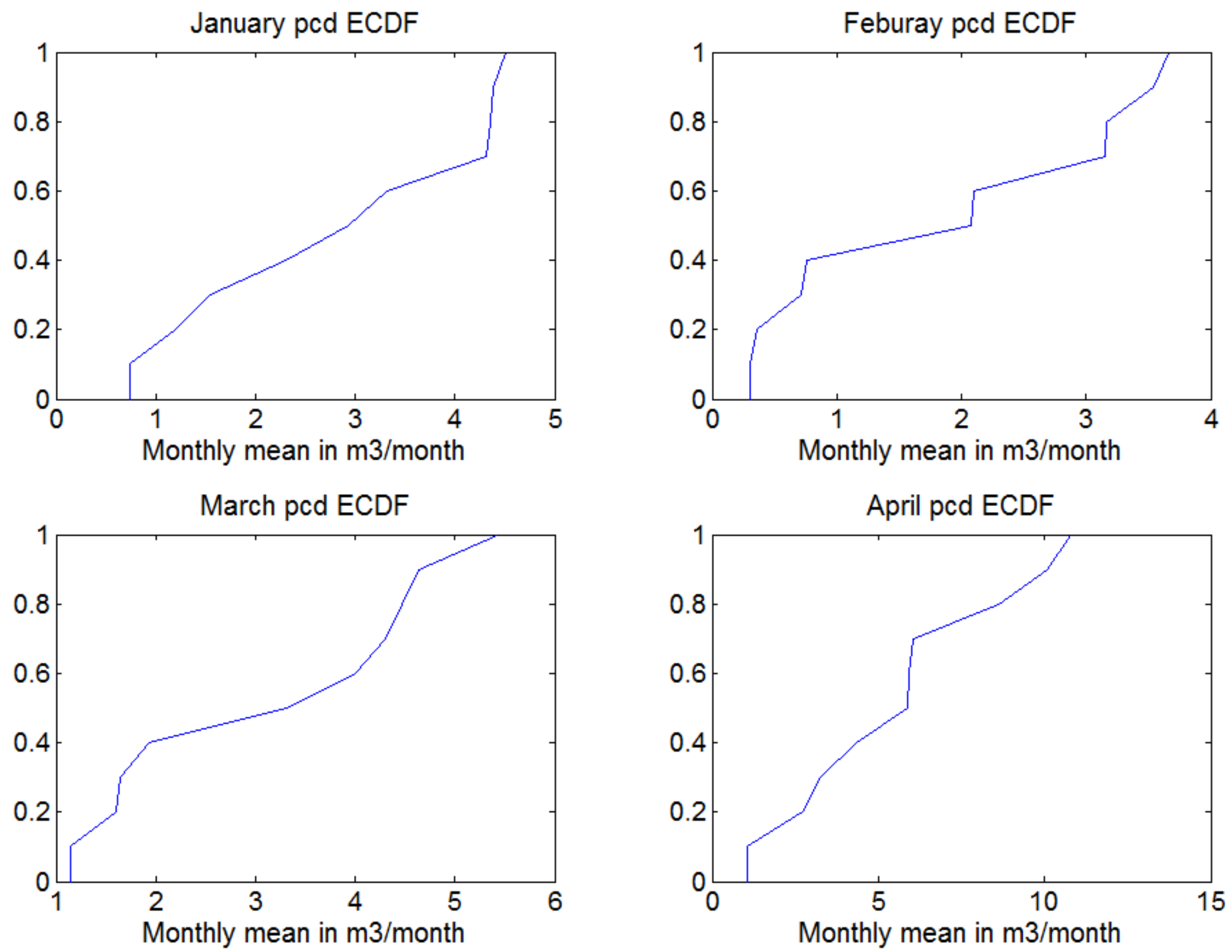


Figure A5: Per capita irrigation demand ECDF from January to April.

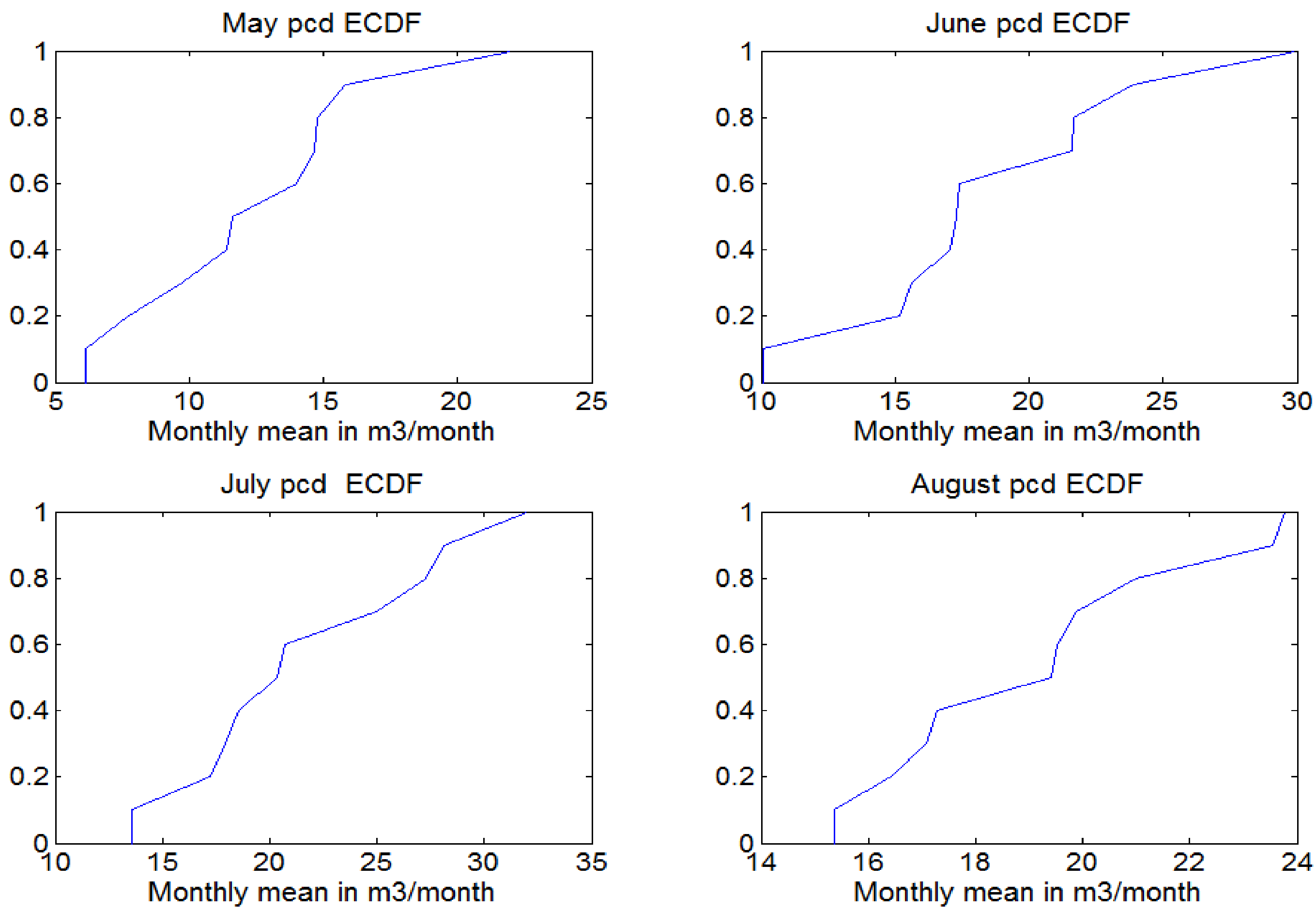


Figure A6: Per capita irrigation demand ECDF from May to August.

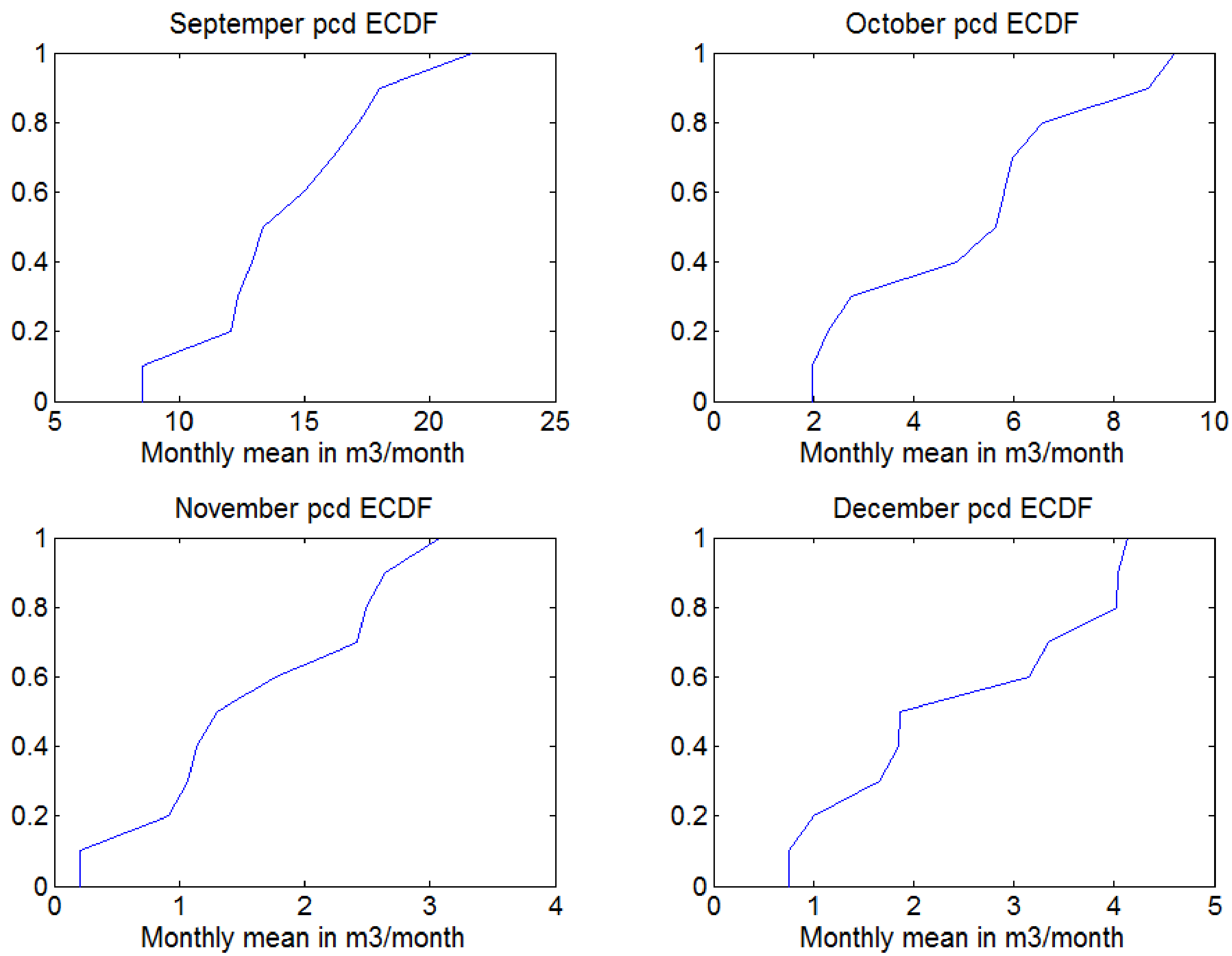


Figure A7: Per capita irrigation demand ECDF from September to December.

APPENDIX B: RS Means Tables

Table B1 shows the cost of ductile iron pipes per unit length (RSMeans, 2012).

Diameter	Total cost Including O&P ($/ft)
4"	29.5
6"	36
8"	47
10"	56
12'	64
14"	85
16"	99
18"	105
20"	117
24"	135

APPENDIX C: Deterministic Model

Input File

```
%% Hydraulic Input parameters
Population = 152061*.4;
Pop_Growth_rate = 2.35; %  percent
N_years = 30;    % years
WTP_capacity = 115455*3;   % m^3/month    1 MGD = 3785.41 m^3/day = 115455.005 m^3/month
WTP_expansion_increment= 115455*3; % m^3
WTP_expansion_limit= 115455*30; % m^3
monthlyFlow = [3000095.603 2731844.654 3678795.858,...     % m^3/month
              7537887.701 51500451.99 103331300.3,...
              48686240.56 22130923.54 10762296.09,...
             4664127.877 3738076.995 3073850.622];

Pop_demand_perCapita= [ 12.96 11.98 13.25 15.87 22.79 28.98,...   % m^3/month
    32.07 29.33 24.70   15.38 11.7 12.58];
Transmissivity= 2.5*10^-3 ;     % m^2/sec
Storativity= .0001;
Drawdown= 100; % meter ( Target Drawdown)
well_spacing= 1000; % meter
Storage_needed = 1233.48184*60000;  % m^3     1AF = 1233.48184 m^3 this means we have storage of 30,000 AF
Aquifer_volume=1233.48184*30000;  %m^3 ( Initial)
Distance_Drains_WTP=  450 ; %m
Distance_WTP_ASR=  2100; %m
Distance_WTP_city=  1000  ; %m
Injection_percentage=10; % percentage to the total demand
TDH_pumping= 100;  % Pumping Total dynamic head in meters
TDH_injection=100;  %  Injection Total dynamic head in meters
Well_land= 5; % acres per well
WTP_land= 20; % acre per WTP
Labor= 2; % person
pump_efficiency= .8; % from zero to 1
Water_rights_Oct_Apr= 15 ; % csf
Water_rights_Apr_Aug= 120 ; % csf
Water_rights_Aug_Oct= 30 ; % csf




%% Cost Input parameters
WTP_Initial_cost = 730000;   % USD per 3MGD
WTP_expansion_cost= 510000;  % USD per 3MGD
SWTP_OM_cost= 0.01       ; % 0.038 USD per 1000 US gallons = 0.01 USD per m^3 ( 1000 US gallon =
3.78541m^3)
GWTP_OM_cost= 0.01       ; % 0.038 USD per 1000 US gallons = 0.01 USD per m^3
ASR_Well_Cost = 1000000 ;   % USD per ASR well
ASR_OM_Cost = 15000;    % USD per ASR well
well_life = 30;       % well life in years
WTP_life=30;          % WTP life in years
Pipes_life=50;          % pipes life in years
ASR_rehabilitation_cost = 50000;    % USD per well
Rehabilitation_frequency = 11; % years
New_Inflow_drains_cost= 100000; %USD per Unit ( 500 meters and 2000 gpm capacity)
```

```
New_Inflow_drains_OM= 10000  ; %USD per Unit
Intrest_Rate = 0.03;
RawWaterPriceAcreFoot =0;
project_contingency= 25 ; % percent to the total capital
Design_cost= 5     ;       % percent to the total capital
Land_cost= 5000; % USD per acre
Labor_cost= 50000; % USD per person
kW_cost= .04; % USD per kW
```

Hydraulic Calculation File

```
Final_ASR_Input

Simulated_Months = N_years * 12;
Current_Pop = Population;
OutPutChart = [];
Injection = 0;
Pumping = 0;
WTP_expansion=0;
Q_max1=[];
WTP_yearly_cost=[];
Monthly_stream_inflow = repmat(monthlyFlow',N_years,1);
capita_demand= repmat(Pop_demand_perCapita',N_years,1);
Current_Pop1=[0 Population];
Current_Pop2=[0 Population];
Aquifer_space= Storage_needed - Aquifer_volume;
for i = 1: N_years
    Current_Pop =  Current_Pop * (((Pop_Growth_rate)/100)+1);
    Current_Pop1=[Current_Pop1; i*12 Current_Pop];
    Current_Pop2=[Current_Pop2; i Current_Pop];
end
L=[];
pop1=[];
Demand5=[];
for i = 1:Simulated_Months
%   calculate monthly population and PCD
   population_monthy = ceil(interp1( Current_Pop1(:,1),Current_Pop1(:,2),i));
   pop1= [ pop1 ; population_monthy];
   Demand1= population_monthy*capita_demand(i,1);
   Demand5=[ Demand5; Demand1];
   L = round(((i/12)- floor(i/12))*12);
   if L==0
      L=12;
   end
   if (L ==1) | (L==2 )|(L==3)  | (L==11) | (L==12)

      Water_right= Water_rights_Oct_Apr *74620.55428; % 1 cfs = 74620.55428 m^3/month ( 1 cfs = 2446.57555 m^3/day)
   elseif (L ==4)
       Water_right = ((Water_rights_Apr_Aug + Water_rights_Oct_Apr)/2)* 74620.55428;
   elseif(L==10 )
      Water_right = ((Water_rights_Aug_Oct + Water_rights_Oct_Apr)/2)* 74620.55428;
   elseif (L ==8) | (L==9 )
      Water_right=Water_rights_Aug_Oct* 74620.55428 ;
   else
```

```
        Water_right=Water_rights_Apr_Aug* 74620.55428 ;
    end


    stream_flow_raw =Monthly_stream_inflow(i);
    Demand= Demand5(i);
    Aquifer_space= Aquifer_space -  Injection + Pumping;
    Aquifer_volume= Aquifer_volume - Pumping + Injection;

    if stream_flow_raw> Water_right
        stream_flow=Water_right;
    else
        stream_flow = stream_flow_raw;
    end

%     Injection
    if (stream_flow > Demand)
        if ( Aquifer_space > (stream_flow-Demand))
             Injection= (stream_flow-Demand);
             if (stream_flow-Demand) > (Injection_percentage/100) * Demand
        Injection = (Injection_percentage/100) * Demand;
    end
        elseif ((stream_flow-Demand)> (Aquifer_space))
            Injection= Aquifer_space;
            if Aquifer_space > (Injection_percentage/100) * Demand
        Injection = (Injection_percentage/100) * Demand;
    end
        else
            Injection=0;
        end
    else
        Injection=0;
    end


 %         Pumping
    if ( Demand > stream_flow)
        if  ( Aquifer_volume > Demand-stream_flow)
            % pump
            Pumping = Demand-stream_flow;
        elseif ( (stream_flow-Demand) >  Aquifer_volume)
            % pump
            Pumping = Aquifer_volume;
        else
            Pumping = 0 ;
        end
    else
        Pumping = 0 ;
    end

    if stream_flow >= Demand
        Inflow = Injection;
    else
        Inflow=0;
```

```
 end
 % WTP restrection
 if Pumping >= WTP_expansion_limit
    Pumping = WTP_expansion_limit;
 end
 if Injection >= WTP_expansion_limit
    Injection = WTP_expansion_limit;
 end
  %  WTP expansion
  if WTP_capacity < Inflow && WTP_capacity <= WTP_expansion_limit
     WTP_expansion= (ceil((Inflow - WTP_capacity)/WTP_expansion_increment)*WTP_expansion_increment );

  elseif WTP_capacity < Pumping && WTP_capacity <= WTP_expansion_limit
     WTP_expansion= (ceil((Pumping - WTP_capacity)/WTP_expansion_increment)*WTP_expansion_increment
);
  else
     WTP_expansion=0;
  end

  WTP_capacity = WTP_capacity + WTP_expansion;
     if WTP_capacity > WTP_expansion_limit
        WTP_capacity = WTP_expansion_limit;
     end



     if stream_flow>Demand
     met_Demand= Demand;
     else
        met_Demand=Pumping+stream_flow;
     end
      if stream_flow>Demand
     met_Demand_S= 0;
     else
        met_Demand_S=Pumping+0;
     end

 Water_balance = round(Inflow + Pumping - Injection -met_Demand_S );
% plot Results
OutPutChart = [OutPutChart; [i   stream_flow   Demand   Pumping  ...
  Injection   Aquifer_volume   Aquifer_space WTP_capacity  ...
    Inflow   Water_balance population_monthy met_Demand...
    Demand-met_Demand WTP_expansion Water_right stream_flow_raw ]];
end
n= 0;
pumping_months=6;   %months
Qt=0;   % m^3/day
Qmax= Storage_needed/(365*.5) ;   % m^3/day
OUTPUT=[];
while Qt < Qmax
  n=n+1;
  r0 = 0.152;
  i = 1:1:n;
  j = 1:1:n;
  s = Drawdown.* ones(n,1);
  t = pumping_months.*30.5*24.*60.*60;
```

```
    X = 0:well_spacing: (n-1)*well_spacing;
    X= X';
    Y = zeros(n,1);
    XY = [X Y];
    Z = dist(XY,XY');
    Z(Z==0)= r0;
    U = (Z.^2 .* Storativity )./(4.* Transmissivity.* t);
    if U>0.01
       W= expitn(U);
    else
       W= -0.5722-log(U);
    end
     Q = (inv(W) * s) * 4 * pi .* Transmissivity ;
     Q = Q .*60 .*60.*24 ;
     Qt= sum(Q);
     Qm= mean(Q);  % m^3/day
     OUTPUT=[ OUTPUT; n Qt];
end
% calculating number of wells
Wells_total=[];
New_Wells=[];
Inflow_drains_total=[];
New_Inflow_units=[];
Inflow_units=[];
Inflow_units_total=[];
SWTP_yearly_cost=[];
GWTP_yearly_cost=[];
New_Inflow_units2=[];
Water_injected=[];
Water_pumped=[];
Total_wells_XXX=[];
% Inflow_drains_capacity = 2000gpm for 500 ft of drains
% which is 332328 m^3/month
Inflow_drains_capacity= 332328; % m^3/month;
for i=1:N_years
    x0 = (i-1)*12 + 1 ;
    x1 = i * 12;

    % Maximum Q monthly
    Q_max_Inflow=max(OutPutChart(x0:x1,9));
    Q_max_Pumping=max(OutPutChart(x0:x1,4));
    Q_max_Injection=max(OutPutChart(x0:x1,5));

    % Inflow drains


    Inflow_units1= ceil(Q_max_Inflow/ Inflow_drains_capacity);
    Inflow_units=[Inflow_units; i Inflow_units1];
    New_Inflow_units1= Inflow_units1-max(Inflow_units(1:i-1,2));

    if New_Inflow_units1 > 0
       New_Inflow_units2= New_Inflow_units1;
    else
       New_Inflow_units2=0;
    end
    New_Inflow_units= [ New_Inflow_units; i New_Inflow_units2];  % meters
```

```
    New_Inflow_units(1,2)= Inflow_units(1,2);

% %   ASR wells
    Wells_pumping= Q_max_Pumping/ (Qm*30.5);
    Wells_Injection= Q_max_Injection/ (0.8*Qm*30.5);
    Wells_Number_year= ceil(max(Wells_pumping, Wells_Injection));
    Wells_total=[Wells_total; i Wells_Number_year];
    New_wells_1= Wells_Number_year- max(Wells_total(1:i-1,2));
    if New_wells_1>0
        New_wells_2=New_wells_1;
    else
        New_wells_2=0;
    end
     Total_wells_XX= max(Wells_total(1:i,2));
    Total_wells_XXX=[Total_wells_XXX; i Total_wells_XX];
    New_Wells= [New_Wells; i New_wells_2];
    New_Wells(1,2) = Wells_total(1,2);
    SWTP_yearly= sum(OutPutChart(x0:x1,9));
    SWTP_yearly_cost= [SWTP_yearly_cost ; SWTP_yearly];
    GWTP_yearly= sum(OutPutChart(x0:x1,4));
    GWTP_yearly_cost= [GWTP_yearly_cost ; GWTP_yearly];



    % water volume calculation
    Water_injected1= sum((OutPutChart(x0:x1,5)));
    Water_pumped1= sum((OutPutChart(x0:x1,4)));
    Water_injected= [ Water_injected; i Water_injected1];
    Water_pumped= [ Water_pumped; i Water_pumped1];



end

pipe_area_Q_max_Inflow=(max(OutPutChart(:,9))/(30.5*24*60*60*1.524));  % 5ft/sec = 1.52400 m/s
pipe_d_Inflow= 2*ceil(((sqrt( (pi*pipe_area_Q_max_Inflow)/4))*39.3701)/2); % 1m = 39.3701 inch
% 1ft/sec = 26334.72 meters / day, then 5 ft/sec = 131673.6 m / day
V= 1.524;
D=[];
for X=1: max(Wells_total(:,2))
    d=2*ceil(((sqrt((4*X*Qm)/(pi*V*24*60*60)))*39.3701)/2);% d= inch     1m = 39.3701 inch
    D=[D;d];
end

BHP=[];
for i = 1: Simulated_Months
    BHP_pumping = (OutPutChart(i,4)*0.0115740741/30.5)*TDH_pumping  / (102*pump_efficiency);
    BHP_Injection = (OutPutChart(i,5)*0.0115740741/30.5) *TDH_injection  / (102*pump_efficiency);
    BHP1 = BHP_pumping + BHP_Injection;
    BHP=[BHP; BHP1]; % kW
end
BHP_year=[];
for i=1:N_years
    x0 = (i-1)*12 + 1 ;
    x1 = i * 12;
    BHP_year1= sum(BHP(x0:x1))*24*30.5;
```

```
   BHP_year= [BHP_year;BHP_year1];
end
%

Wells_total1111=[Total_wells_XXX(:,1) Total_wells_XXX(:,2)*Qm*30.5*12];

wells_total2112_X=[0 Wells_total(1,2)*Qm*30.5 Wells_total(1,2)*Qm*30.5*.8];

for i=1:N_years*12
   x=ceil(i/12);
   wells_total2112= [ i Wells_total(x,2)*Qm*30.5 Wells_total(x,2)*Qm*30.5*.8];
   wells_total2112_X= [ wells_total2112_X ;wells_total2112];
end

Inflow_units111111_X=[];
for i=1:N_years*12
    x=ceil(i/12);
   Inflow_units111111= [ i Inflow_units(x,2)*332328];
   Inflow_units111111_X= [ Inflow_units111111_X ;Inflow_units111111];
end
```

Cost Calculation File

Final_ASR_Hydraulic

```
H= [D; pipe_d_Inflow];
cost_d=[];
for i=1:1:max(Wells_total(:,2))+1
   if H(i,1)== 4
   pipe_cost_d= 29.5;
   elseif H(i,1)==6
      pipe_cost_d= 36;
    elseif H(i,1)==8
      pipe_cost_d= 47;
      elseif H(i,1)==10
      pipe_cost_d=56;
      elseif H(i,1)==12
      pipe_cost_d= 64;
      elseif H(i,1)==14
      pipe_cost_d= 85;
      elseif H(i,1)==16
      pipe_cost_d= 99;
      elseif H(i,1)==18
      pipe_cost_d= 105;
      elseif H(i,1)==20
      pipe_cost_d= 117;
      elseif H(i,1)==22
      pipe_cost_d= 126;
      elseif H(i,1)==24
      pipe_cost_d= 135;
      elseif H(i,1)==26
      pipe_cost_d= 145;
      elseif H(i,1)==28
```

```
        pipe_cost_d= 155;
    else
        pipe_cost_d= 170;
    end
    cost_d= [ cost_d ; pipe_cost_d];
end



% pipes cost
cost_pipes=[];
for i=1:1:max(Wells_total(:,2))-1
    cost_pipes1= cost_d(i)*0.3048 *well_spacing;
    cost_pipes=[cost_pipes; cost_pipes1];
end
% Inflow to ASR pipes cost
Inflow_pipes_cost= cost_d(max(Wells_total(:,2))+1)* (Distance_Drains_WTP);
pumping_pipes_cost= cost_d(max(Wells_total(:,2)))* ( Distance_WTP_ASR+Distance_WTP_city);

Total_pipes_cost=(Inflow_pipes_cost+ pumping_pipes_cost+ sum(cost_pipes))*1.15;

OUTPUT_Incremental=[];
Incremental=[];

for i= 1:N_years
    New_wells_Capital_cost= ((New_Wells(i,2))*ASR_Well_Cost);
    ASR_OM= (Wells_total(i,2))*ASR_OM_Cost;
    Power_cost= BHP_year(i)* kW_cost;
    Inflow_drains_cost= (New_Inflow_units(i,2)* New_Inflow_drains_cost);
    Inflow_drains_OM = Inflow_units(i,2)*New_Inflow_drains_OM;
    Capital_SWTP= (SWTP_OM_cost * SWTP_yearly_cost(i));
    WTP_expansion_cost1= WTP_expansion_cost * (sum(OutPutChart((i-
1)*12+1:12*i,14))/WTP_expansion_increment);
    Capital_GWTP= (GWTP_OM_cost * GWTP_yearly_cost(i));
    Well_replacement= max((Wells_total(1:i,2)))*(ASR_Well_Cost/well_life);
    WTP_replacement = (max((OutPutChart(1:i,8)))/WTP_capacity)*(WTP_Initial_cost/WTP_life);
    pipes_replacement= Total_pipes_cost/Pipes_life;
    Total_replacement= Well_replacement+WTP_replacement+pipes_replacement;
    Labor_total_cost= Labor*Labor_cost;

   Incremental1 = (New_wells_Capital_cost+
ASR_OM+Inflow_drains_cost+Inflow_drains_OM+Capital_SWTP+WTP_expansion_cost1...
      +
Capital_GWTP+Total_replacement+Power_cost+Labor_total_cost)*(((project_contingency+Design_cost)/100)+1) ;
    %    plot
   OUTPUT_Incremental= [ OUTPUT_Incremental;  New_wells_Capital_cost ASR_OM  Inflow_drains_cost
Inflow_drains_OM ...
       Capital_SWTP WTP_expansion_cost1 Capital_GWTP   Total_replacement  Power_cost  Labor_total_cost];
   Incremental=[Incremental;Incremental1];
end
% Land cost
Well_land_cost= Land_cost * (Well_land*max(Wells_total(:,2))+
WTP_land)*(((project_contingency+Design_cost)/100)+1);
Well_land_cost_Array= zeros(N_years,1);
Well_land_cost_Array(1,1)=Well_land_cost;
% pipes cost
```

```
Pipes_cost_total= Total_pipes_cost*(((project_contingency+Design_cost)/100)+1);
Pipes_cost_total_Array= zeros(N_years,1);
Pipes_cost_total_Array(1,1)=Pipes_cost_total;



% capital cost
Capital_cost=(WTP_Initial_cost)*(((project_contingency+Design_cost)/100)+1);
Capital_costs_Array=zeros(N_years,1);
Capital_costs_Array(1,1)= Capital_cost;
% total cost
OUTPUT_total=[];
for i=1:N_years

OUTPUT_total1= Capital_costs_Array(i)+Pipes_cost_total_Array(i)+Well_land_cost_Array(i)+Incremental(i);
OUTPUT_total=[OUTPUT_total;OUTPUT_total1];

end

XXX=[
Capital_costs_Array';Pipes_cost_total_Array';Well_land_cost_Array';(((project_contingency+Design_cost)/100)+1)
.* OUTPUT_Incremental'];
YY= XXX';
% present value

present_value_total2=[];
for i=1:N_years
   present_value_total1=( OUTPUT_total(i)/( 1+ Intrest_Rate)^(i-1));
   present_value_total2= [present_value_total2; present_value_total1];
end
Total_present_value= sum(present_value_total2)
Capital= OUTPUT_total(1,1)
```

APPENDIX D: Stochastic Model

Input File

```
%% Hydraulic Input parameters
Population = 152061*.4;
% Pop_Growth_rate = 2.35; %  percent
N_years = 30;    % years
WTP_capacity = 115455*3;   % m^3/month    1 MGD = 3785.41 m^3/day = 115455.005 m^3/month
WTP_expansion_increment= 115455*3; % m^3
WTP_expansion_limit= 115455*15; % m^3
% monthlyFlow = [3000095.603 2731844.654 3678795.858,...     % m^3/month
%               7537887.701 51500451.99 103331300.3,...
%               48686240.56 22130923.54 10762296.09,...
%              4664127.877 3738076.995 3073850.622];

% Pop_demand_perCapita= [ 12.96 11.98 13.25 15.87 22.79 28.98,...   % m^3/month
%     32.07 29.33 24.70   15.38 11.7 12.58];
Transmissivity= 2.5*10^-3 ;     % m^2/sec
Storativity= .0001;
Drawdown= 100; % meter ( Target Drawdown)
well_spacing= 1000; % meter
Storage_needed = 1233.48184*60000;  % m^3     1AF = 1233.48184 m^3 this means we have storage of 30,000 AF
Aquifer_volume=1233.48184*30000;  %m^3 ( Initial)
Distance_Drains_WTP=  450 ; %m
Distance_WTP_ASR=  2100; %m
Distance_WTP_city=  1000  ; %m
Injection_percentage=10; % percentage to the total demand
TDH_pumping= 100;  % Pumping Total dynamic head in meters
TDH_injection=100;  %  Injection Total dynamic head in meters
Well_land= 5; % acres per well
WTP_land= 20; % acre per WTP
Labor= 2; % person
pump_efficiency= .8; % from zero to 1
Water_rights_Oct_Apr= 15 ; % csf
Water_rights_Apr_Aug= 120 ; % csf
Water_rights_Aug_Oct= 30 ; % csf




%% Cost Input parameters
WTP_Initial_cost = 730000;   % USD per 3MGD
WTP_expansion_cost= 510000;  % USD per 3MGD
SWTP_OM_cost= 0.01       ; % 0.038 USD per 1000 US gallons = 0.01 USD per m^3 ( 1000 US gallon = 
3.78541m^3)
GWTP_OM_cost= 0.01       ; % 0.038 USD per 1000 US gallons = 0.01 USD per m^3
ASR_Well_Cost = 1000000 ;   % USD per ASR well
ASR_OM_Cost = 15000;    % USD per ASR well
well_life = 30;       % well life in years
WTP_life=30;          % WTP life in years
Pipes_life=50;          % pipes life in years
ASR_rehabilitation_cost = 50000;    % USD per well
```

```
Rehabilitation_frequency = 11; % years
New_Inflow_drains_cost= 100000; %USD per Unit ( 500 meters and 2000 gpm capacity)
New_Inflow_drains_OM= 10000  ; %USD per Unit
Intrest_Rate = 0.03;
RawWaterPriceAcreFoot =0;
project_contingency= 25 ; % percent to the total capital
Design_cost= 5     ;       % percent to the total capital
Land_cost= 5000; % USD per acre
Labor_cost= 50000; % USD per person
kW_cost= .04; % USD per kW
```

Stochastoc File

```
Stochastic2_Input
%% Import the data
[~, ~, raw] = xlsread('U:\Final Code\Final code data.xlsx','Sheet1');

%% Create output variable
data = reshape([raw{:}],size(raw));

%% Allocate imported array to column variable names
year = data(:,1);
Jan = ((data(:,2))*(1233.48184));
Feb = ((data(:,3))*(1233.48184));
Mar = ((data(:,4))*(1233.48184));
Apr = ((data(:,5))*(1233.48184));
May = ((data(:,6))*(1233.48184));
Jun = ((data(:,7))*(1233.48184));
Jul = ((data(:,8))*(1233.48184));
Aug = ((data(:,9))*(1233.48184));
Sep = ((data(:,10))*(1233.48184));
Oct = ((data(:,11))*(1233.48184));
Nov = ((data(:,12))*(1233.48184));
Dec = ((data(:,13))*(1233.48184));
% Growth rate data
growth = (data(:,15));
% per capita demand data (m^3/month)
% pcd ecdf
year_pcd = data(:,17);
Jan_pcd = data(:,18);
Feb_pcd = data(:,19);
Mar_pcd = data(:,20);
Apr_pcd = data(:,21);
May_pcd = data(:,22);
Jun_pcd = data(:,23);
Jul_pcd = data(:,24);
Aug_pcd = data(:,25);
Sep_pcd = data(:,26);
Oct_pcd = data(:,27);
Nov_pcd = data(:,28);
Dec_pcd = data(:,29);

%% Clear temporary variables
clearvars data raw;
```

```
% flow ecdf
[FJan,XJan]= ecdf(Jan);
[FFeb,XFeb]= ecdf(Feb);
[FMar,XMar]= ecdf(Mar);
[FApr,XApr]= ecdf(Apr);
[FMay,XMay]= ecdf(May);
[FJun,XJun]= ecdf(Jun);
[FJul,XJul]= ecdf(Jul);
[FAug,XAug]= ecdf(Aug);
[FSep,XSep]= ecdf(Sep);
[FOct,XOct]= ecdf(Oct);
[FNov,XNov]= ecdf(Nov);
[FDec,XDec]= ecdf(Dec);

% growth rate ecdf
[Fgrowth,Xgrowth]= ecdf(growth);



% pcd ecdf
[FJan_pcd,XJan_pcd]= ecdf(Jan_pcd);
[FFeb_pcd,XFeb_pcd]= ecdf(Feb_pcd);
[FMar_pcd,XMar_pcd]= ecdf(Mar_pcd);
[FApr_pcd,XApr_pcd]= ecdf(Apr_pcd);
[FMay_pcd,XMay_pcd]= ecdf(May_pcd);
[FJun_pcd,XJun_pcd]= ecdf(Jun_pcd);
[FJul_pcd,XJul_pcd]= ecdf(Jul_pcd);
[FAug_pcd,XAug_pcd]= ecdf(Aug_pcd);
[FSep_pcd,XSep_pcd]= ecdf(Sep_pcd);
[FOct_pcd,XOct_pcd]= ecdf(Oct_pcd);
[FNov_pcd,XNov_pcd]= ecdf(Nov_pcd);
[FDec_pcd,XDec_pcd]= ecdf(Dec_pcd);

Stochastic2_Input
Pop_Growth_rate=[];
Monthly_mean_flow1=[];
pcd_monthly1=[];


for i=1:N_years
X= rand();
if X>0.1
   Y=1-X;
else
   Y=0;
end
Z=rand(i);
% growth rate interpolation
Vgrowth= interp1( Fgrowth,Xgrowth,Z);
Pop_Growth_rate= [Pop_Growth_rate; Vgrowth];


% flow Interpolation
VJan= interp1( FJan,XJan,X);
```

```
VFeb= interp1( FFeb,XFeb,X);
VMar= interp1( FMar,XMar,X);
VApr= interp1( FApr,XApr,X);
VMay= interp1( FMay,XMay,X);
VJun= interp1( FJun,XJun,X);
VJul= interp1( FJul,XJul,X);
VAug= interp1( FAug,XAug,X);
VSep= interp1( FSep,XSep,X);
VOct= interp1( FOct,XOct,X);
VNov= interp1( FNov,XNov,X);
VDec= interp1( FDec,XDec,X);
Monthly_mean_flow1=[Monthly_mean_flow1;  VJan VFeb VMar VApr VMay VJun VJul VAug VSep VOct
VNov VDec];

%  pcd interpolation
VJan_pcd= interp1( FJan_pcd,XJan_pcd,Y);
VFeb_pcd= interp1( FFeb_pcd,XFeb_pcd,Y);
VMar_pcd= interp1( FMar_pcd,XMar_pcd,Y);
VApr_pcd= interp1( FApr_pcd,XApr_pcd,Y);
VMay_pcd= interp1( FMay_pcd,XMay_pcd,Y);
VJun_pcd= interp1( FJun_pcd,XJun_pcd,Y);
VJul_pcd= interp1( FJul_pcd,XJul_pcd,Y);
VAug_pcd= interp1( FAug_pcd,XAug_pcd,Y);
VSep_pcd= interp1( FSep_pcd,XSep_pcd,Y);
VOct_pcd= interp1( FOct_pcd,XOct_pcd,Y);
VNov_pcd= interp1( FNov_pcd,XNov_pcd,Y);
VDec_pcd= interp1( FDec_pcd,XDec_pcd,Y);
pcd_monthly1=[pcd_monthly1;  VJan_pcd VFeb_pcd VMar_pcd VApr_pcd...
   VMay_pcd VJun_pcd VJul_pcd VAug_pcd VSep_pcd VOct_pcd VNov_pcd VDec_pcd];
   end
Simulated_Months= N_years*12;
Monthly_mean_flow=Monthly_mean_flow1';
pcd_monthly= pcd_monthly1';
PCD_MONTHLY=[];
for i=1:Simulated_Months
   PCD_MONTHLY1=pcd_monthly(i);
   PCD_MONTHLY= [ PCD_MONTHLY; PCD_MONTHLY1];
end
```

Hydraulic Calculation File

```
Stochastic2_Stochastic
Stochastic2_Input

Simulated_Months = N_years * 12;
Current_Pop = Population;
OutPutChart = [];
Injection = 0;
Pumping = 0;
SWTP_expansion=0;
Q_max1=[];
SWTP_yearly_cost=[];
% Monthly_stream_inflow = repmat(monthlyFlow',N_years,1);
% capita_demand= repmat(Pop_demand_perCapita',N_years,1);
Current_Pop1=[0 Population];
```

```
Current_Pop2=[0 Population];
Aquifer_space= Storage_needed - Aquifer_volume;
for i = 1: N_years
    Current_Pop =  Current_Pop * (((Pop_Growth_rate(i))/100)+1);
    Current_Pop1=[Current_Pop1; i*12 Current_Pop];
    Current_Pop2=[Current_Pop2; i Current_Pop];
end

pop1=[];
Demand5=[];
for i=1:Simulated_Months
   %   calculate monthly population and PCD
   population_monthy = ceil(interp1( Current_Pop1(:,1),Current_Pop1(:,2),i));
   pop1= [ pop1 ; population_monthy];
   Demand1= population_monthy*(10+pcd_monthly(i));
   Demand5=[ Demand5; Demand1];

end
stream_flow_raw=[];
for i = 1:Simulated_Months
    L = round(((i/12)- floor(i/12))*12);
    if L==0
      L=12;
   end
   if (L ==1) | (L==2 )|(L==3)  | (L==11) | (L==12)

      Water_right= Water_rights_Oct_Apr *74620.55428; % 1 cfs = 74620.55428 m^3/month ( 1 cfs = 2446.57555
m^3/day)
   elseif (L ==4)
       Water_right = ((Water_rights_Apr_Aug + Water_rights_Oct_Apr)/2)* 74620.55428;
   elseif(L==10 )
      Water_right = ((Water_rights_Aug_Oct + Water_rights_Oct_Apr)/2)* 74620.55428;
   elseif (L ==8) | (L==9 )
      Water_right=Water_rights_Aug_Oct* 74620.55428 ;
   else
      Water_right=Water_rights_Apr_Aug* 74620.55428 ;
   end
   stream_flow_raw =Monthly_mean_flow(i);
   Demand= Demand5(i);
   Aquifer_space= Aquifer_space -  Injection + Pumping;
   Aquifer_volume= Aquifer_volume - Pumping + Injection;

   if stream_flow_raw> Water_right
      stream_flow=Water_right;
   else
      stream_flow = stream_flow_raw;
   end

%     Injection
   if (stream_flow > Demand)
      if ( Aquifer_space > (stream_flow-Demand))
          Injection= (stream_flow-Demand);
          if (stream_flow-Demand) > (Injection_percentage/100) * Demand
      Injection = (Injection_percentage/100) * Demand;
   end
```

```
        elseif ((stream_flow-Demand)> (Aquifer_space))
            Injection= Aquifer_space;
            if Aquifer_space > (Injection_percentage/100) * Demand
        Injection = (Injection_percentage/100) * Demand;
    end
        else
            Injection=0;
        end
    else
        Injection=0;
    end

%       Pumping
    if ( Demand > stream_flow)
        if  ( Aquifer_volume > Demand-stream_flow)
            % pump
            Pumping = (Demand-stream_flow);
        elseif ( (stream_flow-Demand) >  Aquifer_volume)
            % pump
            Pumping = Aquifer_volume;
        else
            Pumping = 0 ;
        end
    else
        Pumping = 0 ;
    end

    if stream_flow >= Demand
        Inflow = Injection;
    else
        Inflow=0;
    end
   % WTP restrection
   if Pumping >= WTP_expansion_limit
       Pumping = WTP_expansion_limit;
   end
   if Injection >= WTP_expansion_limit
       Injection = WTP_expansion_limit;
   end

 %  WTP expansion
    if WTP_capacity < Inflow && WTP_capacity <= WTP_expansion_limit
        WTP_expansion= (ceil((Inflow - WTP_capacity)/WTP_expansion_increment)*WTP_expansion_increment );

    elseif WTP_capacity < Pumping && WTP_capacity <= WTP_expansion_limit
        WTP_expansion= (ceil((Pumping - WTP_capacity)/WTP_expansion_increment)*WTP_expansion_increment
);
    else
        WTP_expansion=0;
    end

    WTP_capacity = WTP_capacity + WTP_expansion;
        if WTP_capacity > WTP_expansion_limit
            WTP_capacity = WTP_expansion_limit;
        end
```

```
        if stream_flow>Demand
        met_Demand= Demand;
        else
           met_Demand=Pumping+stream_flow;
        end
         if stream_flow>Demand
        met_Demand_S= 0;
        else
           met_Demand_S=Pumping+0;
        end

   Water_balance = round(Inflow + Pumping - Injection -met_Demand_S );
% plot Results
OutPutChart = [OutPutChart; [i   stream_flow   Demand   Pumping  ...
   Injection   Aquifer_volume   Aquifer_space WTP_capacity  ...
     Inflow   Water_balance population_monthy met_Demand...
     Demand-met_Demand WTP_expansion Water_right stream_flow_raw ]];
end
n= 0;
pumping_months=6;   %months
Qt=0;   % m^3/day
Qmax= Storage_needed/(365*.5) ;   % m^3/day
OUTPUT=[];
while Qt < Qmax
   n=n+1;
   r0 = 0.152;
   i = 1:1:n;
   j = 1:1:n;
   s = Drawdown.* ones(n,1);
   t = pumping_months.*30.5*24.*60.*60;
   X = 0:well_spacing: (n-1)*well_spacing;
   X= X';
   Y = zeros(n,1);
   XY = [X Y];
   Z = dist(XY,XY');
   Z(Z==0)= r0;
   U = (Z.^2 .* Storativity )./(4.* Transmissivity.* t);
   if U>0.01
      W= expitn(U);
   else
      W= -0.5722-log(U);
   end
    Q = (inv(W) * s) * 4 * pi .* Transmissivity ;
    Q = Q .*60 .*60.*24 ;
    Qt= sum(Q);
    Qm= mean(Q);  % m^3/day
    OUTPUT=[ OUTPUT; n Qt];
end
% calculating number of wells
Wells_total=[];
New_Wells=[];
Inflow_drains_total=[];
New_Inflow_units=[];
Inflow_units=[];
Inflow_units_total=[];
SWTP_yearly_cost=[];
```

```
GWTP_yearly_cost=[];
New_Inflow_units2=[];
Water_injected=[];
Water_pumped=[];
Total_wells_XXX=[];
% Inflow_drains_capacity = 2000gpm for 500 ft of drains
% which is 332328 m^3/month
Inflow_drains_capacity= 332328; % m^3/month;
for i=1:N_years
   x0 = (i-1)*12 + 1 ;
   x1 = i * 12;

   % Maximum Q monthly
   Q_max_Inflow=max(OutPutChart(x0:x1,9));
   Q_max_Pumping=max(OutPutChart(x0:x1,4));
   Q_max_Injection=max(OutPutChart(x0:x1,5));

   % Inflow drains


   Inflow_units1= ceil(Q_max_Inflow/ Inflow_drains_capacity);
   Inflow_units=[Inflow_units; i Inflow_units1];
   New_Inflow_units1= Inflow_units1-max(Inflow_units(1:i-1,2));

   if New_Inflow_units1 > 0
      New_Inflow_units2= New_Inflow_units1;
   else
      New_Inflow_units2=0;
   end
   New_Inflow_units= [ New_Inflow_units; i New_Inflow_units2];  % meters
   New_Inflow_units(1,2)= Inflow_units(1,2);

% %   ASR wells
   Wells_pumping= Q_max_Pumping/ (Qm*30.5);
   Wells_Injection= Q_max_Injection/ (0.8*Qm*30.5);
   Wells_Number_year= ceil(max(Wells_pumping, Wells_Injection));
   Wells_total=[Wells_total; i Wells_Number_year];
   New_wells_1= Wells_Number_year- max(Wells_total(1:i-1,2));
   if New_wells_1>0
      New_wells_2=New_wells_1;
   else
      New_wells_2=0;
   end
   Total_wells_XX= max(Wells_total(1:i,2));
   Total_wells_XXX=[Total_wells_XXX; i Total_wells_XX];
   New_Wells= [New_Wells; i New_wells_2];
   New_Wells(1,2) = Wells_total(1,2);
   SWTP_yearly= sum(OutPutChart(x0:x1,9));
   SWTP_yearly_cost= [SWTP_yearly_cost ; SWTP_yearly];
   GWTP_yearly= sum(OutPutChart(x0:x1,4));
   GWTP_yearly_cost= [GWTP_yearly_cost ; GWTP_yearly];



   % water volume calculation
   Water_injected1= sum((OutPutChart(x0:x1,5)));
```

```
    Water_pumped1= sum((OutPutChart(x0:x1,4)));
    Water_injected= [ Water_injected; i Water_injected1];
    Water_pumped= [ Water_pumped; i Water_pumped1];


end

pipe_area_Q_max_Inflow=(max(OutPutChart(:,9))/(30.5*24*60*60*1.524));  % 5ft/sec = 1.52400 m/s
pipe_d_Inflow= 2*ceil(((sqrt( (pi*pipe_area_Q_max_Inflow)/4))*39.3701)/2); % 1m = 39.3701 inch
% 1ft/sec = 26334.72 meters / day, then 5 ft/sec = 131673.6 m / day
V= 1.524;
D=[];
for X=1: max(Wells_total(:,2))
    d=2*ceil(((sqrt((4*X*Qm)/(pi*V*24*60*60)))*39.3701)/2);% d= inch     1m = 39.3701 inch
    D=[D;d];
end

BHP=[];
for i = 1: Simulated_Months
    BHP_pumping = (OutPutChart(i,4)*0.0115740741/30.5)*TDH_pumping  / (102*pump_efficiency);
    BHP_Injection = (OutPutChart(i,5)*0.0115740741/30.5) *TDH_injection  / (102*pump_efficiency);
    BHP1 = BHP_pumping + BHP_Injection;
    BHP=[BHP; BHP1]; % kW
end
BHP_year=[];
for i=1:N_years
    x0 = (i-1)*12 + 1 ;
    x1 = i * 12;
    BHP_year1= sum(BHP(x0:x1))*24*30.5;
    BHP_year= [BHP_year;BHP_year1];
end

    Wells_total1111=[Total_wells_XXX(:,1) Total_wells_XXX(:,2)*Qm*30.5*12];
```

Cost Calculation File

```
Stochastic2_Hydraulic


H= [D; pipe_d_Inflow];
cost_d=[];
for i=1:1:max(Wells_total(:,2))+1
    if H(i,1)== 4
    pipe_cost_d= 29.5;
    elseif H(i,1)==6
        pipe_cost_d= 36;
     elseif H(i,1)==8
        pipe_cost_d= 47;
        elseif H(i,1)==10
        pipe_cost_d=56;
        elseif H(i,1)==12
        pipe_cost_d= 64;
```

```
        elseif H(i,1)==14
        pipe_cost_d= 85;
        elseif H(i,1)==16
        pipe_cost_d= 99;
        elseif H(i,1)==18
        pipe_cost_d= 105;
        elseif H(i,1)==20
        pipe_cost_d= 117;
        elseif H(i,1)==22
        pipe_cost_d= 126;
        elseif H(i,1)==24
        pipe_cost_d= 135;
        elseif H(i,1)==26
        pipe_cost_d= 145;
        elseif H(i,1)==28
        pipe_cost_d= 155;
    else
        pipe_cost_d= 170;
    end
    cost_d= [ cost_d ; pipe_cost_d];
end



% pipes cost
cost_pipes=[];
for i=1:1:max(Wells_total(:,2))-1
    cost_pipes1= cost_d(i)*0.3048 *well_spacing;
    cost_pipes=[cost_pipes; cost_pipes1];
end
% Inflow to ASR pipes cost
Inflow_pipes_cost= cost_d(max(Wells_total(:,2))+1)* (Distance_Drains_WTP);
pumping_pipes_cost= cost_d(max(Wells_total(:,2)))* ( Distance_WTP_ASR+Distance_WTP_city);

Total_pipes_cost=(Inflow_pipes_cost+ pumping_pipes_cost+ sum(cost_pipes))*1.15;

OUTPUT_Incremental=[];
Incremental=[];

for i= 1:N_years
    New_wells_Capital_cost= ((New_Wells(i,2))*ASR_Well_Cost);
    ASR_OM= (Wells_total(i,2))*ASR_OM_Cost;
    Power_cost= BHP_year(i)* kW_cost;
    Inflow_drains_cost= (New_Inflow_units(i,2)* New_Inflow_drains_cost);
    Inflow_drains_OM = Inflow_units(i,2)*New_Inflow_drains_OM;
    Capital_SWTP= (SWTP_OM_cost * SWTP_yearly_cost(i));
    WTP_expansion_cost1= WTP_expansion_cost * (sum(OutPutChart((i-
1)*12+1:12*i,14))/WTP_expansion_increment);
    Capital_GWTP= (GWTP_OM_cost * GWTP_yearly_cost(i));
    Well_replacement= max((Wells_total(1:i,2)))*(ASR_Well_Cost/well_life);
    WTP_replacement = (max((OutPutChart(1:i,8)))/WTP_capacity)*(WTP_Initial_cost/WTP_life);
    pipes_replacement= Total_pipes_cost/Pipes_life;
    Total_replacement= Well_replacement+WTP_replacement+pipes_replacement;
    Labor_total_cost= Labor*Labor_cost;
```

```
  Incremental1 = (New_wells_Capital_cost+
ASR_OM+Inflow_drains_cost+Inflow_drains_OM+Capital_SWTP+WTP_expansion_cost1...
     +
Capital_GWTP+Total_replacement+Power_cost+Labor_total_cost)*(((project_contingency+Design_cost)/100)+1) ;
   %    plot
  OUTPUT_Incremental= [ OUTPUT_Incremental;  New_wells_Capital_cost ASR_OM  Inflow_drains_cost
Inflow_drains_OM ...
      Capital_SWTP WTP_expansion_cost1 Capital_GWTP   Total_replacement  Power_cost  Labor_total_cost];
  Incremental=[Incremental;Incremental1];
end
% Land cost
Well_land_cost= Land_cost * (Well_land*max(Wells_total(:,2))+
WTP_land)*(((project_contingency+Design_cost)/100)+1);
Well_land_cost_Array= zeros(N_years,1);
Well_land_cost_Array(1,1)=Well_land_cost;
% pipes cost
Pipes_cost_total= Total_pipes_cost*(((project_contingency+Design_cost)/100)+1);
Pipes_cost_total_Array= zeros(N_years,1);
Pipes_cost_total_Array(1,1)=Pipes_cost_total;



% capital cost
Capital_cost=(WTP_Initial_cost)*(((project_contingency+Design_cost)/100)+1);
Capital_costs_Array=zeros(N_years,1);
Capital_costs_Array(1,1)= Capital_cost;
% total cost
OUTPUT_total=[];
for i=1:N_years

OUTPUT_total1= Capital_costs_Array(i)+Pipes_cost_total_Array(i)+Well_land_cost_Array(i)+Incremental(i);
OUTPUT_total=[OUTPUT_total;OUTPUT_total1];

end

XXX=[
Capital_costs_Array';Pipes_cost_total_Array';Well_land_cost_Array';(((project_contingency+Design_cost)/100)+1)
.* OUTPUT_Incremental'];
YY= XXX';
% present value

present_value_total2=[];
for i=1:N_years
   present_value_total1=( OUTPUT_total(i)/( 1+ Intrest_Rate)^(i-1));
   present_value_total2= [present_value_total2; present_value_total1];
end
Total_present_value= sum(present_value_total2);
Capital= OUTPUT_total(1,1);
Life_Cycle_cost= sum(OUTPUT_total);
TOTAL_PUMPING_FINAL= sum(OutPutChart(:,4));
TOTAL_INJECTION_FINAL= sum(OutPutChart(:,5));
MAX_WTP_CPACITY= max(OutPutChart(:,8));
MAX_ASR_WELLS= max(Wells_total(:,2));
MAX_INFLOW_UNITS= max(Inflow_units(:,2));
MAX_POPULATION= max(Current_Pop2(:,2));
```

```
LAST_TABLE=[ MAX_POPULATION  TOTAL_PUMPING_FINAL TOTAL_INJECTION_FINAL
MAX_WTP_CPACITY...
    MAX_ASR_WELLS MAX_INFLOW_UNITS Capital Total_present_value Life_Cycle_cost];
```