THESIS

COMBINED SOURCE INFRASTRUCTURE ASSESSMENT MODEL

Submitted by

Anne Maurer

Department of Civil and Environmental Engineering

In partial fulfillment of the requirements

For the Degree of Master of Science

Colorado State University

Fort Collins, Colorado

Summer 2012

Master's Committee:

Advisor: Tom Sale

Domenico Bau
William Sanford

ABSTRACT

COMBINED SOURCE INFRASTRUCTURE ASSESSMENT MODEL

Integrated utilization of surface and groundwater is a promising strategy that has the potential to reduce the costs associated with water system infrastructure projects and improve the sustainability of yields from finite water resources. Planning and design of conjunctive use systems can be complicated. Key challenges include resolving the timing of withdrawals, timing of storage, sizing of infrastructure components, and efficiently estimating costs. A combined source infrastructure assessment model (CSIAM) has been developed in this study using a decision programming approach. The CSIAM is designed for single-and multi-source water systems including surface water-only, groundwater-only, and combined surface water and groundwater sources. Aquifer Storage and Recovery (ASR) via groundwater injection wells is a primary component of the CSIAM when there is surplus surface water available to store. Primary model inputs include project life-span, per capita demands, initial population, population growth rate, surface water treatment capacity, number of existing wells, inflows, reservoir stage-storage, evaporative and seepage losses, and unit costs for capital expenditures and operations and maintenance. Model outputs include project water demands, surface reservoir storage, volume of monthly surface water treatment, groundwater extraction and/or injection volumes, cumulative groundwater extraction and/or injection volumes, number of wells, capital costs, operation and maintenance costs, life-cycle costs, and present value.

The model is demonstrated via analysis of three scenarios involving groundwater-only, combined groundwater and surface water, and surface water-only. The scenarios are predicated on data provided by the town of Castle Rock, Colorado. While the Town of Castle Rock provides a

basis for applying the model, the results should not be viewed as having direct bearing on future actions in the Town of Castle Rock. Many of the key issues that will ultimately drive the Town's water supply plans are not included in this analysis.

Use of a combined groundwater and surface water system is $91 million and $231 million less than a groundwater-only system and streamflow-only system, respectively. Furthermore, the use of a combined groundwater and surface water system reduces groundwater depletion by 55%, relative to a groundwater-only system. In addition, a total of 107 pumping wells will need to be installed in a groundwater-only system versus 67 pumping wells in a combined groundwater/surface water system. Both deterministic and stochastic inputs are used in the model, wherein the principle stochastic input is urban irrigation demands. The differences between results using deterministic and stochastic inputs vary depending on the output. In general, analyses using stochastic inputs lead to a need for infrastructure with greater capacities and higher costs. The CSIAM also can be used to resolve costs as a function of groundwater depletion by testing different surface water treatment plant sizes.

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1 INTRODUCTION

1.1 Problem Statement

The world is facing the critical problems of increasing population, climate change, and intensifying competition for water resources. With all of this, integrated utilization of surface and groundwater is becoming an evermore critical strategy for sustaining water production needed to address irrigation, domestic, and industrial demands (de Wrachien and Fasso 2002). Following Todd (1959), Lettenmaier and Burges (1982), and de Wrachien and Fasso (2002), the coordinated management and development of surface and groundwater is defined as conjunctive use. Conjunctive use includes the ability to store and/or utilize surplus water from one source to meet the deficit of another source (Fisher et al. 1995). Unfortunately, design and analysis of costs associated with conjunctive use projects can be difficult. Challenges include:

- Appropriate sizing of water storage, water treatment, and well fields under conditions of evolving demands
- Resolving timing of surface water use, groundwater use, and groundwater storage
- Efficiently estimating costs associated with a range of options

Depending on the available surface water source(s), one practice that is becoming more commonly implemented in conjunctive use projects is Aquifer Storage and Recovery (ASR). ASR is the storage of water in aquifers, via wells, when surface water supplies are available and extraction of groundwater from the same well when it is needed.

1.2 Research Objectives

The objective of this research is to develop a model that can assist with design and analysis of costs associated with conjunctive use projects, and more specifically, ASR projects. While ASR is the method utilized to recharge groundwater within the model, the model can also be applied to other recharge methods. Following function, the model is referred to as the Combined Source Infrastructure Assessment Model or CSIAM. Overall, the model is a general tool that can be used for a wide variety of circumstances.

The basis for developing the model has been the needs of the Town of Castle Rock, Colorado. Per Castle Rock's 2006 Water Facilities Master Plan, the town is in the process of transitioning from a groundwater only water source to combined use of groundwater and surface water. Currently, Castle Rock is evaluating a range of conjunctive use options. Key variables associated with each of the options include quantities of water, timing of water delivery, and water quality. While the Town of Castle Rock provides a basis for applying the model, the results should not be viewed as having direct bearing on future actions in the Town of Castle Rock. Many of the key issues that will ultimately drive the Town's water supply plans are not included in this analysis. A conceptual model for the CSIAM is presented in Figure 1.

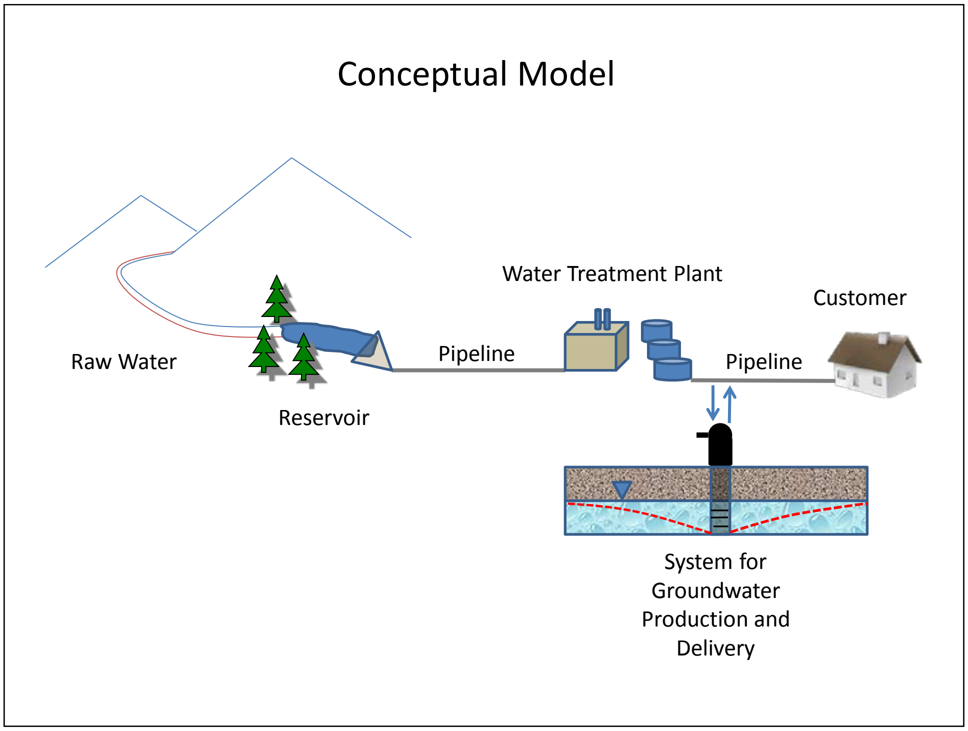


Figure 1. Conceptual Model

1.3 Content and Organization

This thesis is divided into seven chapters. This chapter provides an introduction to the objective and content of this thesis. The Chapter 2 provides a review of relevant literature. Chapter 3 discusses the conceptual model and process flow diagram used in model development. Chapter 4 describes the structure of the model. Chapter 5 focuses on the decision programming algorithm. Chapter 6 presents the results from test applications of the model. Chapter 7 presents conclusions and recommendations for further work. Complementary information is included in three appendices addressing Monte Carlo simulations, example program worksheets, and a user's guide for the program.

2 LITERATURE REVIEW

2.1 Conjunctive Use

Up to the 1950's, the management and development of surface water and groundwater were typically dealt with separately (de Wrachien and Fasso 2002). Moving beyond this, Todd (1959) provides an early introduction to conjunctive use. Specifically, Todd (1959) described conjunctive use as the integrated utilization of surface and groundwater. In the 1970's, water supply research began to focus on developing optimization tools for prediction of local responses of aquifer and stream systems to withdrawals and recharge (Bredehoeft and Young 1970, Young and Bredehoeft 1972, and Yu and Haimes 1974). In the early 1980's, Bredehoeft and Young (1983) wrote a seminal paper on a coupled hydrologic and economic mathematical model for conjunctive use pertaining to irrigated agriculture. Bredehoeft and Young (1983) wanted to develop a tool to better understand the relationship between water supply and economic factors that would influence farmer's operational decisions. Since then, many economic-engineering simulation conjunctive use models have been developed that focus on the representation of the economics of water demands with the simulation of physical water systems (Andrews et al. 1992, McCarl et al. 1999, Gillig et al. 2001, Marques et al. 2006, Harou and Lund 2008, Bharati et al. 2008, Chiu et al. 2009, Harou et al. 2009, Chang et al. 2011, and Vieira et al. 2011). Although the economic models deal with costs associated with pumping groundwater in terms of head and economic representations of surface water demands using water demand curves (McCarl et al. 1999, Gillig et al. 2001, Marques et al. 2006, Bharati et al. 2008, Harou and Lund 2008, and Chiu et al. 2009), they do not address costs associated with infrastructure, operations, and maintenance.

2.2 Artificial Recharge

General approaches to conjunctive use include combined use of surface and groundwater with and without groundwater recharge. The primary advantages to systems with groundwater recharge include an ability to 1) "bank" water in aquifers during periods when surplus surface water is available and 2) reduce the necessary capacities of surface water infrastructure (e.g. water treatment plants) to meet peak demands (Pyne 2005) . Artificial recharge approaches include direct-surface, direct-subsurface, or indirect recharge techniques (Asano 1985 and Bouwer 1989). Direct-surface techniques include surface flooding, ditch and furrow systems, infiltration basins, and stream channel modification (Asano 1985). Direct-surface techniques allow groundwater to be delivered to an aquifer at one location and produced at another distal location. This practice is used in Los Angeles County where spreading basins are used to recharge approximately 2,000 acre-feet of water annually (Jones 2003). A limitation of this approach include 1) a tendency of the recharge systems to plug over time as suspended solids accumulate at water-porous media interfaces and 2) uncertainty as to the source of the produced water. Direct-subsurface techniques include subsurface injection through wells (Asano 1985 and Bouwer 1989) and drainlines. One of the most common direct- subsurface techniques is Aquifer Storage and Recovery (ASR). ASR requires use of wells that are equipped to both pump groundwater and inject treated water into a suitable storage zone (Pyne 1989). Advantages of ASR include 1) periodic back flushing of suspended solids that can accumulate at water-porous media interfaces and 2) an ability to produce the same water that was delivered. Indirect recharge techniques include pumping aquifers to induce recharge from hydraulically connected surface waters and modifying existing aquifers or constructing new aquifers to enhance or create groundwater reservoirs (Oaksford 1985).

2.3 Aquifer Storage and Recovery Projects

Currently, there are ASR projects in eleven countries including the United States, Australia, Canada, United Kingdom, South Africa, Israel, the Netherlands, New Zealand, Thailand, Taiwan, and Kuwait (Pyne 2009). In the United States, ASR projects have been implemented to serve a myriad of purposes including seasonal groundwater storage to help meet peak demands, establishment of emergency water supplies during drought cycles, reduction in aquifer overdraft, storage of reclamation water for reuse, and improvement in water quality in saline or brackish aquifers for irrigation (Jones 2003, Sheng 2004, Pyne and Howard 2004, and Misut and Voss 2007). As of 2009, there were at least 90 operational ASR wellfields in the United States (Pyne 2011). A brief review of ASR initiatives in select states includes:

- California- There are numerous large-scale groundwater storage projects that range in scope from seawater intrusion control, conjunctive use, agricultural storage, municipal storage, and banking for future use (Jones 2003).
- Florida-Numerous cities utilize ASR as a means to meet peak demands and reduce the need to expand their existing wellfields (Buros and Pyne 1994 and Pyne 2005).
- Kansas- Wichita, Kansas instituted an integrated conjunctive use water supply plan that went into full effect this year (Desilva and Ary 2011). The plan included construction of an extensive ASR system that would have the capacity to recharge 100 MGD (Desilva and Ary 2011).

Examples of ASR projects in other countries include:

- Portugal-Projects have been implemented to determine the most optimal use of ASR in drought-prone areas (Ferreira et al.2010).

- Australia-Studies have shown that urban stormwater receiving passive pre-treatment can be effectively used to freshen a brackish aquifer for irrigation use (Pavelic et al. 2006, Rinck-Pfeiffer et al. 2008, Page et al. 2010). In addition, reclaimed wastewater is being stored via ASR wells for indirect agricultural reuse in Australia (Dillon et al. 2006).
- Jordan-Studies indicate that artificial groundwater recharge will help to avoid depletion of the existing aquifers in semi-arid basins (Al-Assa'd and Abdulla 2010).

2.4 Conjunctive Use Models

Models for conjunctive use have been developed by Marques et al. 2006, Uddameri 2007, Harou and Lund 2008, Khan et al. 2008, Bharati et al. 2008, Harou et al. 2009, and Vieira et al. 2011. To varying degrees these model address hydraulic routing through systems (e.g. reservoirs and wells) and economics from the perspective of the value of water. Unfortunately, these models do not directly address costs associated with infrastructure, operations, and maintenance of the conjunctive use system. As an example, Uddameri (2007) developed a decision programming model for optimal (least cost) planning of ASR facilities. The term decision programming refers to a programming technique that iteratively makes decisions (e.g. use of surface or groundwater) based on evolving system conditions. In Uddameri (2007) costs are associated with the volume of water stored in the aquifer, not the costs associated with development and operations of the infrastructure components of the combined source system. Another example is Khan et al. (2008). This work examined the technical and economic potential of developing ASR facilities for drought mitigation in a region in Australia. They performed benefit-cost analyses using a groundwater flow model to simulate recovery and injection volumes coupled with the general infrastructure costs of different groundwater storage methods (i.e. spreading basins and injection wells) (Khan et al. 2008). While this effort addresses infrastructure costs it does it via a site specific analysis that is not suited to use in general applications.

2.5 Decision Programming

A key element of conjunctive use models is decision programming or the "theory of multistage decision processes" (Yakowitz 1984). Decision programming has been used to solve water resource problems that deal with optimization of complex processes via conditions based decision that are made at discrete time intervals through a process (Yakowitz 1984). Decision programming models are capable of operating both surface water delivery and groundwater storage systems over a given planning horizon, based on system conditions (Yakowitz 1984 and Uddameri 2007). In decision programming, the model is based on a problem that can be divided into several stages with a decision required at each stage (Uddameri 2007). Each stage is characterized by a specific state (Uddameri 2007). The states determine the information necessary to make an optimal decision in that time-period (stage) (Uddameri 2007). The decision made at any stage dictates how the system moves from one state to the next.

2.6 Deterministic vs. Stochastic Inputs

Lastly, inputs to mathematical models can be deterministic (fixed values) or stochastic (probabilistic values). The advantage of fixed a deterministic approach is simplicity. The key advantage to a stochastic approach is an ability to explore system reliability by simulating multiple periods of records. Stochastic inputs, such as streamflow, precipitation, and water demands, are varied through time using probability density functions predicated on historical data. Based on simulation of multiple periods of interests, the frequency of events of interest (e.g. not being able to meet demands) can be defined. A common approach to generating stochastic inputs is Monte Carlo simulations (Linsley et al. 1982). Further attention to development of deterministic and stochastic inputs is developed in the following sections.

3 CONCEPTUAL MODEL

3.1 Overview

The following section introduces the conceptual basis for the conjunctive use model developed in this thesis (See Figure 1 in Chapter 1). Based on Figure 1, key elements of the model include:

- A raw water source
- Surface water storage
- A water treatment plant for surface water
- Systems for groundwater production and delivery
- Customers

3.2 Process Flow Diagram

Figure 2 presents a process flow diagram for primary infrastructure components in the CSIAM. Figure 2 is the basis of the CSIAM.

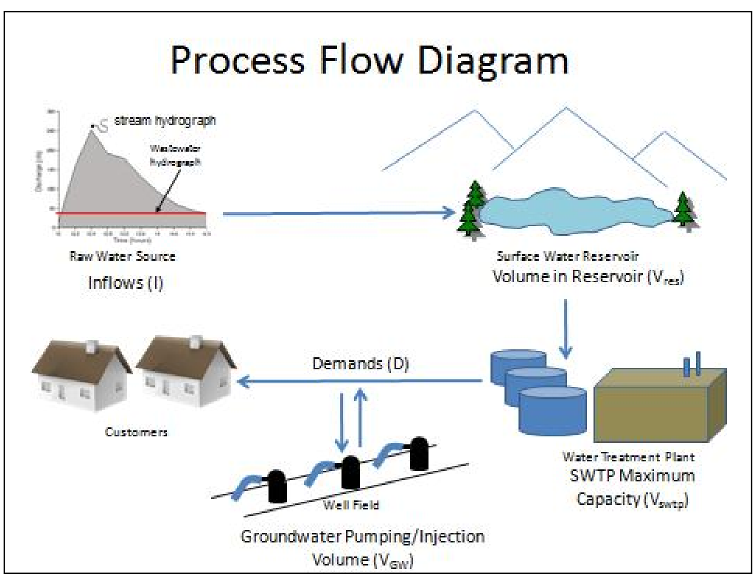


Figure 2. Process Flow Diagram

As shown in the process flow diagram, surface water is routed to a surface water reservoir for storage and then used to meet demands when needed. The primary basis for decisions in the CSIAM is using surface water first to meet demands. This minimizes the size of the reservoir and reservoir losses (seepage and evaporative losses). Uses of surface water include meeting demands and subsurface water storage when capacity is available. Groundwater is produced when surface water capacity (stored water and/or surface water treatment capacity) is less than demands.

In the model, critical elements that need to be defined to implement the CSIAM include:

- Raw water source(s) (i.e. system inflows)
- Surface reservoir size
- Maximum surface water treatment plant (SWTP) capacity
- Number of pumping and/or ASR wells
- Maximum aquifer capacity

Pipeline capacity is assumed to be equal to the maximum SWTP capacity. In addition, the model only addresses the components of the water distribution system up to the surface water treatment plant. It is viewed that that the infrastructure requirements after the treatment plant (i.e., water delivery system to the customers, pump and/or lift stations, and treated storage) are common to most water distribution systems and can best be addressed separately.

4 CSIAM-COMBINED SOURCE INFRASTURCRTURE ASSESSMENT MODEL

4.1 Overview

The following chapter describes the design and operation of the CSIAM Following Figure 3, the model includes subroutines for hydraulic inputs, cost inputs, hydraulic calculations, cost calculations, hydraulic outputs, and cost outputs All programming was conducted using Mathcad® 14 (Parametric Technology Corporation 2011). Per Parametric Technology Corporation's 2011 webpage "Mathcad simplifies engineering calculations by combining equations, text and graphics in a presentable format, making it easy to keep track of the most complex calculations" (http://www.ptc.com/products/mathcad/#1). A key advantage of Mathcad is ease of use for unfamiliar practitioners.

Topics addressed in this section include:

- Hydraulic Inputs
- Hydraulic Calculations
- Hydraulic Outputs
- Cost Inputs
- Cost Calculations
- Cost Outputs

Specifically, the CSIAM is composed of six Mathcad worksheet that are linked as indicated by arrows (see Figure 3).

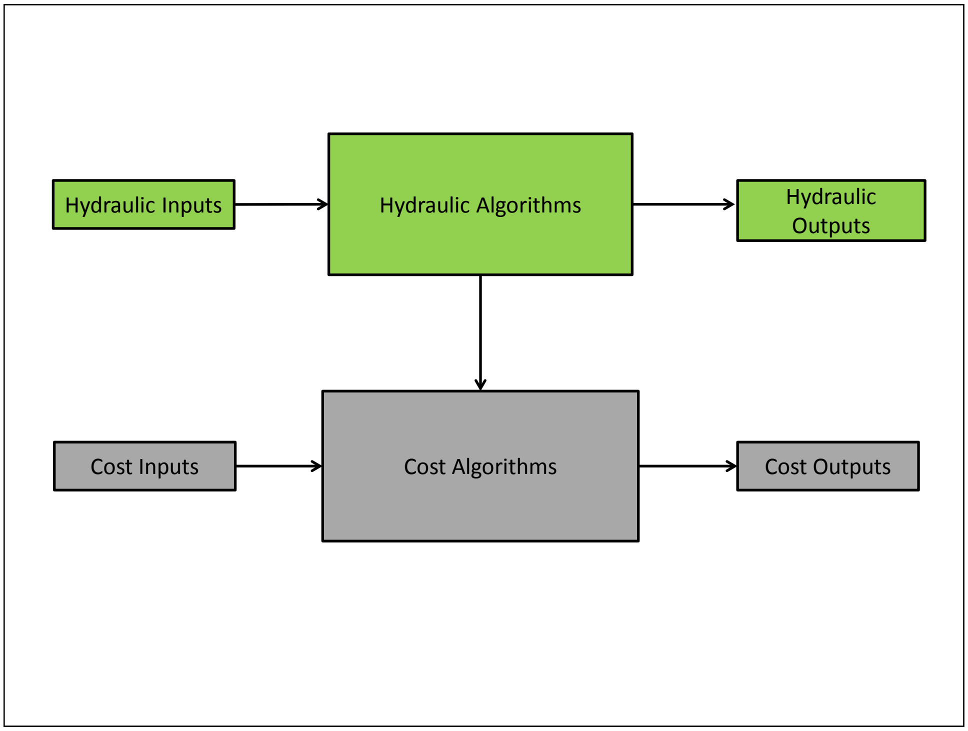


Figure 3. Components of CSIAM

Two versions of the model were developed using deterministic and stochastic inputs. There are separate worksheets for deterministic and stochastic hydraulic inputs and hydraulic calculations, respectively. These are discussed in more detail in the following sections.

The model uses units of cubic meters for volumes, square meters for areas, and $US for currency. Units of time include days, months, and years. Appendix A presents examples of the Monte Carlo simulations generated for an example model run. Appendix B contains example worksheets for a model run. Appendix C presents the User's Guide for the CSIAM.

4.2 Hydraulic Inputs

The inputs in the model are the same with the exception of the inflows, pan evaporation values, and irrigation demands which vary based on whether they are a deterministic or stochastic input. Discussions of the inputs in each version of the model are subdivided into two sections: the deterministic inputs and the stochastic inputs.

Hydraulic inputs are entered using the Hydraulic Inputs Worksheet (see Appendix B). All hydraulic inputs are listed in Table 1.

Table 1. List of Elements in Hydraulic Input File

Variable Name	Description	Model		Units
		Deterministic	Stochastic	
N_{years}	Number of years to reach full build-out or project life span	X	X	years
PCD	Per capita average monthly in-house demand	X	X	m^3/month
Growth	Annual population growth rate	X	X	%/year
$Initial_p$	Initial population	X	X	integer
$V_{swtpmaxday}$	Maximum daily surface water treatment plant capacity	X	X	m^3/day
$V_{swtpmaxmonthly}$	Maximum monthly surface water treatment plant capacity	X	X	m^3/month
$V_{gwwtpmaxday}$	Maximum daily ground water treatment plant capacity	X	X	m^3/day
$V_{gwwtpmaxmonth}$	Maximum monthly ground water treatment plant capacity	X	X	m^3/month
Max_{Qrate}	Average monthly pumping volume	X	X	m^3/month
Max_{ASR}	Average monthly ASR injection volume	X	X	m^3/month
Existing_Pumping_Wells	Existing number of pumping wells	X	X	integer
Existing_ASR_Wells	Existing number of	X	X	integer

	ASR wells			
Nu_ASR_Retrofits	Number of ASR retrofits	X	X	integer
Vol_Recoverable_GW	Volume of recoverable water in aquifer	X	X	m^3
Area(Storage)	Reservoir Area as a function of volume	X	X	m^2
V_{resmin}	Minimum reservoir pool	X	X	m^3
Init_Stor	Initial reservoir volume	X	X	m^3
Seepage_Losses	Seepage loss	X	X	m/month
Evaporation	Average monthly pan evaporation	X		m
INF	Average monthly inflow	X		m^3
IRR	Irrigation-use multiplier	X		N/A
Irrigated_acreage	Irrigated acreage		X	m^2
s1,s2	Pan evaporation shape factors		X	(1)
pan_scale	Pan evaporation scaling factors		X	(2)
$s1_{IF}$,$s2_{IF}$	Inflow shape factors		X	(1)
pan_scale_{IF}	Inflow scaling factor		X	(2)
Percent	Inflow percent monthly allocation		X	%/month
$s1_{IR}$,$s2_{IR}$	Irrigation demands shape factors		X	(1)
pan_scale_{IR}	Irrigation demands scaling factors		X	(2)

Footnotes:

(1) Shape factors are discussed in Section 4.2.2.

(2) Scaling factors are discussed in Section 4.2.2.

4.2.1 Deterministic Inputs

Deterministic inputs provide the simpler approach to using the model. Inflows, pan evaporation, and irrigation demands are entered as constant average monthly values. Historical records can be used to obtain this data. Other parameters such as SWTP capacity, initial reservoir volume, minimum reservoir pool, etc. are user inputs that can be set by the model user.

4.2.2 Stochastic Inputs

Use of multiple sets of stochastically generated inputs records provides an opportunity to test the reliability of a select system to meet demands. Stochastic inputs are developed using 1) historical records to generate probability density functions (PDFs) for inflows, pan evaporation, and irrigation consumptive and 2) Monte Carlo simulation methods Mathcad has a built-in Monte Carlo simulation method that determines the probability that a random variable will take on a particular value. The first step involves fitting probability density functions to a histogram for the parameter of interest. In Mathcad, two shape factors are used to fit PDFs to histograms. The shape factors govern the width and height of the probability density function. A scaling factor is used to adjust the magnitude of the probability density function. Mathcad also has a random number function. Application of random numbers to the PDFs produces stochastic records that are used as inputs to the Hydraulic calculations worksheet. There is a great deal more pre-processing in the model using stochastic inputs than in the deterministic version because historical data must be obtained and then PDFs are calculated. Examples of the data processing, PDFs, and Monte Carlo simulations are shown in Appendix A. The User's Guide (Appendix C) has a detailed description of each input.

4.3 Hydraulic Calculations

The primary programming routine in the hydraulic calculations worksheet is a reservoir routing routine wherein the reservoir is operated using surface water and groundwater. Mathematical functions simulate the overall water balance in the surface water reservoir and aquifer, and controls how water is routed through the system. The water routing in the hydraulic worksheet is based on decision programming that focuses on 1) minimizing stored surface water, 2) recharging groundwater whenever possible, and 3) meeting demands. Chapter 6 discusses the decision programming elements in more detail. The hydraulic model is built using a monthly (1/12th of a year) time-step. An example of each programming algorithm in the hydraulic model is shown in Appendix B and in the User's Guide (Appendix C). Table 2 shows key calculations employed in the in the hydraulic calculations worksheet.

Table 2. Hydraulic Calculations Parameters

Parameter	**Description**	**Calculation**	**Units**
Capita	Population	$Initial_p * (1 + \frac{Growth}{12})$ (1)	N/A
$Demand_{MH}$	Monthly In-House Demand	$Capita * PCD$ (2)	m^3/month
$Demand_{IR}$	Monthly Irrigation Demand	$IRR * Demand_{MH}$ (3) (deterministic) See Equation (7) in Appendix (C) for stochastic inputs (4) (stochastic)	m^3/month
$Demand_{MT}$	Monthly Total Demands	$Demand_{MH} + Demand_{IR}$ (5)	
Inflow	Monthly Inflows	N/A (deterministic) (6) See Equation (9) in Appendix (C) for stochastic inputs (7) (stochastic)	m^3/month
PE	Monthly Pan Evaporation Rates	N/A (deterministic) (8) See Equation (10) in Appendix (C) for stochastic inputs (9) (stochastic)	m/month
reservoir_route	System water balance	See Equation (11) in Appendix (C) (10)	m^3/month

4.4 Hydraulic Outputs

Table 3 shows the hydraulic outputs and Table 4 shows an example of the reservoir routing matrix. This matrix is defined as AA in the worksheet. Appendix B shows an example of the Mathcad worksheet with the hydraulic outputs.

Table 3. Hydraulic Outputs

Variable Name	**Description**	**Units**
Reservoir_GW_Operations	AA matrix of water supply mass balance	m^3/month
Demands	Vector of demands	m^3/month
Res_OP	Vector of stage-storage volumes	m^3/month
GW	Vector of groundwater (recovery or injection) volumes	m^3/month
Cum_GW	Vector of cumulative groundwater extraction volumes	m^3/month

Table 4. Reservoir Route (AA Matrix) Output for 12 months

Reservoir_GW_Operations =

	1	2	3	4	5	6	7	8	9	10	11
1	1	$1.386\cdot10^{7}$	$2.61\cdot10^{7}$	$2.178\cdot10^{7}$	0	$2.61\cdot10^{7}$	4	0	0	0	$1.525\cdot10^{10}$
2	2	$1.386\cdot10^{7}$	$2.613\cdot10^{7}$	$3.564\cdot10^{7}$	$1.386\cdot10^{7}$	$1.227\cdot10^{7}$	4	0	0	0	$1.525\cdot10^{10}$
3	3	$1.386\cdot10^{7}$	$2.616\cdot10^{7}$	$3.564\cdot10^{7}$	$1.386\cdot10^{7}$	$1.23\cdot10^{7}$	4	0	0	0	$1.525\cdot10^{10}$
4	4	$1.386\cdot10^{7}$	$2.619\cdot10^{7}$	$3.564\cdot10^{7}$	$1.386\cdot10^{7}$	$1.233\cdot10^{7}$	4	0	0	0	$1.525\cdot10^{10}$
5	5	$1.386\cdot10^{7}$	$3.146\cdot10^{7}$	$3.564\cdot10^{7}$	$1.386\cdot10^{7}$	$1.76\cdot10^{7}$	4	0	0	0	$1.525\cdot10^{10}$
6	6	$1.386\cdot10^{7}$	$5.59\cdot10^{7}$	$3.564\cdot10^{7}$	$1.386\cdot10^{7}$	$4.204\cdot10^{7}$	4	0	0	0	$1.525\cdot10^{10}$
7	7	$1.386\cdot10^{7}$	$8.643\cdot10^{7}$	$3.564\cdot10^{7}$	$1.386\cdot10^{7}$	$7.257\cdot10^{7}$	4	0	0	0	$1.525\cdot10^{10}$
8	8	$1.386\cdot10^{7}$	$8.416\cdot10^{7}$	$3.564\cdot10^{7}$	$1.386\cdot10^{7}$	$7.03\cdot10^{7}$	4	0	0	0	$1.525\cdot10^{10}$
9	9	$1.386\cdot10^{7}$	$9.083\cdot10^{7}$	$3.564\cdot10^{7}$	$1.386\cdot10^{7}$	$7.697\cdot10^{7}$	4	0	0	0	$1.525\cdot10^{10}$
10	10	$1.386\cdot10^{7}$	$4.876\cdot10^{7}$	$3.564\cdot10^{7}$	$1.386\cdot10^{7}$	$3.49\cdot10^{7}$	4	0	0	0	$1.525\cdot10^{10}$
11	11	$1.386\cdot10^{7}$	$2.639\cdot10^{7}$	$3.564\cdot10^{7}$	$1.386\cdot10^{7}$	$1.253\cdot10^{7}$	4	0	0	0	$1.525\cdot10^{10}$
12	12	$1.386\cdot10^{7}$	$2.641\cdot10^{7}$	$3.564\cdot10^{7}$	$1.386\cdot10^{7}$	$1.255\cdot10^{7}$	4	0	0	0	...

Column Headers:

1. Months
2. Demands (m^3)
3. Inflows (m^3)
4. Volume in Reservoir (m^3)
5. Volume out of Reservoir (SWTP) (m^3)
6. Groundwater (Injection(-)/Recovery(+)) (m^3)
7. Decision Criteria Flag (1-Surplus Water, 2-SWTP Capacity Constraint, 3-Available Surface Water Constraint, 4-Both SWTP Capacity and Available Surface Water Constraint
8. Total Losses (Evaporation and Seepage) (m^3)
9. Water System Mass Balance (m^3)
10. Groundwater Flag (1-Groundwater Cap Exceeded, 0-Groundwater Cap Not Exceeded)
11. Total Groundwater Mass Balance (m^3)

4.5 Cost Inputs

The cost inputs are the same for deterministic and stochastic input versions of the model. The cost inputs are separated into capital costs for infrastructure and operations and maintenance costs (O&M). All cost inputs are in U.S. dollars ($). Table 5 describes the cost inputs. Appendix B presents an example input file.

Table 5. Cost Inputs

Variable Name	**Description**	**Units**
	Capital Costs	
Cost_per_V_{res}	Cost per reservoir capacity	$/m^3
Cost_per_V_{wtp}	Construction cost per SWTP capacity	$/m^3
Cost_per_V_{wtpgw}	Construction cost for groundwater treatment plant capacity (GWTP)	$/m^3
$Cost_{pumpwell}$	Cost for construction of a pumping well. Includes well, pump, wellhead facility, and transmission lines.	$/well
$Cost_{ASRwell}$	Cost for construction of ASR well. Includes well, pump, wellhead facility, and transmission lines.	$/well
$ASR_{retrofit}$	Cost to retrofit existing pumping well.	$/well
$Interest_{rate}$	Project interest rate.	%
	O&M Costs	
Res_OM_monthly	Cost for monthly reservoir operations and maintenance	$/month
Cost_per_$V_{surfacetreatment}$	Cost for surface water treatment	$/1000 gallons
Cost_per_$V_{gwtreatment}$	Cost for groundwater treatment	$/1000 gallons
Cost_per_V_{asr}	Cost for injection	$/1000 gallons
Cost_per_$V_{pumping}$	Cost for recovery	$/1000 gallons
$Cost_{wellrehab}$	Cost to rehabilitate existing well	$/well

$Well_{life}$	Life expectancy of each well	years
$Rehab_{frequency}$	Frequency of well rehabilitation	years

4.6 Cost Calculations

The cost calculations worksheet estimates costs based on the output from the hydraulic worksheet and the cost input worksheet. The numbers of wells needed to meet demands are calculated in this worksheet. Capital costs, O&M costs, life-cycle costs, and present-worth costs are calculated using the calculations from the hydraulic calculations file. Table 6 shows the cost calculations employed in the Cost Calculations worksheet. Appendix B shows examples of the programming calculations. Appendix C (User's Guide) discusses each calculation in more detail.

Table 6. Cost Calculation Parameters

Parameter	**Description**	**Calculation**	**Units**
Max_Q	Calculates the maximum groundwater volume pumped each month	See Equation (13) in Appendix (C) (11)	m^3/month
Min_Q	Calculates the maximum volume of surface water injected into the aquifer each month	See Equation (14) in Appendix (C) (12)	m^3/month
$Annual_Q$	Calculates the annual groundwater pumping and injection volume	See Equation (15) in Appendix (C) (13)	m^3/year
$Cum_Q(Annual_Q)$	Calculates the	See Equation (16) in Appendix (C) (14)	m^3/year

	cumulative annual groundwater pumping and injection volumes		
$Q_{well}(Max_Q)$	Calculates well capacity with well capacity decline	$\left(1 - \frac{Cum_Q(Annual_Q)}{Vol\_Recoverable_{GW}}\right) * Max_{QRate}$ (15)	m^3/month
$Q_{wellasr}(Min_Q)$	Calculates ASR injection capacity with well capacity decline	$\left(1 - \frac{Cum_Q(Annual_Q)}{Vol\_Recoverable_{GW}}\right) * Max_{ASR}$ (16)	m^3/month
$Num_{pumpwells}$	Calculates the number of pumping wells needed to meet demands with well capacity decline	$\left(\frac{Max_Q}{Q_{Well}(Max_Q)}\right)$ (17)	Integer
$Num_{ASRwells}$	Calculates the number of ASR wells needed to meet injection volumes with well capacity decline	$\left(\frac{Min_Q}{Q_{Well}(Min_Q)}\right)$ (18)	Integer
$Num_{totpumpwells}$	Calculates the number of new pumping wells needed to meet demands based on the number of existing wells	See Equation (19) in Appendix (C) (19)	Integer
$Num_{totasrwells}$	Calculates the number of new ASR wells needed to meet demands based on the number of existing wells	See Equation (20) in Appendix (C) (20)	Integer
$Capital_{pump}$	Calculates total	$Cost_{pumpwell} * Num_{totpumpwells}$ (21)	\$/month

	cost for pumping wells		
$Capital_{asr}$	Calculates total cost for ASR wells	$Cost_{asrwell} * Num_{totasrwells}$ (22)	\$/month
$Capital_{total}$	Calculates cumulative annual capital costs	See Equation (23) in Appendix (C) (23)	\$/year
$Capital_{incremental}$	Calculates annual capital costs	See Equation (24) in Appendix (C) (24)	\$/year
$Monthly_{CRW}$	Calculates monthly cost for replacement wells	$[\frac{(Existing\_Pumping\_Wells * Cost_{pumpwell})}{Well_{life}} + \frac{(Num_{totpumpwells} * Cost_{pumpwell})}{Well_{life}}]/12$ (25)	\$/month
O_M_{Total}	Calculates monthly O&M costs	$Res\_OM\_Monthly + Vol\_WTP * Cost_{surfacetreatment} + Vol\_Pumping\_Well * Cost\_per\_V_{gwtreatment} + Vol\_Pumping\_Well * Cost\_per\_V_{pumping} + Vol\_Injection\_Well * Cost\_per\_V_{asr} + Monthly_{CRW}$ (26)	\$/month
O_M_{cum}	Calculates monthly cumulative O&M costs	See Equation (27) in Appendix (C) (27)	\$/month
O_M_{annual}	Calculates annual O&M costs	See Equation (28) in Appendix (C) (28)	\$/year
Total_Costs	Calculates total annual costs	$Capital_{incremental} + O\_M_{annual}$ (29)	\$/year
Cum_Tot_Cost	Calculates cumulative annual costs	See Equation (30) in Appendix (C) (30)	\$/year
Present_Value	Calculates the annual present value	$\frac{Total\_Costs}{(1+Interest_{rate})^{Nyears}}$ (31)	\$/year

4.7 Cost Outputs

Table 7 shows the cost outputs found in the cost output worksheet. Appendix B contains examples of the Mathcad outputs with figures.

Table 7. Cost Outputs

Variable Name	**Description**	**Units**
Volume_Groundwater_Extraction	Monthly volume of groundwater extracted.	m^3 /month
$Num_{pumpwells}$	Number of pumping wells by month.	Integer
$Num_{ASRwells}$	Number of ASR wells by month.	Integer
$Capital_{total}$	Cumulative annual capital costs.	$/year
$Capital_{incremental}$	Annual capital costs.	$/year
O_M_{total}	Monthly O&M costs.	$/month
O_M_{cum}	Cumulative monthly O&M costs.	$/month
O_M_{annual}	Annual O&M costs.	$/year
Cum_Tot_Cost	Cumulative annual costs of capital and O&M.	$/year
Total_Costs	Total annual costs of capital and O&M.	$/year
Life_Cycle_Cost	Total cost of the project.	$
Present_Value	Annual present value.	$/year
Net_Present_Value	Total present value.	$

5 WATER BALANCE

5.1 Overview

This chapter describes the water balance approach employed in the CSIAM. The objectives for the water balance are to 1) minimize storage surface water, 2) recharge groundwater whenever possible, and 3) meet demands.

5.2 Routing Algorithm

The routing algorithm is built using the storage indication method (Linsley et al. 1982 and Bedient et al. 2008). The storage indication method uses the finite-difference form of the continuity equation combined with a storage indication curve (Bedient et al. 2008), which can be generalized in the following format for two points in time:

$$(I_{\mathrm{t}} + I_{\mathrm{t+\Delta t}}) + (\frac{2S_{\mathrm{t}}}{\Delta t} - Q_{\mathrm{n}}\ ) = (\frac{2S_{\mathrm{t+\Delta t}}}{\Delta t} + Q_{\mathrm{t+\Delta t}})\ (32)$$

where:

I = inflow (m^3)
S = storage volume (m^3)
Q= outflow (m^3)
t = time (months)

The routing algorithm has been modified to account for losses. The algorithm tracks the storage in the reservoir at time t and t+Δt by accounting for inflows and outflows including losses. If the envisioned system does not include a reservoir, the routing algorithm routes all of the water through a reservoir with zero storage and does not calculate losses as long as the user specifies that the initial reservoir volume, minimum pool volume, and losses are zero in the input worksheet.

The routing algorithm uses a series of decision variables to determine how water is routed through the system. The basis for the routing algorithm is shown in Figure 4. A discussion of the decision criteria is presented in the following section.

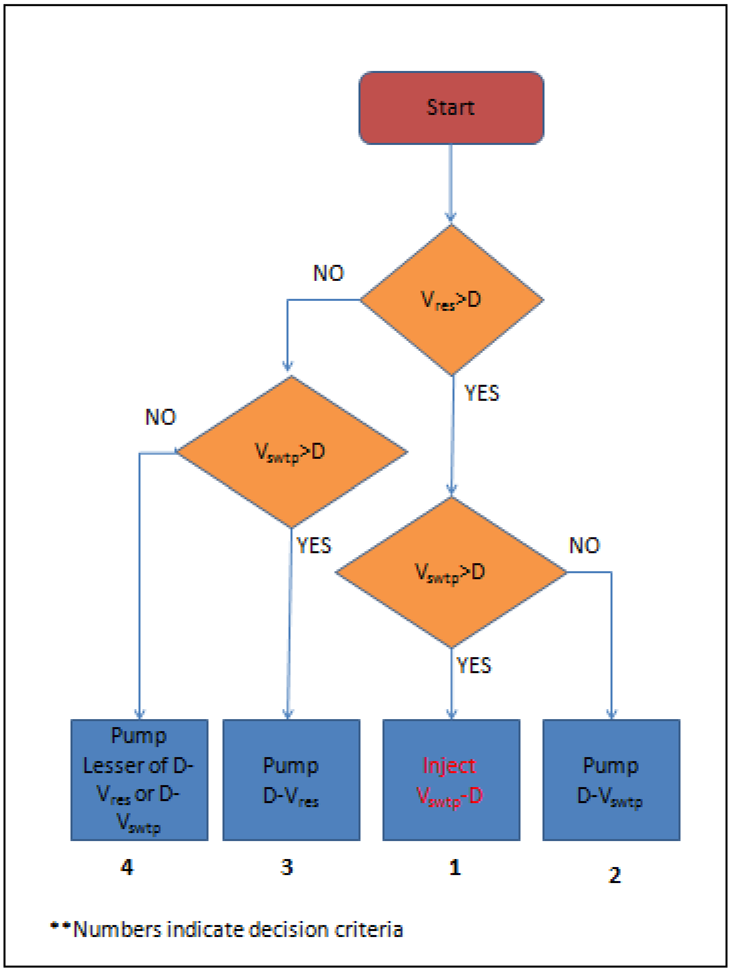


Figure 4. Routing Algorithm (numbers 1 through 4 are flags that are included in the AA Hydraulic Output matrix)

5.3 Decision Criteria

As discussed in Chapter 4, the CSIAM is operated based on a set of decision criteria. In order to maintain a water balance in the system, inflows (surface water and/or groundwater) must equal outflows (demands), with losses accounted for. The decision criteria control how water is routed through the system. Figure 4 illustrates the decision criteria process.

There are four decision criteria that govern how the CSIAM system is operated. The decision criteria are based on the available water in the reservoir and/or the size of the SWTP, relative to demands. The decision criteria are as follows:

1. Surplus Water Opportunity - If the volume in the reservoir is greater than the demands and the SWTP capacity is greater than demands, the surplus water in the reservoir is delivered to the aquifer.
2. SWTP Capacity Constraint - If the volume in the reservoir is greater than demands, but the maximum SWTP capacity is less than demands, the volume of the maximum SWTP capacity will be used to meet demands and then groundwater will be pumped to meet the deficit.
3. Available Surface Water Constraint - If the volume in the reservoir is less than demands, but the maximum SWTP capacity is greater than demands, the volume available in the reservoir (less the minimum pool) will be used to meet demands and the deficit will be met using groundwater.
4. SWTP and Available Surface Water Constraints - If the volume in the reservoir is less than demands and the maximum SWTP capacity is less than demands, the lesser of the demands minus the volume in the reservoir or the demands minus the SWTP capacity will be used to first meet demands and the deficit will be met using groundwater.

The routing algorithm uses the decision criteria to operate the infrastructure components. Table 8 shows how the surface water reservoir, SWTP, and groundwater reservoir are operated using the decision criteria. A detailed discussion of each element in the routing algorithm is presented in the next section.

Table 8 . Infrastructure Operation

Decision Criteria	Equations	Reservoir Storage	Outflow to SWTP	Groundwater
1a. If $V_{res} > D$ and $V_{SWTP} > D$ and $V_{res} > V_{SWTP}$	$D + (V_{SWTP} - D)$(33)	$S_{t+1}=S_t+I-(33)-L$	O=(33)	$D - V_{SWTP}$ (39)
1b. If $V_{res} > D$ and $V_{SWTP} > D$ and $V_{res} < V_{SWTP}$	$D + (V_{res} - V_{resmin} + D)$ (34)	$S_{t+1}=S_t+I-(34)-L$	O=(34)	$D - (V_{res} - V_{resmin})$ (40)
2. If $V_{res} > D$ and $V_{SWTP} < D$	V_{SWTP} (35)	$S_{t+1}=S_t+I-(35)-L$	O=(35)	$D - V_{SWTP}$ (41)
3. If $V_{res} < D$ and $V_{SWTP} > D$	$V_{res} - V_{resmin}$ (36)	$S_{t+1}=S_t+I-(36)-L$	O=(36)	$D - (V_{res} - V_{resmin})$ (42)
4a. If $V_{res} < D$ and $V_{SWTP} < D$ and $V_{res} > V_{SWTP}$	V_{SWTP} (37)	$S_{t+1}=S_t+I-(37)-L$	O=(37)	$D - V_{SWTP}$ (43)
4b. If $V_{res} < D$ and $V_{SWTP} < D$ and $V_{res} < V_{SWTP}$	$V_{res} - V_{resmin}$ (38)	$S_{t+1}=S_t+I-(38)-L$	O=(38)	$D - (V_{res} - V_{resmin})$ (44)

Where:

V_{res} = Volume in the reservoir (m^3)
D = Demands (m^3)
V_{SWTP} = Maximum treatment volume capacity in SWTP (m^3)
S = Volumetric storage in reservoir (m^3)
I = Inflows (m^3)
O = Outflows (m^3)
V_{resmin} = Minimum reservoir pool (m^3)
L = Evaporative and seepage losses (m^3)
t = time

5.4 Elements in Routing Algorithm

The output from the algorithm is shown as a matrix where each column represents a specific calculation with an output. An example of the matrix is shown in the hydraulic output section (Table 4, Chapter 4). The matrix is referred to as the AA matrix. Elements by columns include:

- Months
- Inflows
- Demands
- Storage in the reservoir
- Outflows from the reservoir to the SWTP
- Groundwater injection or recovery volumes
- A decision flag that indicates which decision criteria was used
- Volumetric losses
- System mass balance
- Groundwater flag that indicates if the groundwater cap has been violated
- Total groundwater mass balance

The following subsections discuss each element in the routing algorithm.

5.4.1 Inflows

Inflows are acquired from the hydraulic input worksheet. In the deterministic version, average monthly inflows are used and are repeated every year. In the model using stochastic inputs, synthetic inflows are generated using a Monte Carlo simulation calculated in the hydraulic calculations file, which is then called into the routing algorithm.

5.4.2 Demands

Demands are calculated in the hydraulic calculations worksheet and then acquired by the routing algorithm. Demands include in-house and lawn and garden irrigation.

5.4.3 Storage in Reservoir

The reservoir storage element is the most important calculation in the routing algorithm because it controls how the whole system is operated (see Table 8). It can be operated with or without water in a reservoir and controls how much groundwater is either recovered or injected (if ASR is an option). The decision criteria govern how water is routed through the reservoir and into the SWTP. If the water system option does not include a reservoir, water is simply routed through an empty reservoir and is not stored.

5.4.4 Outflows to SWTP

Outflows to the SWTP are dependent on the available water in the reservoir and/or the SWTP maximum capacity (see Table 8). This is a function of the demands and the inflows. The decision criteria govern how water is routed through the reservoir and into the SWTP.

5.4.5 Groundwater Pumping/Injection

Table 8 shows how the groundwater recovery or injection volumes are calculated in the routing algorithm. If there is a surplus in the system, water will be routed to ASR injection wells. If there is a deficit in the system, water will be pumped from wells to help meet demands.

5.4.6 Decision Criteria Flag

The flags are used to determine which decision criteria was implemented based on demands, stored surface water, and the SWTP capacity. The following lists the flags that are used in the model:

1. Surplus Water Opportunity -Indicates that there is surplus water in the system available for injection.
2. SWTP Capacity Constraint -Indicates that there is a limitation in the maximum capacity of the SWTP.
3. Available Surface Water Constraint -Indicates that there is a limitation in the amount of water available in the reservoir.
4. SWTP and Available Surface Water Constraints -Indicates that demands are greater than both the SWTP maximum capacity and the water available in the reservoir.

5.4.7 Losses

Losses are calculated using the reservoir surface area, which is a function of storage volume. The storage volume is different at the beginning of the month vs. the end of the month; therefore the average area is used (i.e. average of the end-of-the month and beginning-of-the month areas). The end-of-the month volume in the reservoir with losses accounted for is not known; therefore, a root function is used to calculate the end-of-the month storage that takes into account the losses as a function of area. The root function finds where the following function becomes zero:

$$0 = V_{\text{resfinal}} - V_{\text{resinitial}} - I + D + (SL + E) * [\frac{Area(V_{\text{resfinal}}) + Area(V_{\text{resinitial}})}{2}] \quad (45)$$

where:

$V_{resfinal}$ = End-of-month volume in reservoir (m^3)
$V_{resinitial}$ = Beginning-of-month volume in reservoir (m^3)
I = Inflows (m^3)
D = Demands (m^3)
SL = Seepage Losses (m)
E = Evaporative Losses (m)

5.4.8 System Mass Balance

The system mass balance was built into the routing algorithm as a check to ensure that the system is balanced each month. If at any point the system mass balance is greater than one m^3, this indicates that there is a flaw in the mass balance; therefore, the water balance needs to be checked.

5.4.9 Groundwater Flag

In most aquifers, there is a finite amount of available water to recover. It was important to add a groundwater capacity to the system to determine when pumping exceeds the available supply. The groundwater cap represents the mass balance of groundwater (i.e. sum of all of the groundwater pumped and injected over the life-span of the project). If pumping in any individual month exceeds the total amount recovered from the aquifer over the life span of the project, the aquifer becomes depleted. A groundwater flag was built into the routing algorithm to indicate if and when pumping exceeds the groundwater cap. The following are the flags used to indicate when pumping exceeds the groundwater cap:

- 1-The volume pumped in an individual month exceeds the groundwater capacity.
- 0-The volume pumped in an individual month is less than the groundwater capacity.

5.4.10 Groundwater Mass Balance

The groundwater mass balance tracks the amount of water in the groundwater system. The following equation is used to determine the groundwater mass balance:

$$GW_{Cap} = \sum(GW_{pumping} + GW_{injection}) \quad (46)$$

where:

$GW_{pumping}$ = Volume of groundwater pumped (m^3/month)
$GW_{injection}$ = Volume of water injected into aquifer (m^3/month)

6 CSIAM DEMONSTRATION APPLICATIONS

The objective of this chapter is to demonstrate the CSIAM model by presenting results from six model runs and an optimization analysis. In addition, there is a demonstration of how the model operates when there is a groundwater penalty (i.e. the amount of recoverable groundwater is reduced). This is important because the amount of recoverable water in aquifers is not infinite, and therefore, the model can show the effects of reduced availability through the addition of wells and increased costs. The basis for the model inputs comes from our understanding of water demands and costs for the Town of Castle Rock. While the Town of Castle Rock provides a basis for applying the model, the results should not be viewed as having direct bearing on future actions in the Town of Castle Rock. Many of the key issues that will ultimately drive the Town's water supply plans are not included in this analysis.

This chapter is split into sections providing background information, descriptions of the modeled scenarios, and results. Background information includes a brief introduction to the Town of Castle Rock and a section on model inputs. Model runs include three scenarios:

- Use of groundwater, treated wastewater, and return flows (treated surface water collected downstream of the Town's wastewater treatment plant)
- Use of groundwater-only
- Use of a hypothetical new stream surface water source

Each scenario is evaluated using deterministic and stochastic inputs in the CSIAM. In addition, the model is evaluated using a range of SWTP capacities to determine if there is an optimal design with respect to costs using the stream surface water option.

6.1 Background Information

6.1.1 Town of Castle Rock

The Town of Castle Rock is located in the high plains of central Colorado at the base of the Front Range. The Town is underlain by the Denver basin including the Dawson, Denver, Arapahoe, and Laramie-Foxhills Aquifers. Historically, the Town has relied primarily on groundwater from the Denver, and Arapahoe Aquifers. Per the Town of Castle Rock 2006 Water Facilities Master Plan (CH2MHill, Inc., 2006) Castle Rock is currently developing surface water supplies to augment their groundwater resources.

6.2 Modeled Scenarios

6.2.1 Scenario A- Combined Source with Treated Wastewater and Return Flows

One option that Castle Rock is evaluating is using treated wastewater and treated surface water return flows from Plum Creek, an ephemeral creek that flows through Castle Rock. The volume of inflows available are constant throughout the year (i.e. the same amount each month). Castle Rock will have to construct a small surface water treatment plant in order to treat the raw surface water. They have existing groundwater treatment plants that are capable of treating their peak demands; therefore, new groundwater treatment capacity will not need to be added. The Town has 52 active wells that are used to meet demands that each average approximately 140 gallons per minute (GPM). Castle Rock currently does not have any ASR wells. A surface water reservoir is not needed because all of the available surface and treated wastewater will be used to meet demands. A 30-year analysis is employed in this analysis.

Deterministic inputs for this scenario are shown in Section 6.3. Stochastic inputs are the same as the deterministic inputs with the exception of the irrigation demands. Reservoir losses were designated as zero because it was assumed that there were not enough available inflows to store. The only stochastic input in the model run is the irrigation demands.

6.2.2 Scenario B-Groundwater-Only

In this scenario, the model is applied to a groundwater-only system. This may be important to a user to compare the infrastructure and costs associated with a groundwater-only system to other water supply options. In the Castle Rock case, the model was run without any surface inflows to compare the cumulative volume of water extracted in a groundwater-only system and system costs to the other options being evaluated.

The CSIAM was run using both deterministic and stochastic inputs. Inputs to the deterministic model are shown in Section 6.3. Both models were run without surface inflows to evaluate the infrastructure and costs associated with a groundwater-only system. The only stochastic input utilized in the model run were the irrigation demands.

6.2.3 Scenario C- Streamflows

Castle Rock is interested in developing an ASR program; however, the surface water supplies that they have available to them at this point in time are not sufficient to develop long-term groundwater storage. In order to show an ASR option, the model was run using streamflows in Plum Creek as a hypothetical new source of raw water. Also, the size of the SWTP was expanded to accommodate the maximum demands. This allowed the model to be run unrestricted (i.e. not constrained by the available water in the reservoir or the size of the SWTP). In addition, a reservoir was needed to store the surplus surface flows. The construction costs were based on the cost to build Reuter-Hess Reservoir (i.e. cost per acre-foot equals $165 million/72,000 acre-feet), which is a newly constructed reservoir located north of Castle Rock.

The CSIAM was run using both deterministic and stochastic inputs. Section 6.3 presents the inputs used in the deterministic model runs. The deterministic model used average monthly inflows in Plum Creek. In addition, the CSIAM was run using synthetic inflows based on historical monthly streamflows in Plum Creek. In addition, synthetic pan evaporation and irrigation demands also were used in the model run. There is available water to store under this option; therefore, a reservoir is utilized.

6.3 Inputs

Inputs to the deterministic model runs are presented in Table 9 and Table 10. The stochastic inputs are the same as the deterministic inputs with the exception of pan evaporative losses used in the streamflow model, inflows in the streamflow model, and irrigation demands utilized in all three scenarios. The stochastic inputs are shape and scaling factors that are determined using probability density functions as previously discussed.

Table 9. Castle Rock Hydraulic Inputs for Model Runs Using Deterministic Inputs

Hydraulic Input Description	Treated Wastewater/Return Flows	Streamflow	Groundwater Only	Units
Number of Years to Reach Full Build-out	30	30	30	Years
Per Capita Average Monthly In-house Demand	6.9	6.9	6.9	m^3/month
Population Growth Rate	1.3%	1.3%	1.3%	N/A
Initial Population	49244	49244	49244	N/A
Maximum SWTP Daily Capacity	1.514×10^4	1.514×10^4	1.514×10^4	m^3/day
Maximum SWTP Monthly Capacity	4.618×10^5	2.18×10^6	4.618×10^5	m^3/month

Maximum GWTP Daily Capacity	0	0	0	m^3/day
Maximum GWTP Monthly Capacity	0	0	0	m^3 /month
Average Monthly Well Pumping Volume	$2.328x10^4$	$2.328x10^4$	$2.328x10^4$	m^3 /month
Average Monthly Well Injection Volume	$1.862x10^4$	$1.862x10^4$	$1.862x10^4$	m^3 /month
Existing Number of Pumping Wells	52	52	52	Integer
Existing Number of ASR Wells	0	0	0	Integer
Number of ASR Retrofits	0	0	0	Integer
Amount of Recoverable Water	$8.631x10^8$	$8.631x10^8$	$8.631x10^8$	m^3
Area(storage)	$(6 * storage)^{2/3}$	$(6 * storage)^{2/3}$	$(6 * storage)^{2/3}$	m^2
Minimum Reservoir Pool	0	$6.167x10^5$	0	m^3
Initial Reservoir Storage	$3.925x10^5$	$6.167x10^6$	0	m^3
Seepage Loss	0	0.025	0	m
Pan Evaporative Loss	0	Varies by Month	0	m
Inflows	$3.925x10^5$	Varies by Month	0	m^3 /month
Irrigation Multiplier	Varies by Month	Varies by Month	Varies by Month	Integer

Table 10. Castle Rock Cost Inputs for Model Runs Using Deterministic Inputs

Cost Input Description	Treated Wastewater/Return Flows	Streamflow	Groundwater Only	Units
Capital Cost for Reservoir Storage	0	$1.85	0	$/m^3$
Capital Cost for SWTP Treatment Construction	$3.50	$3.50	0	$/gallon
Capital Cost for GW Treatment Plant Construction	0	0	0	$/gallon
Cost per Pumping Well	$114060	$114060	$114060	$/well
Cost per ASR Well	$1239000	$1239000	$1239000	$/well
Cost for ASR retrofit	$143000	$143000	$143000	$/well
Interest Rate	6%	6%	6%	Percentage

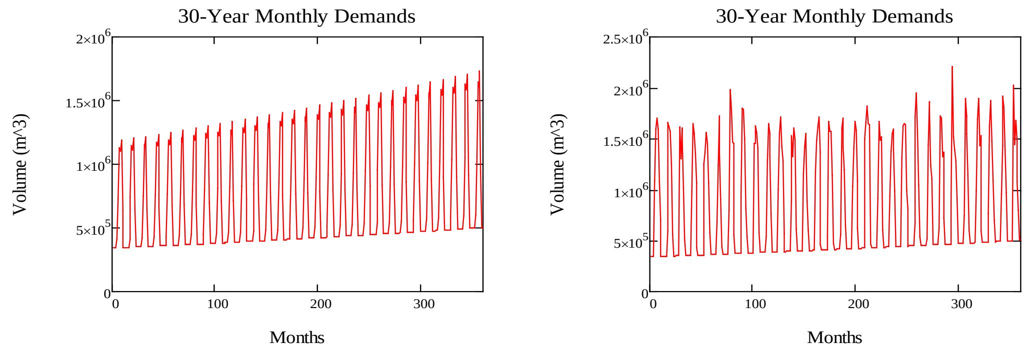
Monthly Reservoir O&M	$4167	$4167	0	$/Month
O&M Cost for SWTP Treatment	$1.50	$1.50	0	$/1000 gallons
O&M Cost for GW Treatment	$1.20	0	$1.20	$/1000 gallons
O&M Cost for ASR Well Operation	$0.428	$0.428	0	$/1000 gallons
O&M Cost for Pumping Well Operation	$2.113	$2.113	$2.113	$/1000 gallons
Cost for Well Rehabilitation	$50000	$50000	$50000	$/well
Well Life	30	30	30	Years
Rehab Frequency	10	10	10	Years

6.4 Results

The following sections present the results from model runs using deterministic and stochastic inputs under each scenario. The results include the demands, incremental groundwater extraction volumes, cumulative groundwater extraction volumes, number of pumping and/or ASR wells, and associated costs.

6.4.1 Demands

The demands using deterministic inputs do not differ between scenarios because the same inputs are used to calculate in-house and irrigation demands. However, the demands differ when using the deterministic inputs vs. stochastic inputs because the irrigation demands use stochastic inputs. The demands do not differ between scenarios when using stochastic inputs because the same inputs are used in each scenario. Figure 5 presents demands calculated for each scenario using both deterministic and stochastic inputs.



Deterministic Demands **Stochastic Demands**

Figure 5. Deterministic and Stochastic Demands for each Scenario

The maximum demand using deterministic inputs is approximately 1.6 million m^3/year, which is equivalent to 4 billion gallons or 1,300 acre-feet/year (AF/year). The maximum demand using stochastic inputs is approximately 2.2 million m^3 /year, which is equivalent to 5.8 billion gallons or 1,800 AF/year.

6.4.2 Groundwater Injection and/or Pumping Volumes

Figure 6 and Figure 7 present the monthly groundwater extraction and/or injection volumes for each scenario using the deterministic and stochastic inputs in the model.

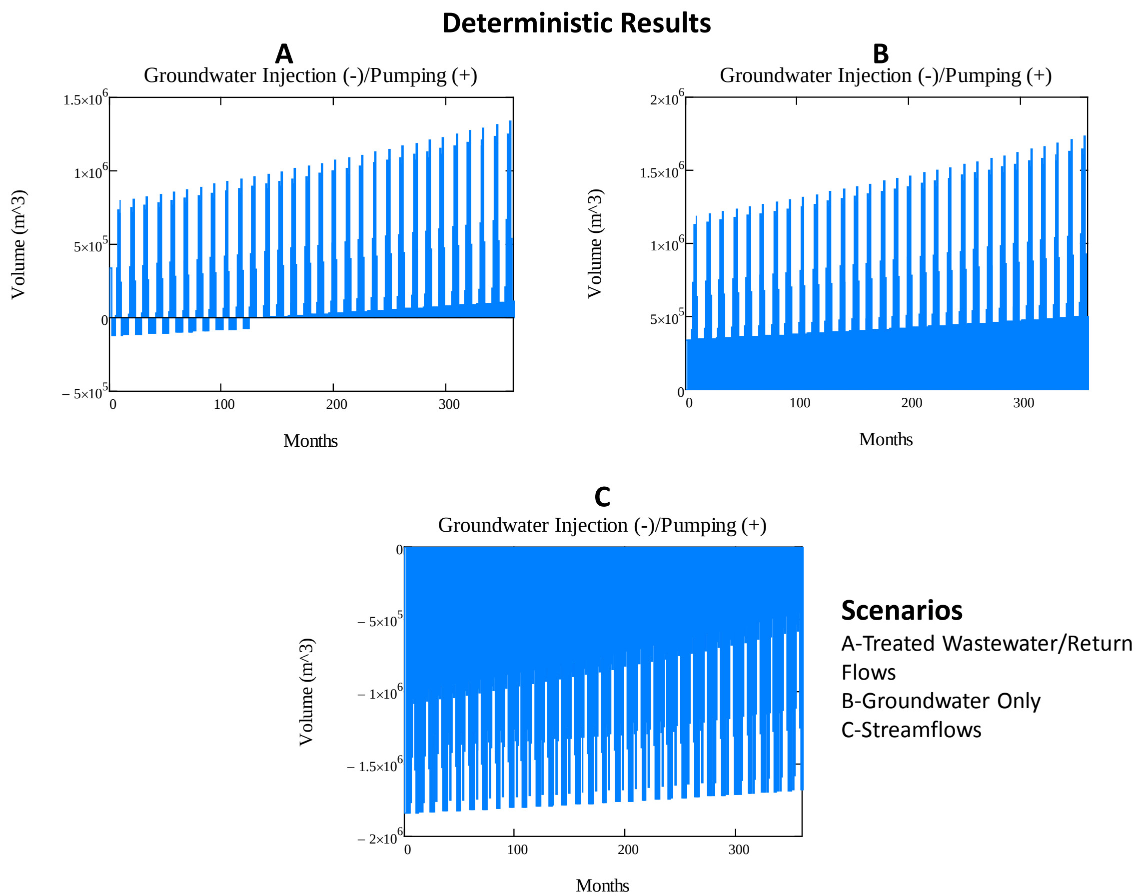


Figure 6. Monthly Groundwater Pumping and/or Injection Volumes for Each Scenario Using Deterministic Inputs

In Scenario A, approximately 6.2 million m^3 is injected into groundwater storage and 125 million m^3 of groundwater is pumped. In Scenario B, approximately 264 million m^3 of groundwater is pumped to meet demands. In Scenario C, approximately 497 million m^3 is injected into groundwater storage. If Scenario A is an option, almost 50% less water will need to be pumped from the aquifer to meet demands compared to Scenario B. If Scenario C is an option, groundwater will not need to be pumped to help meet demands. Significant volumes of water can be injected into groundwater storage under this option.

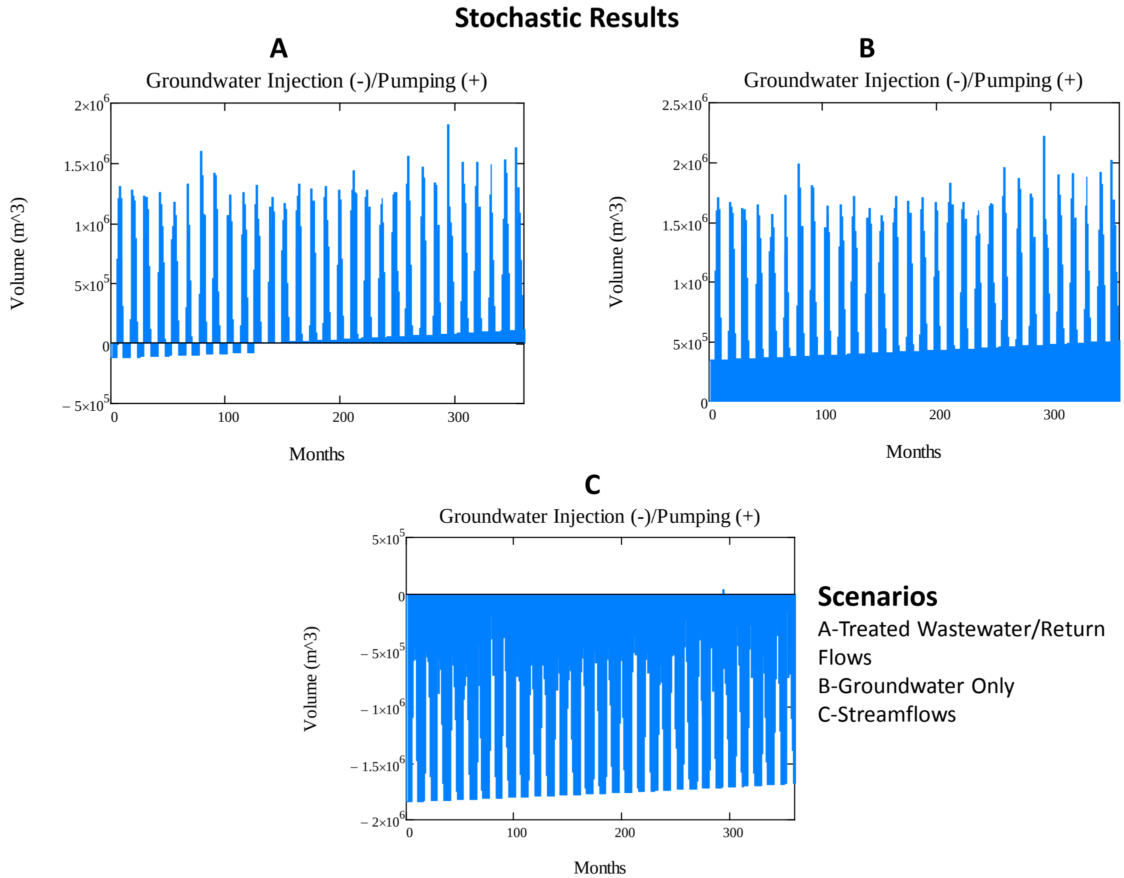


Figure 7. Monthly Groundwater Pumping and/or Injection Volumes for Each Scenario Using Stochastic Inputs

In Scenario A, approximately 6.2 million m^3 of water can be injected and 164 million m^3 of groundwater is pumped. In Scenario B, approximately 304 million m^3 of groundwater is pumped to meet demands. In Scenario C, approximately 480 million m^3 of water is injected into groundwater storage over the course of the planning period (i.e. 30 years).

The results using stochastic inputs in the model indicate that there is more groundwater production in Scenarios A and B and less injection water in Scenario C compared to the deterministic model. However, the values are all within 25% of each other (i.e. 125 million m^3 vs. 164 million m^3, 264 million m^3 vs. 304 million m^3 and 497 million m^3 vs. 480 million m^3). The differences in the values reflect the variability in the historical datasets that are used to generate the synthetic datasets. The probability density functions used in the analysis are the best attempt at capturing the variation in the datasets.

6.4.3 Cumulative Groundwater Pumping or Injection Volumes

Figure 8 and Figure 9 present the cumulative monthly groundwater pumping or injection volumes for each scenario using deterministic and stochastic inputs.

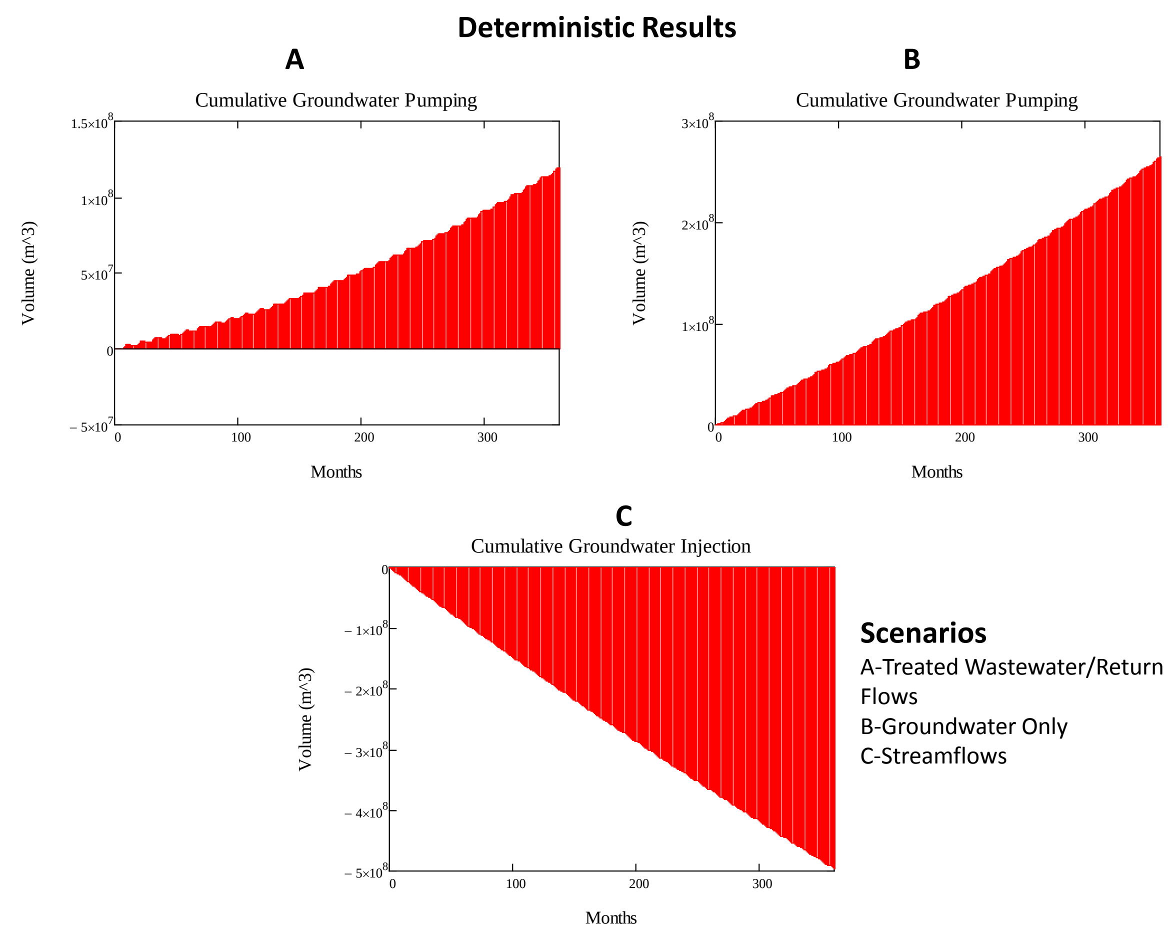


Figure 8. Cumulative Monthly Groundwater Pumping or Injection Volumes for Each Scenario Using Deterministic Inputs

In Scenario A, the cumulative groundwater pumping volume over 30 years is 118 million m^3, which is equivalent to 96,000 AF. In Scenario B, the cumulative groundwater pumping volume over 30 years is 264 million m^3, or 214,000 AF. In Scenario C, the cumulative groundwater injection volume is 496 million m^3, or 401,900 AF. Scenario B pumps 55% more groundwater than Scenario A.

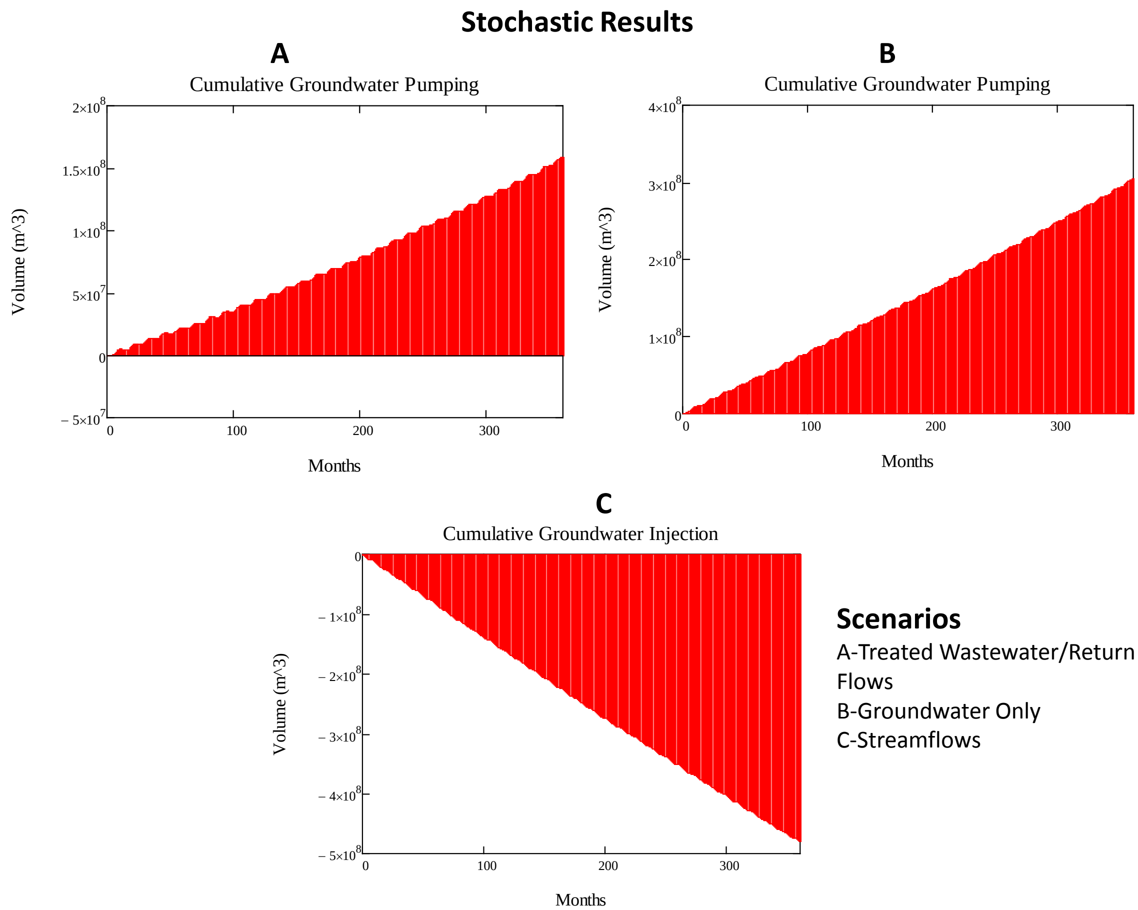


Figure 9. Cumulative Monthly Groundwater Pumping or Injection Volumes Using Stochastic Inputs

Using stochastic inputs, Scenario A produces 158 million m^3 of groundwater over 30 years. This is equivalent to 128,000 AF. In Scenario B, 304 million m^3 or 246,000 AF of groundwater is produced over 30 years. In Scenario C, 408 million m^3 or 390,000 AF of water is injected into groundwater storage over 30 years. Scenario A produces 36% less water than Scenario B.

The results using stochastic inputs in the model yield higher cumulative groundwater pumping and/or injection volumes in Scenario's A and B compared to using deterministic inputs. In Scenario A, 158 million m^3 of water is produced using the stochastic inputs versus 118 million m^3 using the deterministic inputs. In Scenario B, 304 million m^3 are produced using stochastic inputs versus 264 million m^3 in the deterministic inputs. In Scenario C, less water is injected using the stochastic inputs compared to the deterministic inputs (i.e. 408 million m^3 vs. 496 million m^3, respectively).

6.4.4 Number of Pumping Wells

Figure 10 and Figure 11 present the number of wells needed to meet pumping demands for each scenario using deterministic and stochastic inputs in the model.

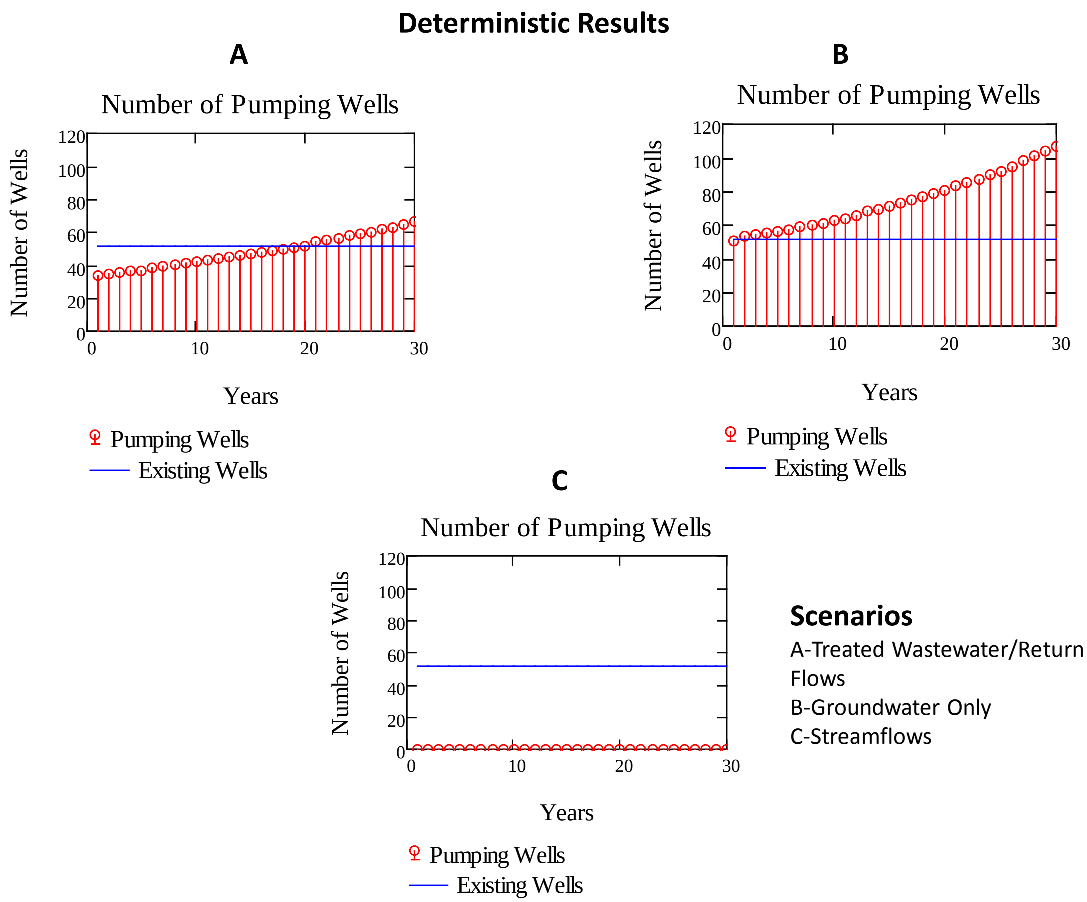


Figure 10. Number of Pumping Wells using Deterministic Inputs for Each Scenario

In Scenario A, a total of 67 pumping wells will be needed to meet demands. Castle Rock has 52 existing wells; therefore, a total of 15 new wells will need to be installed over the project period. It will take 21 years to reach the point where new wells will need to be installed under this scenario. In Scenario B, a total of 107 wells will be needed to meet demands. A total of 55 new wells will need to be installed over the course of the project period. New wells will need to be constructed starting in the second year of the project period. Pumping wells will not need to be installed in Scenario C. Scenario B requires that 40 additional wells will be needed to meet demands compared to the number of wells needed in Scenario A.

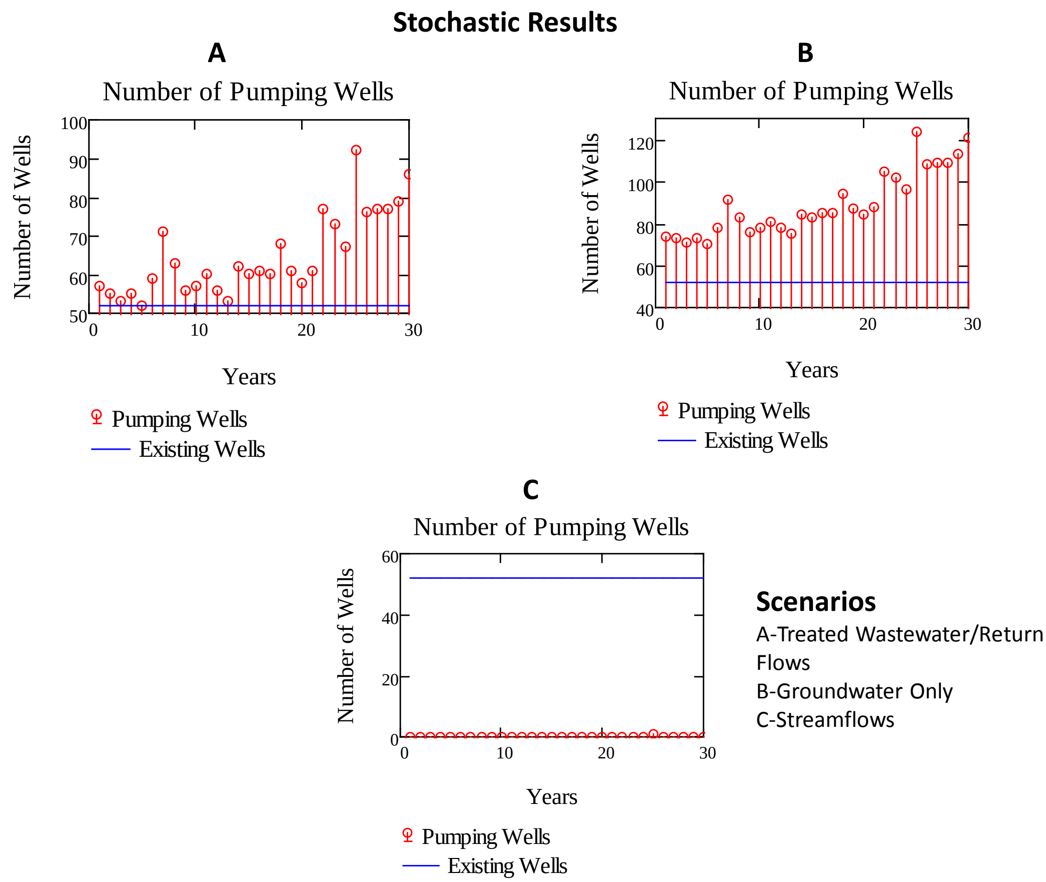


Figure 11. Number of Pumping Wells Using Stochastic Inputs for Each Scenario

A total of 86 pumping wells will be needed to meet demands in Scenario A. Therefore, 34 new wells will need to be installed over the course of the project period starting in the first year. In Scenario B, 121pumping wells will be needed to meet demands. A total of 69 new wells will need to be installed over the course of the project period starting the first year. No pumping wells will need to be installed in Scenario C.

The model predicts that more pumping wells will be needed in Scenario’s A and B using the stochastic inputs compared to using the deterministic inputs. A total of 67 pumping wells are needed in the deterministic version versus 86 wells in the stochastic version. This is a difference of 19 pumping wells. The demands are greater using the stochastic inputs in the model due to an increase in irrigation demands. Therefore, more pumping wells are needed to help meet these demands.

6.4.5 Number of ASR Wells

Figure 12 and Figure 13 present the number of ASR wells needed to meet injection demands using the deterministic and stochastic inputs in the model for each scenario.

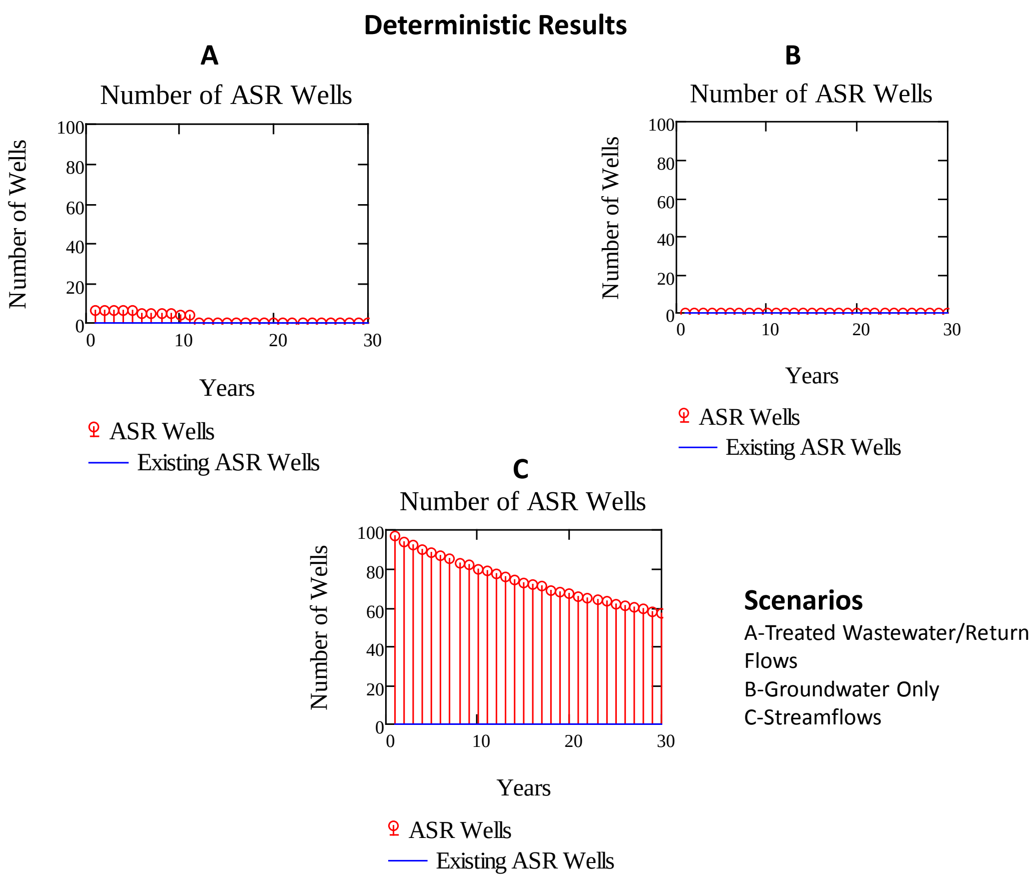


Figure 12. Number of ASR Wells using Deterministic Inputs for Each Scenario

In Scenario A, six ASR wells will need to be installed to meet injection demands. There is no water available to inject in Scenario B; therefore, ASR wells will not need to be installed. In Scenario C, 97 ASR wells will be needed to meet injection demands.

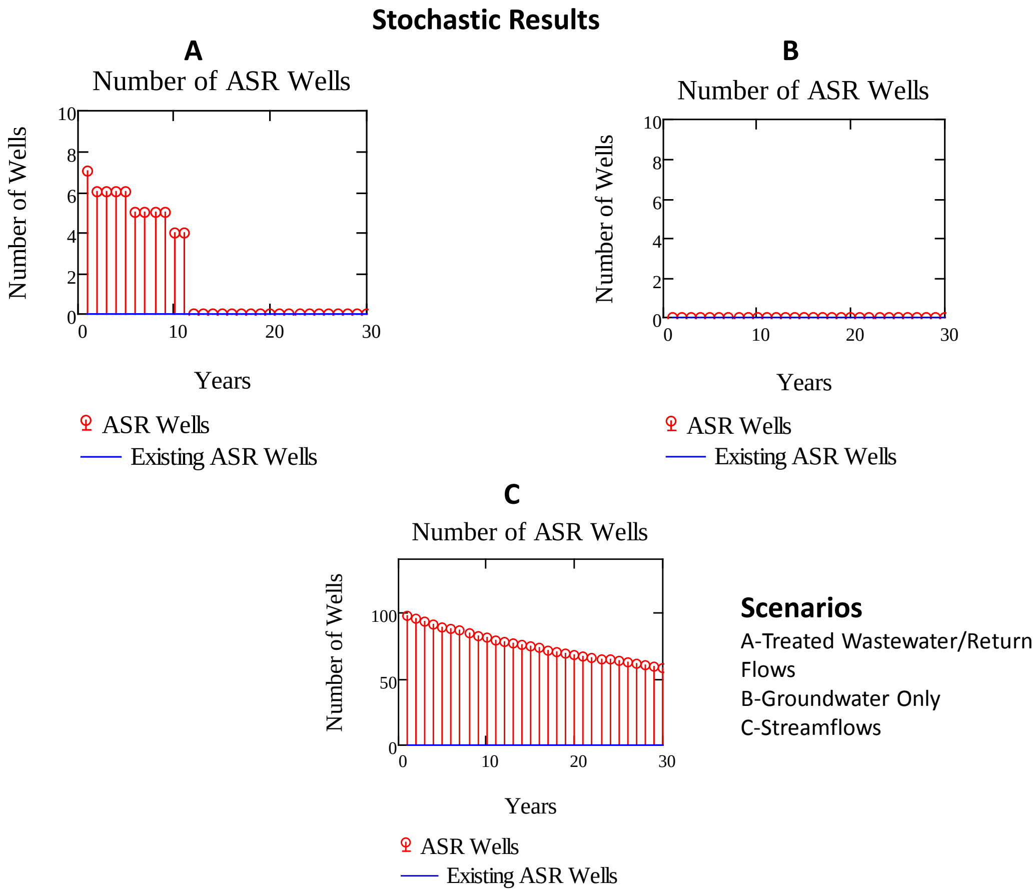


Figure 13. Number of ASR Wells using Stochastic Inputs for Each Scenario

In Scenario A, seven ASR wells will need to be installed to meet injection demands. There is no water available to inject in Scenario B; therefore, no ASR wells are needed. In Scenario C, a total of 97 ASR wells will need to be installed to meet injection demands.

The results obtained using both deterministic and stochastic inputs in the model do not differ, with the exception of Scenario A. In the deterministic version, six ASR wells are needed to meet injection demands versus seven ASR wells using the stochastic inputs. The same number of ASR wells are needed in Scenario C using the deterministic and stochastic inputs in the model.

6.4.6 Surface Reservoir Operations

Figure 14 and Figure 15 show the monthly surface reservoir storage for each scenario using deterministic and stochastic inputs.

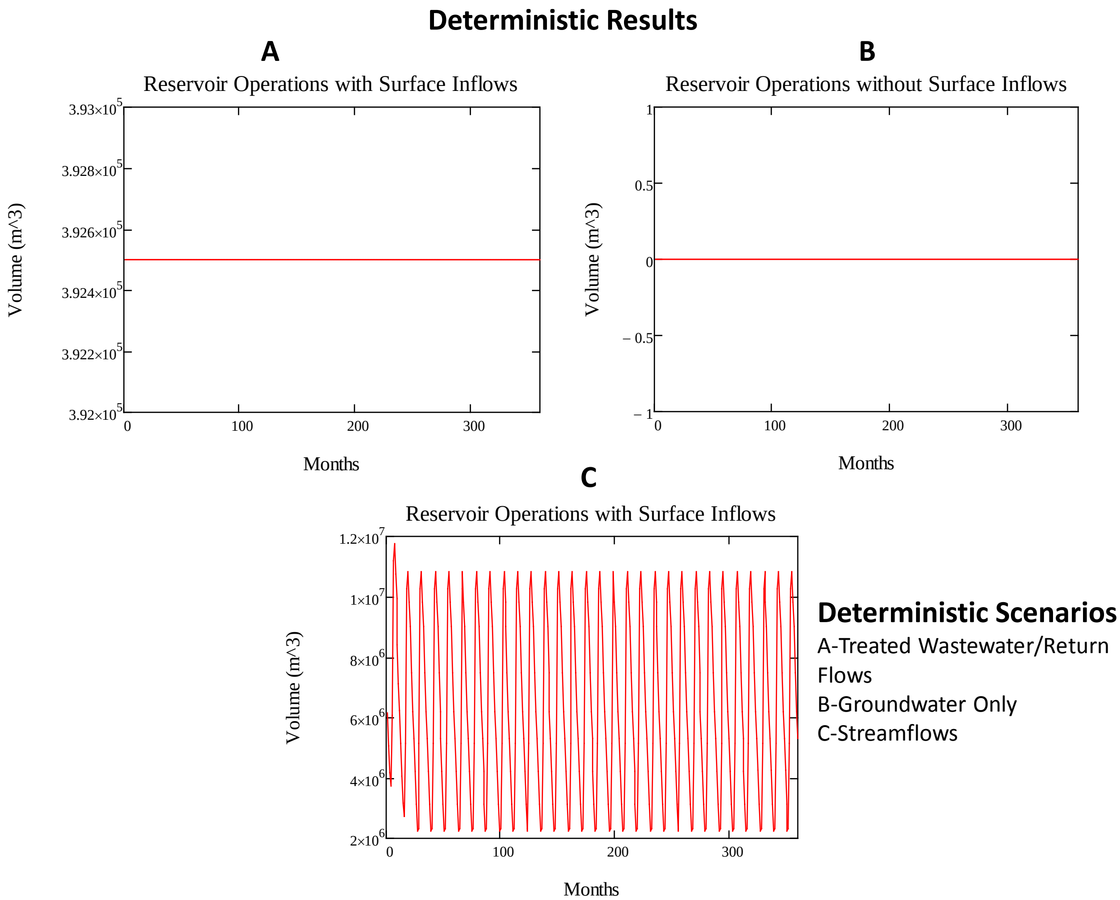


Figure 14. Monthly Surface Reservoir Storage for Each Scenario Using Deterministic Inputs

In Scenario A, the surface inflows are routed through a surface reservoir, but the water is not stored. It is conveyed directly to the SWTP because all of the water available is used to meet demands. There are no evaporative or seepage losses designated in the hydraulic input file because the water is not stored; therefore, the reservoir volume appears static and is equivalent to the volume of the inflow. In Scenario B, there are no surface inflows available because it is a ground-water only system. There is no surface water available for surface storage; therefore, the surface reservoir volume is zero. In Scenario C, there is surface water available to store from the Plum Creek. Figure 14 shows how the reservoir storage fluctuates based on the season (i.e. summer/fall vs. winter/spring). The largest reservoir volumes occur in the late spring/early summer when streamflows are highest (i.e. May or June). The reservoir volume is at its lowest in the late winter/early spring before run-off occurs (i.e. March) in most years. After approximately three years, the reservoir volumes equilibrate.

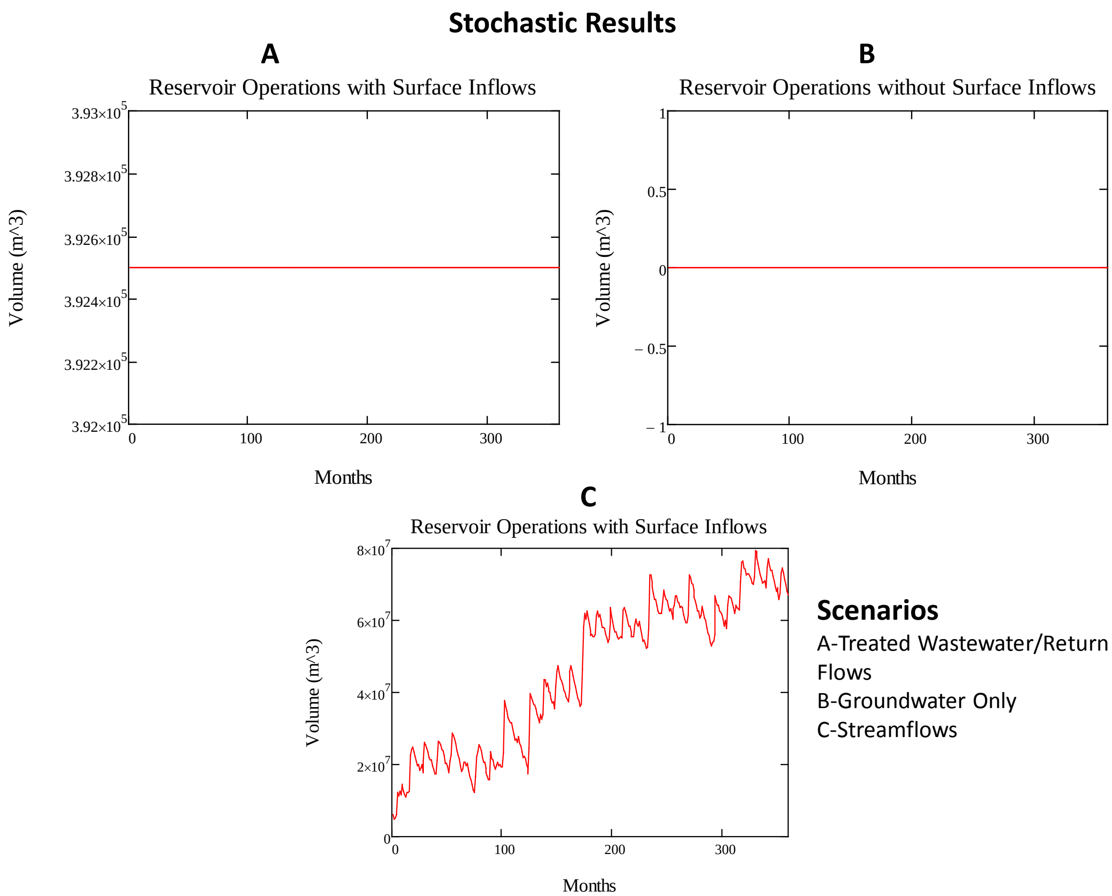


Figure 15. Monthly Surface Reservoir Storage for Each Scenario Using Stochastic Inputs

In Scenario A, the inflows to the reservoir are not variable. All of the inflows are used to meet demands, and therefore, there is no water available to store in a surface reservoir. The inflows are conveyed through a "reservoir," but they are immediately routed to the SWTP as discussed in the deterministic section above. There are no losses designated in the hydraulic input worksheet; therefore, the storage appears static and represents the volume of inflows conveyed to the SWTP on a monthly basis. In Scenario B, there is no surface water available because it is a groundwater-only system. The storage in the surface reservoir is zero as shown in Figure 15. In Scenario C, the inflows generated using stochastic inputs are greater than the demands in most months and the SWTP maximum capacity is less than what is available in the reservoir. As a result, the storage volume increases over time because the maximum volume available to take out of the reservoir in any given month is equivalent to the SWTP capacity.

In Scenario C, storage in the reservoir differs significantly depending on which version of the model is used. The results using stochastic inputs differ from the results using deterministic inputs because average monthly inflows are used in the deterministic inputs worksheet versus synthetic inflows in the stochastic inputs worksheet. The inflows using stochastic inputs are highly variable and are greater than the demands in most months. This causes the storage volume to increase over time. The average monthly inflows in the deterministic version also are greater than demands, but not as much as the synthetic inflows. This causes the reservoir volume to seasonally fluctuate, but not as drastically as the version using stochastic inputs because there is not as much water coming into the reservoir for storage.

6.4.7 Capital Costs

Figure 16 and Figure 17 present the annual capital costs associated with each scenario using deterministic and stochastic inputs.

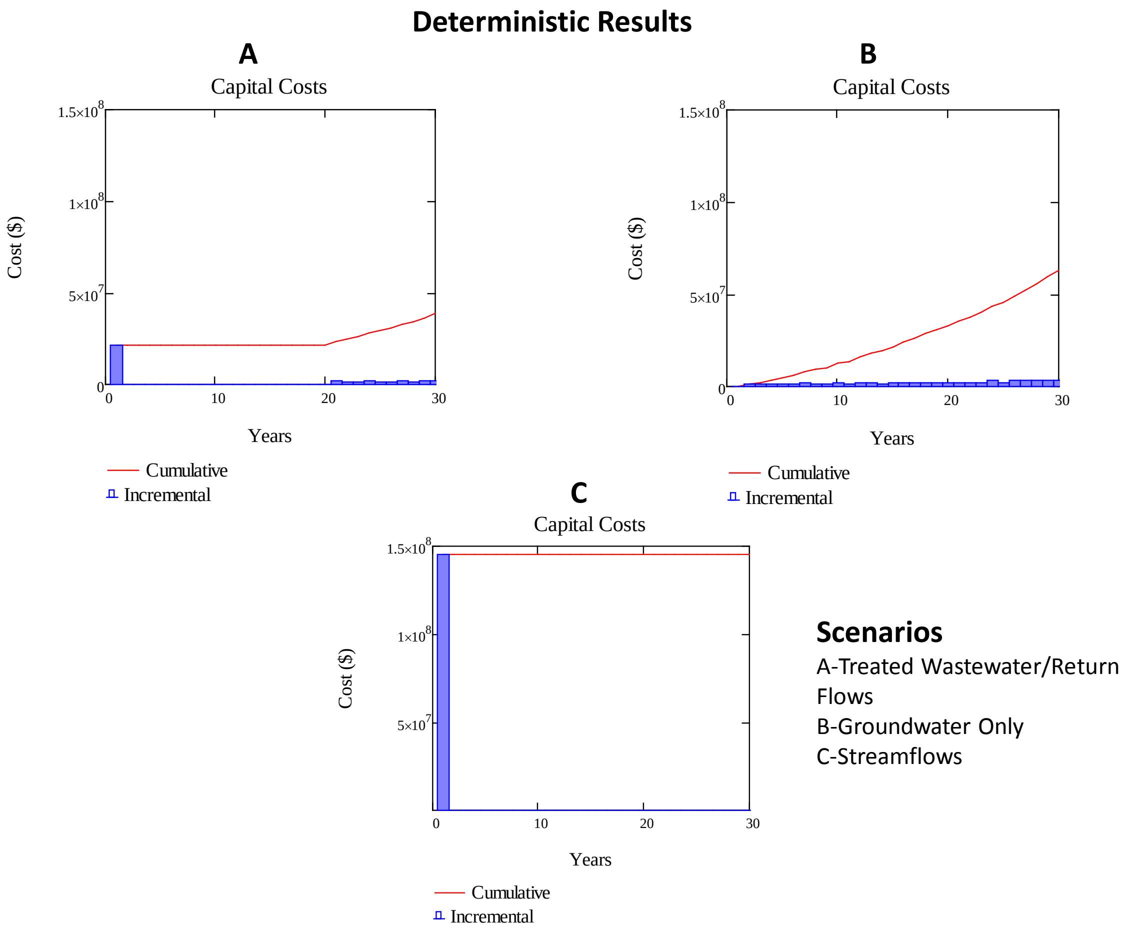


Figure 16. Annual Capital Costs for Each Scenario Using Deterministic Inputs

In Scenario A, the initial capital costs are highest in the first year due to the installation of new ASR wells and construction of a SWTP. The capital costs in the first year equal $21 million. There are no new capital costs until the 21st year of the project, which is the point in the planning period when new pumping wells are needed. Costs increase linearly as new wells are added. The cumulative capital cost at the end of the planning period is $38.5 million. In Scenario B, there are no capital costs in the first year because there are no new infrastructure requirements (i.e. new pumping wells) needed. New pumping wells are needed in the second year of the project, and subsequently, in every following year. The cumulative capital cost at the end of the planning period is $62.7 million. In Scenario C, all of the capital costs occur in the first year of the project because the maximum number of ASR wells for the entire project planning period need to be installed and a new SWTP and surface reservoir need to be constructed. The capital cost in the first year equals $145 million.

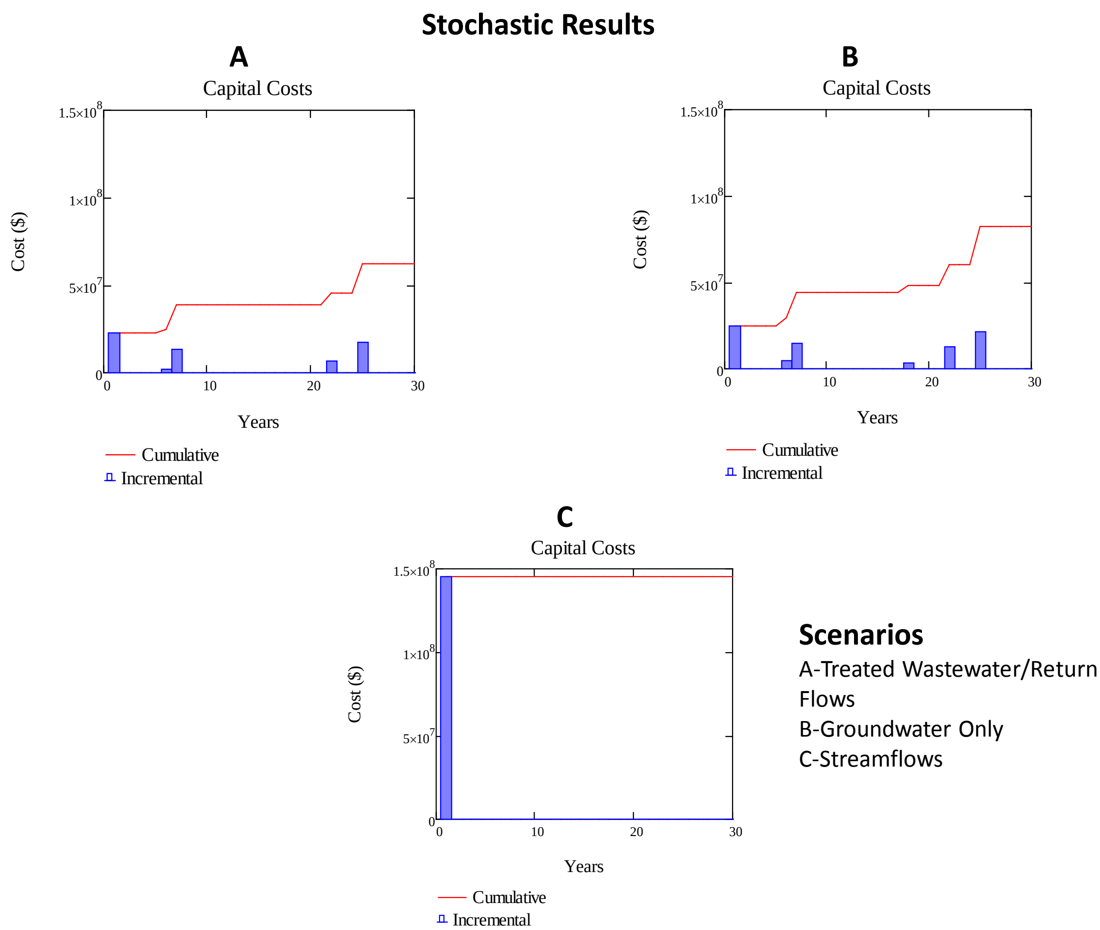


Figure 17. Annual Capital Costs for Each Scenario Using Stochastic Inputs

Using stochastic inputs in Scenario A, the capital costs in the first year are $22.7 million, which are associated with construction of new pumping and ASR wells in addition to construction of a small SWTP. New wells are added over the course of the project period, resulting in additional capital costs. The cumulative capital cost at the end of the project is $62.6

million. In Scenario B, the capital costs in the first year equal $25 million. New wells are added over the course of the project period, resulting in additional capital costs. The cumulative capital cost at the end of the project is $82 million. In Scenario C, all of the capital costs are incurred in the first year due to construction of the ASR wells needed to meet the maximum injection demands. The total capital costs for the project is $145 million.

The cumulative capital costs calculated using the stochastic inputs in the model are higher than the capital costs calculated using the deterministic inputs for Scenario's A and B (i.e. $38.5 million vs. $62.6 million and $63 million vs. $82 million, respectively). More wells are needed using the stochastic inputs in the model in both scenarios, thereby increasing the capital costs over the course of the project. The cumulative capital costs using both deterministic and stochastic inputs in the model are the same for Scenario C (i.e. both equal $145 million).

6.4.8 O&M Costs

Figure 18 and Figure 19 present the annual O&M costs associated with each scenario using deterministic and stochastic inputs.

Deterministic Results

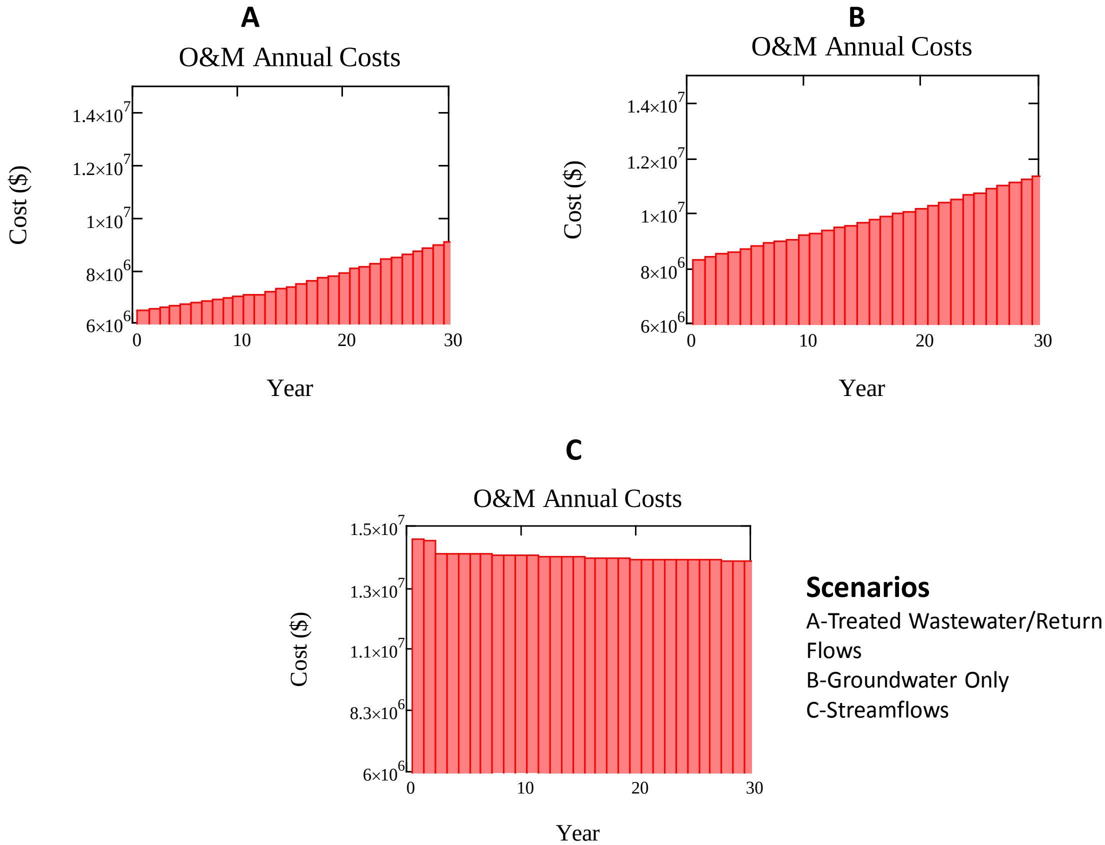


Figure 18. Annual O&M Costs for Each Scenario Using Deterministic Inputs

In Scenario A, O&M costs range from $6.4 million in the first year to $9 million in the 30th year (last year of the planning period). This is an increase of approximately $88,000/year over 30 years. In Scenario B, O&M costs range from $8.3 million in the first year to $11.3 million in the last year of the project. This is an increase of approximately $100,500/year over 30 years. In Scenario C, O&M costs slowly decrease over the course of the planning period because the injection volumes decrease. The O&M costs are $14.5 million in the first year and $13.7 million in the last year of the project. This is a decrease of approximately $27,000/year over 30 years. The O&M costs in Scenario B are 23% higher than Scenario A, due to the cost of pumping and treating groundwater. The O&M costs in Scenario C are significantly higher than Scenario A and B (i.e. 2.25 and 1.75 times higher, respectively) due to the treatment and reservoir maintenance costs.

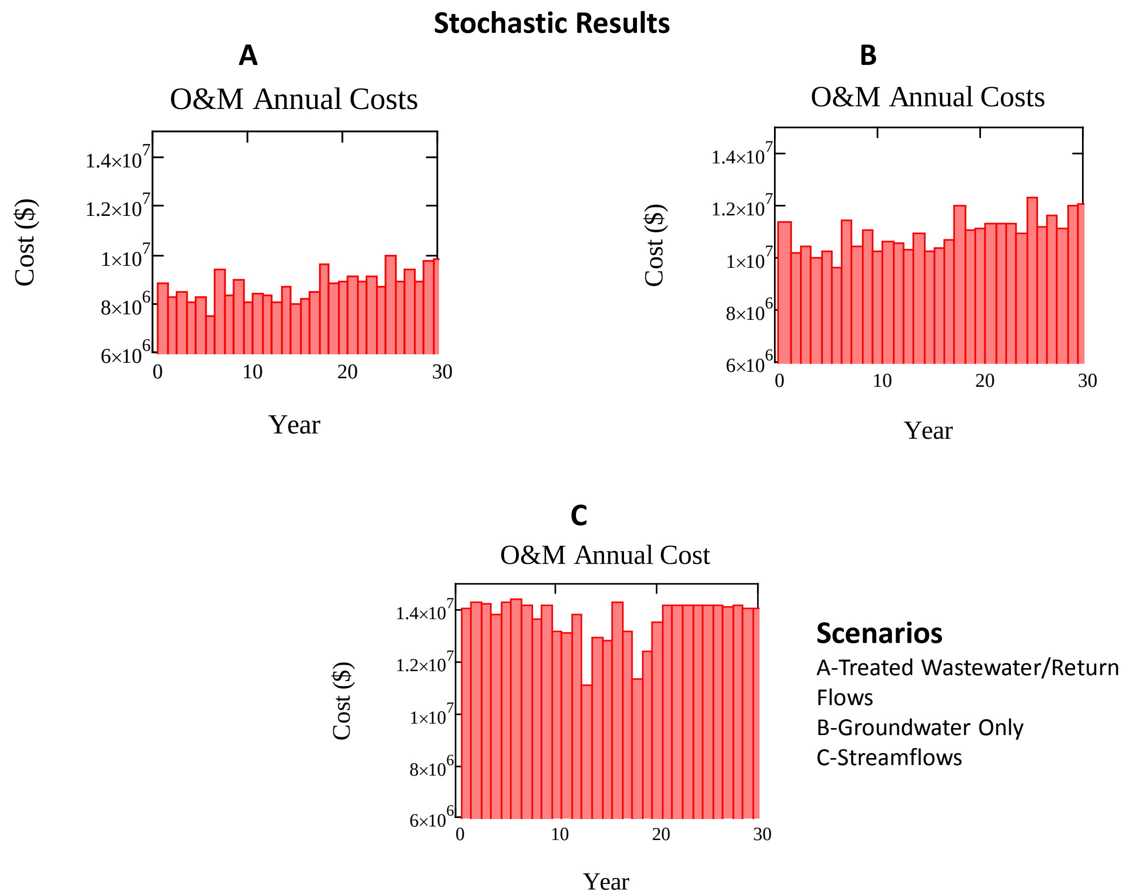


Figure 19. Annual O&M Costs for Each Scenario Using Stochastic Inputs

The annual O&M costs fluctuate between $7.5 million and $9.9 million using stochastic inputs under Scenario A. In Scenario B, the O&M costs fluctuate between $9.6 million and $12 million. In Scenario C, the O&M costs fluctuate between $11 million and $14 million.

The O&M costs using the stochastic inputs in the model do not differ significantly from the results obtained from the deterministic version. In Scenario A, the maximum O&M cost is $9 million using the deterministic inputs versus $9.9 million using the stochastic inputs. In Scenario B, the maximum O&M cost using the deterministic inputs is $11.3 million versus $12 million using the stochastic inputs. In Scenario C, the maximum O&M cost is $14.5 million using the deterministic inputs versus $14 million using the stochastic inputs.

6.4.9 Total and Life-Cycle Costs

Figure 20 and Figure 21 show the annual total costs associated with each scenario using deterministic and stochastic inputs. The total cost is the combination of the capital and O&M costs.

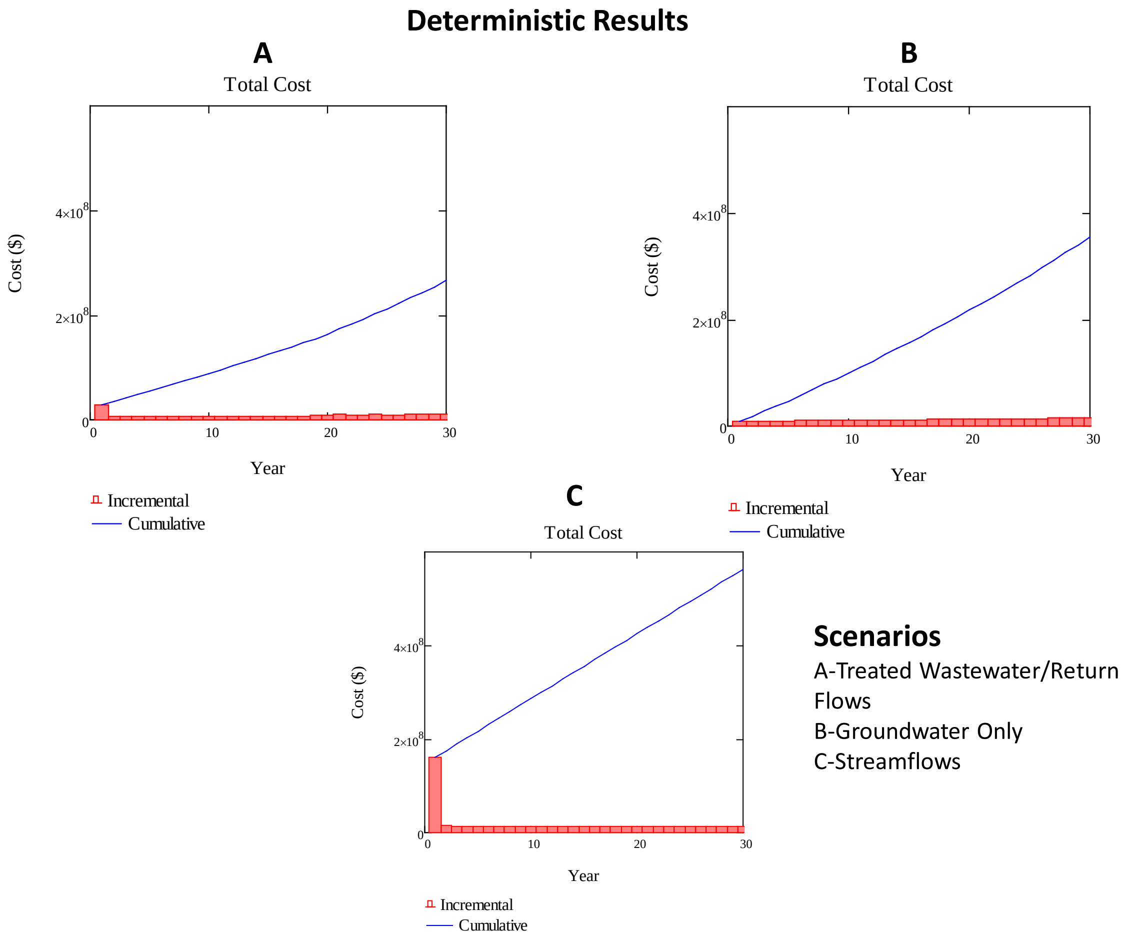


Figure 20. Annual Total Costs for Each Scenario Using Deterministic Inputs

The total annual costs (capital and O&M costs) range from $27.8 million in the first year to $11.3 million in the last year of the project. The total cost differs from the beginning of the project to the end of the project because most of the capital costs occur in the first year of the project. The cumulative total cost ranges from $27.8 million in the first year to $264 million at the end of the project. In Scenario B, the total annual costs range from $8.3 million in the first year to $14.8 million in the last year of the project. The total costs increase over the course of the project because new wells are added each year, resulting in higher capital and O&M costs. The cumulative total cost ranges from $8.3 million in the first year to $355 million in the last year of the project. In Scenario C, the total annual costs range from $160 million in the first year to $13.7 million in the last year of the project. The total annual costs decrease from the beginning of the project to the end of the project because all of the capital costs occur in the first year. The cumulative total costs range from $160 million to $562 million. The annual O&M costs for this scenario are high, due to the treatment and reservoir maintenance costs.

The life-cycle cost is the total cost of the project from the beginning to the end. The life-cycle cost for Scenario A is $264 million, $355 million for Scenario B, and $562 million for Scenario C. The life-cycle cost for Scenario B is $91 million more than Scenario A, which is a 26% increase in cost. Scenario C is more than double the cost of Scenario A (i.e. 2.12 times the cost) and 1.6 times the cost of Scenario B.

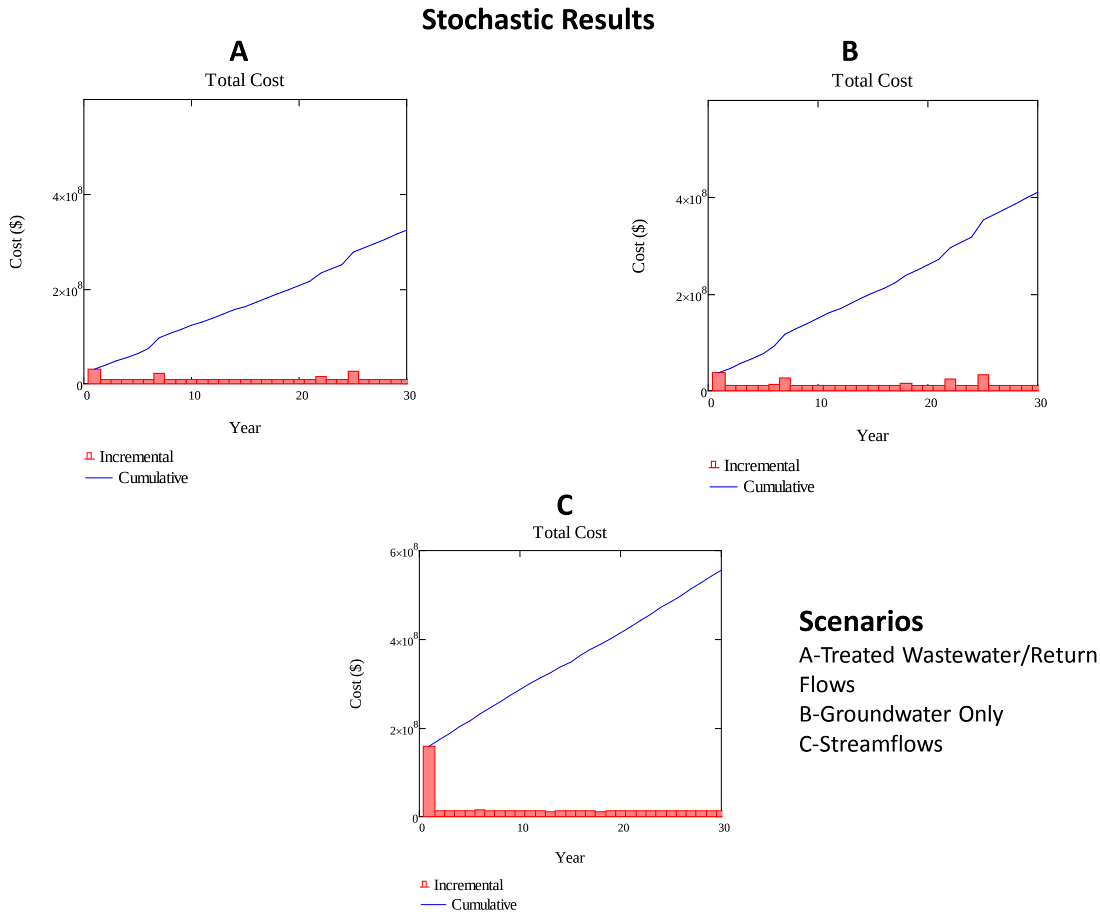


Figure 21. Annual Total Costs for Each Scenario Using Stochastic Inputs

The total annual cost for each scenario is the highest in the first year of the project due to new infrastructure costs. The total cost in the first year for Scenarios A, B, and C are $31.5 million, $36.5 million, and $160 million, respectively. The life-cycle cost for Scenarios A, B, and C are $324 million, $410 million, and $555 million, respectively.

The life-cycle costs are higher using the stochastic inputs in the model in Scenario's A and B compared to the deterministic results (18.5% and 13.4%, respectively). In Scenario A, the life-cycle cost using the deterministic inputs is $264 million versus $324 million using the stochastic inputs. In Scenario B, the life-cycle cost using the deterministic inputs is $355 million versus $410 million using the stochastic inputs. The life-cycle costs are lower (1.2%) using the stochastic inputs in the model in Scenario C ($555 million) versus the deterministic version ($562 million).

6.4.10 Present Value

Figure 22 and Figure 23 present the annual present value costs for each scenario using deterministic and stochastic inputs.

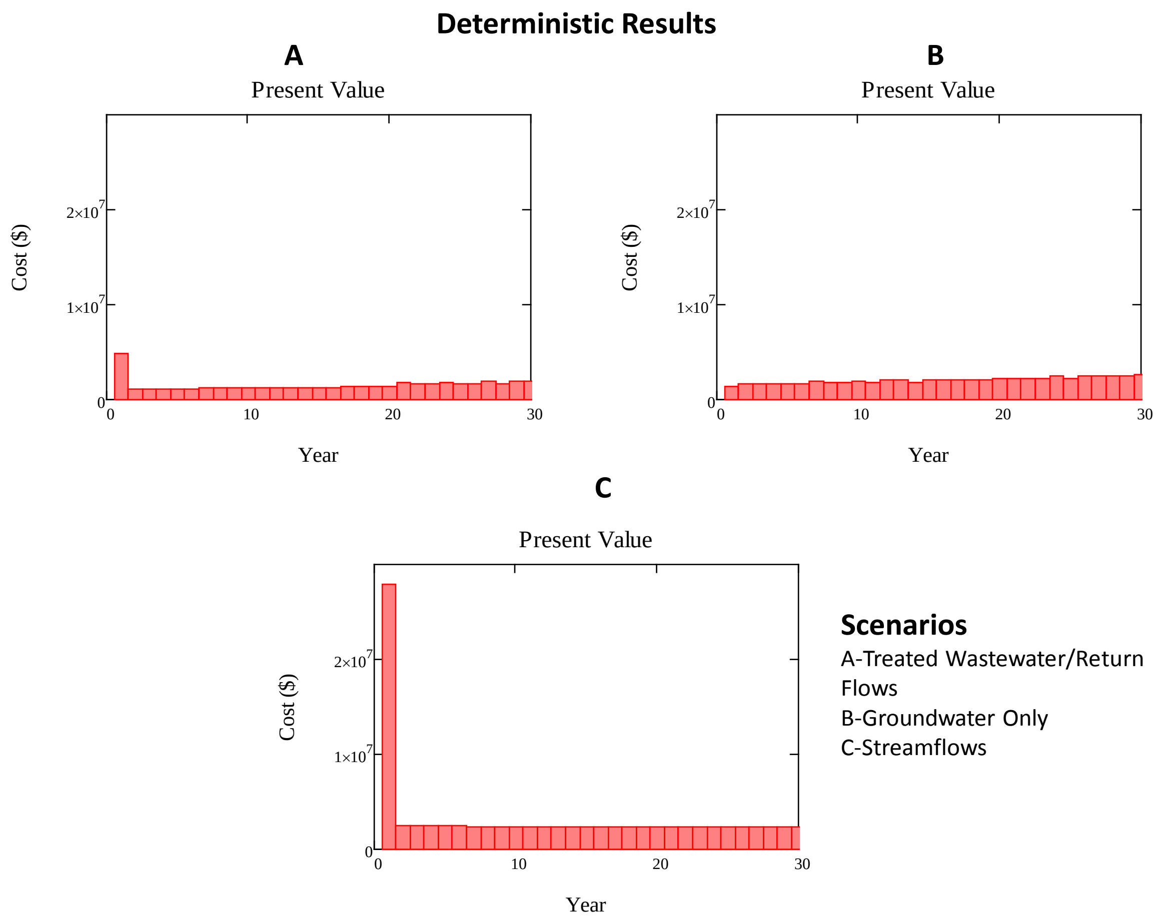


Figure 22. Annual Present Value Cost for Each Scenario Using Deterministic Inputs

The annual present value ranges from \$4.8 million in the first year to \$2 million in the last year of the project in Scenario A. Most of the capital costs occur in the first year resulting in the difference between the costs in the first and last year of the project. In Scenario B, the annual present value ranges from \$1.5 million in the first year to \$2.6 million in the last year of the project. In Scenario C, the annual present value ranges from \$27.9 million in the first year of the project to \$2.4 million in the last year of the project. Most of the capital costs occur in the first year resulting in the large discrepancy between the costs in the first and last year of the project.

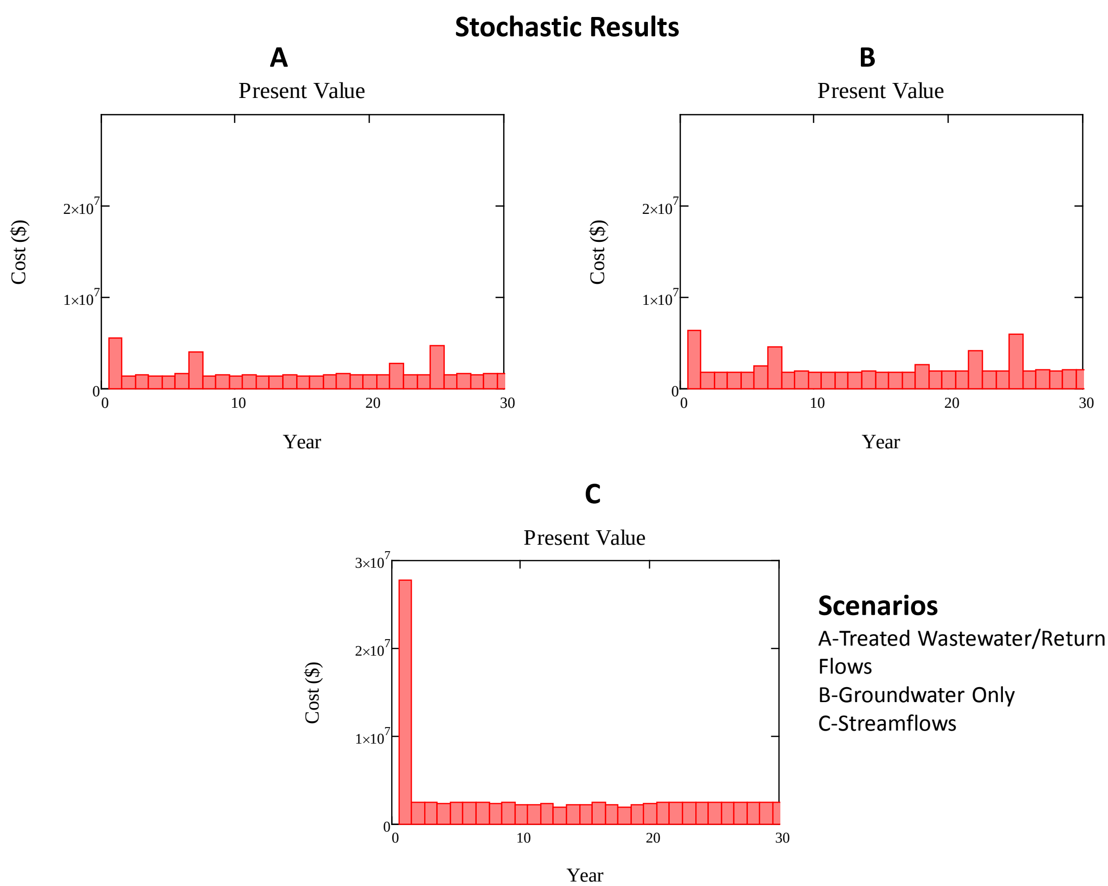


Figure 23. Annual Present Value Costs for Each Scenario Using Stochastic Inputs

Using stochastic inputs in Scenario A, the annual present value ranges from \$1.4 million to \$5.5 million. In Scenario B, the annual present value ranges from \$1.7 million to \$6.35

million. In Scenario C, the annual present value ranges from $1.9 million to $27.8 million. The largest present value occurs in the first year of the project in all of the scenarios due to new infrastructure costs.

The results from the stochastic inputs do not differ significantly from using the deterministic inputs, with the exception of Scenario B. In Scenario A, the maximum present value using deterministic inputs is $4.8 million versus $5.5 million using the stochastic inputs. In Scenario B, the maximum present value in the deterministic version is $2.6 million versus $6.35 million in the version using stochastic inputs. In Scenario C, the maximum present value in the deterministic version is $27.9 million versus $27.8 million.

6.4.11 Comparison of Life-Cycle Costs and Total Groundwater Pumping/Injection Volumes

Table 11 and Figure 24 and Figure 25 present a comparison of the life-cycle cost and cumulative groundwater pumping or injection volumes for each scenario using deterministic and stochastic inputs. The results compared in the table and figures are important because they can be used to determine what the least-cost and most sustainable water-use option is available.

Table 11. Comparison of Different Water Supply System Options for the Town of Castle Rock

Water Scenario	Groundwater Pumping/Injection (m^3)		Total Life-Cycle Cost ($)	
	Deterministic	Stochastic	Deterministic	Stochastic
A-Combined Source-with Treated Wastewater/Return Flows	118,600,000	158,400,000	$264,334,626	$324,217,237
B-Groundwater Only	264,300,000	304,200,000	$355,503,183	$410,420,830
C- Streamflows	-495,700,000	-480,600,000	$562,399,496	$555,663,332

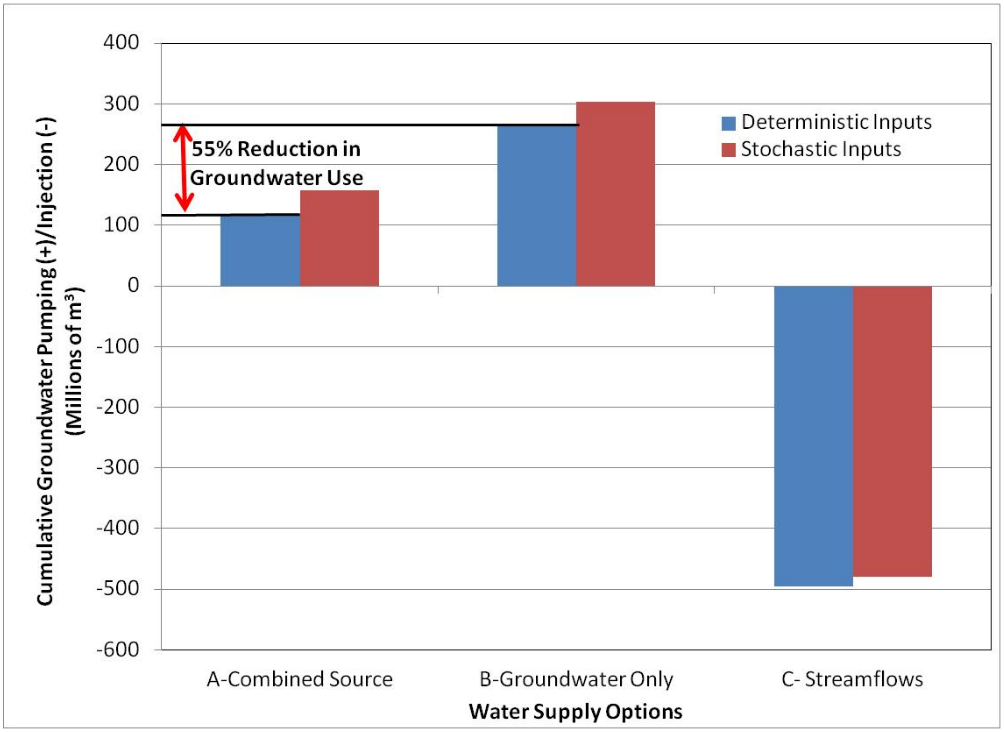


Figure 24. Comparison of Different Water Supply System Options-Cumulative Groundwater Volume Extracted or Injected

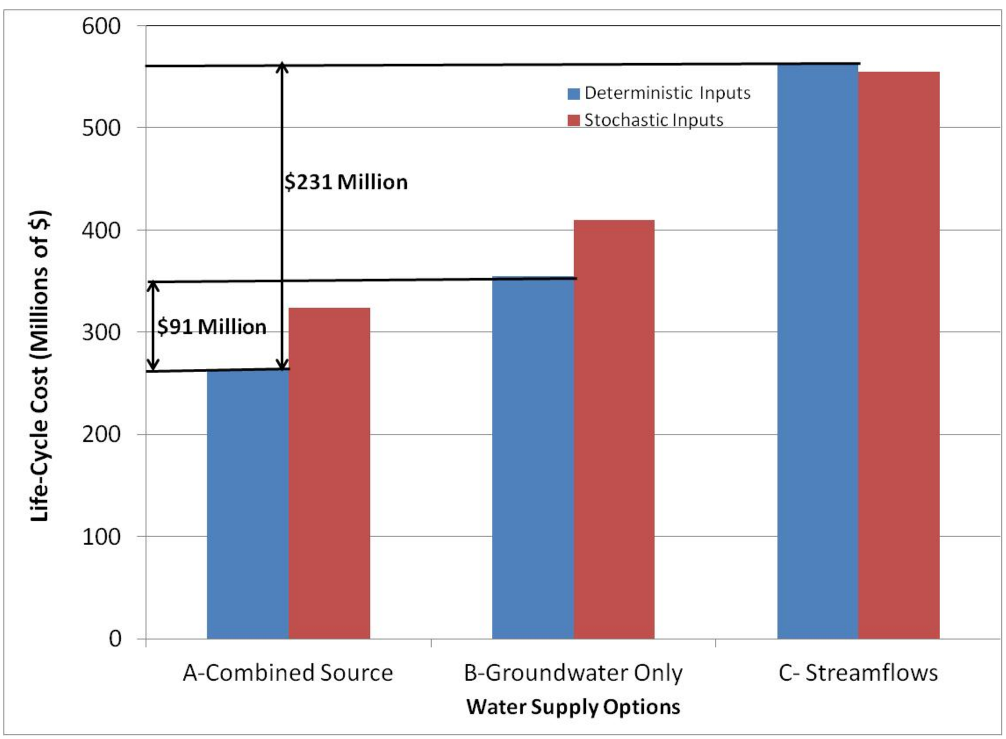


Figure 25. Comparison of Life-Cycle Costs of Different Water Supply System Options

Based on the comparison between scenarios shown in Table 11 and Figure 24 and Figure 25, Scenario A is the least cost option using both the deterministic and stochastic inputs in the model. In addition, Scenario A reduces groundwater extraction by 55% compared to Scenario B. Scenario C is not a realistic option because all of the natural flows in Plum Creek are adjudicated to other users. The model run was performed to show an injection-only system.

6.5 Model Validation with O&M Costs

Castle Rock provided capital and O&M cost data for 2010 in order to validate the results from the groundwater-only model run. In 2010, Castle Rock spent approximately $6.2 million on O&M. This included costs for field service, well and water distribution system maintenance, water treatment plant operations, SCADA operations, and water system upgrades. In comparison, deterministic model results using groundwater-only inputs, indicate that annual O&M costs based on the current Castle Rock population total $8.325 million. The model costs are approximately 34% greater than the actual costs. Castle Rock 2010 capital costs were not compared to model capital costs because Castle Rock did not construct any ASR wells in 2010, which contributes to most of the initial capital costs shown in the model results. The cost differences are attributed to over-estimations of O&M costs provided by Castle Rock that were used as inputs in the model.

6.6 Sizing of Infrastructure

An analysis was performed by running the streamflow model (Scenario C) using various SWTP sizes and deterministic inputs to determine if there was a size option that yielded the least life-cycle cost, while minimizing the depletion of groundwater. It was assumed that a plot of cost vs. SWTP size and cumulative groundwater pumping/injection volume vs. SWTP size could be used to resolve cost as a function of depleted groundwater. For example, if a user was willing to deplete a certain volume of groundwater in the aquifer given a specific SWTP size, the plot could be used to determine the life-cycle cost of the project. One of the three variables (i.e. SWTP size, life-cycle cost, or cumulative groundwater pumping volume) needs to be constrained by the user in order to determine the most optimal (i.e. least-cost) option given the needs and limitations of the system being evaluated.

Available inflows affect the size of the reservoir and the size of SWTP. Using the streamflow inputs shows how the model responds to changes in infrastructure more distinctly than the model with treated wastewater and return flows because the inflows are greater. The model was run using different SWTP sizes that were based on a percentage of the maximum demand. For example, the maximum monthly demand in the 30-year planning horizon was calculated to be 1,730,000 m^3. The maximum SWTP monthly capacity was designated as the maximum monthly demand for the 100% capacity model run. The SWTP sizes were allocated based on the following capacities:

- 100% of Demands
- 80% of Demands
- 60% of Demands
- 50% of Demands
- 40% of Demands
- 20% of Demands

Table 12 shows the results of the model runs. Figure 26 shows the life-cycle cost vs. SWTP size and cumulative groundwater pumping/injection volumes.

Table 12. Comparison of Optimization Model Runs

SWTP Capacity (% of Demands)	Cumulative Groundwater Pumping(+)/Injection (-) Volume (m^3)	Life-Cycle Cost ($)
100%	-358,500,000	$492,298,174
80%	-233,900,000	$400,948,853
60%	-109,300,000	$329,363,056
50%	-47,070,000	$298,421,971
40%	15,210,000	$272303593
20%	139,800,000	$240,463,797

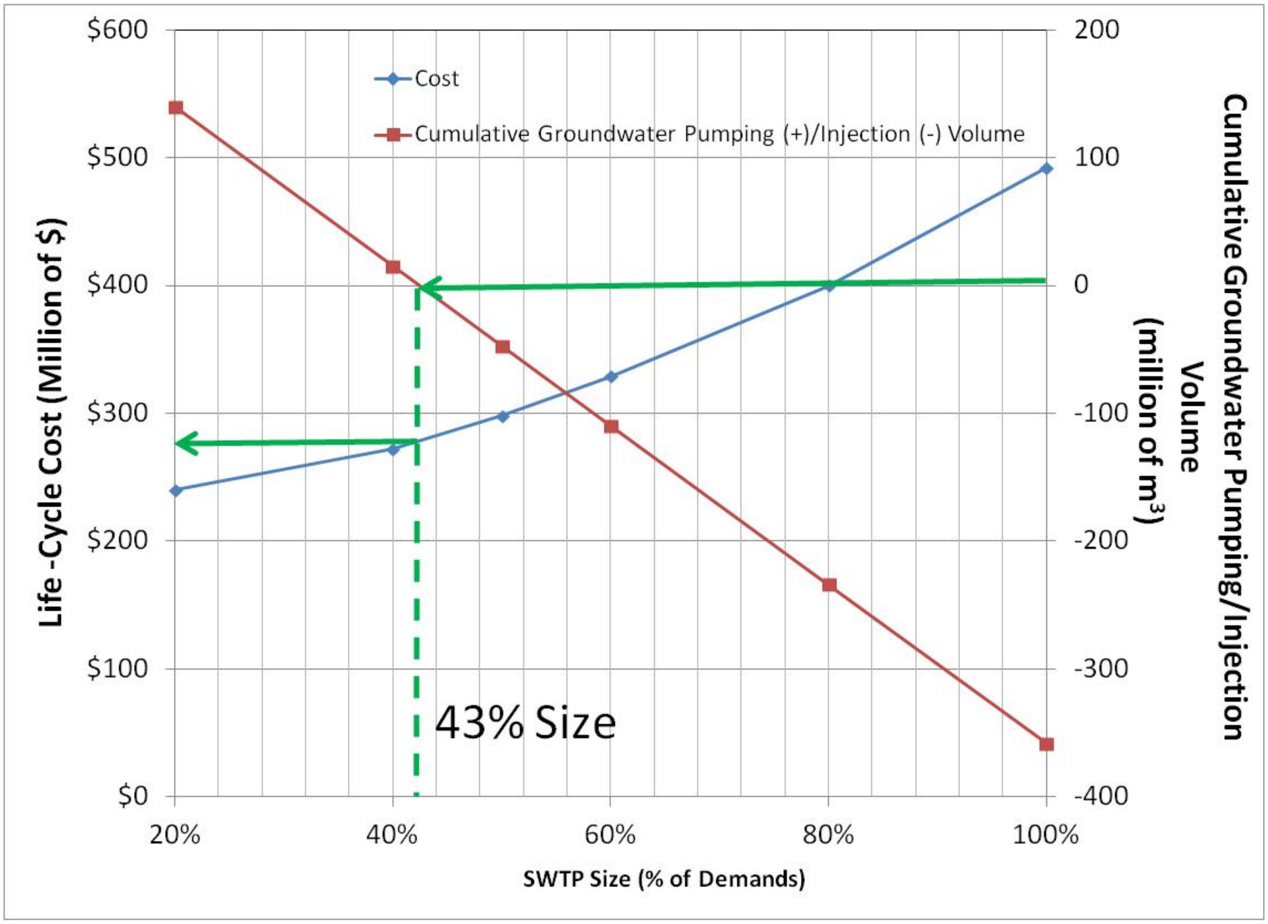


Figure 26. Comparison of SWTP Capacity vs. Groundwater Pumping/Injection Volumes and Cost

Figure 26 shows that as the SWTP size increases, the cost increases and the cumulative groundwater pumping volume decreases. As an example, the graph can be used to determine what size the SWTP would be if a user wanted to limit groundwater depletions. In the example shown in Figure 26, the SWTP size would be 43% of maximum demands if net groundwater depletions are zero. Consequently, the life-cycle cost for the project with zero net groundwater depletions would be approximately $280 million.

6.7 Groundwater Pumping Penalty

The model is designed to decrease the well pumping rate as the amount of recoverable water in the aquifer decreases. The loss in groundwater production over time is a function of the amount of recoverable water in the aquifer and the amount of water extracted from the aquifer over the course of the project. The following equation, which is shown in Table 6 (Equation (15)) was used to determine the well pumping capacity (with a decline in capacity) in each well over time:

$$Well\ Capacity = \left(1 - \frac{\mathrm{Cum_Q(Annual_Q)}}{Vol\_Recoverable_{GW}}\right) * Max_{\mathrm{QRate}} \quad (47)$$

Where:

$\mathrm{Cum_Q(Annual_Q)}$ = The total amount of groundwater extracted per year (m^3/year)
$\mathrm{Vol\_Recoverable_{GW}}$ = The total amount of recoverable groundwater in the aquifer (m^3)
$\mathrm{Max_{QRate}}$ = Average monthly pumping volume based on the pumping rate (m^3/month)

The well pumping rate is used to calculate the number of pumping wells needed to meet demands. If the well pumping rate or well capacity decreases, the number of wells needed to meet demands will increase. The penalty for pumping excess groundwater occurs when the cost for installing new wells becomes exorbitant. The model was run using the groundwater-only scenario (Scenario B) at 100% and 50% of recoverable water availability in the aquifer to show the effects of applying a pumping penalty. Application of a pumping penalty is important because it shows how the aquifer responds as water availability in the aquifer decreases. Figure

27 presents the number of pumping wells needed to meet demands and the life-cycle cost for each model run.

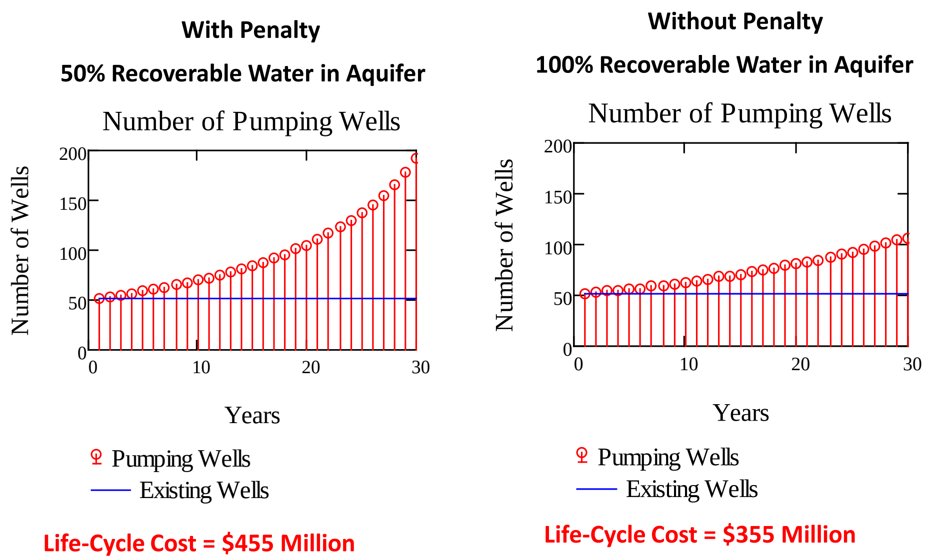


Figure 27. Number of Pumping Wells with and without Groundwater Penalty

If a pumping penalty is applied, 192 pumping wells will be needed to meet demands over 30 years. If there is no penalty, 107 wells will be needed to meet demands. This is a difference of 85 wells. As the number of wells increase, the total cost of the project also increases. The life-cycle cost is $455 million with the penalty and $355 million without the penalty. This is a difference of $100 million, which is a significant increase in cost over the life-span of the project.

7 CONCLUSIONS AND RECOMMENDATIONS

The CSIAM is a decision programming model designed to 1) resolve infrastructure components in a combined source water system, and 2) develop costs of a combined source water system. Results from the Castle Rock model applications indicate that the model is capable of calculating reasonable life-cycle costs for various water supply options. More importantly, the model illustrates the benefits of using a combined source water system in terms of cost. Specifically, use of both groundwater and treated wastewater/returns flows (Scenario A) is $91 million and $231 million less than a groundwater-only (Scenario B) system and streamflow-only (Scenario C) system, respectively. Furthermore, the use of groundwater and treated wastewater/returns flows reduces groundwater depletion by 55%, relative to a groundwater-only system. Both deterministic and stochastic inputs are used in the model, wherein the principle stochastic input is urban irrigation demands. The differences between the results vary depending on the use of deterministic or stochastic inputs. In general, the model using stochastic inputs leads to a need for infrastructure with greater capacities and higher costs. For example, the life-cycle costs calculated using the stochastic inputs in the model in Scenario's A and B are higher (18.5% and 13.4%, respectively) than the deterministic version, but less than (1.2%) the life-cycle costs calculated in Scenario C. While stochastic inputs lead to higher costs, it follows that it would also lead to greater reliability. The CSIAM has the potential to be used as a planning tool to help determine the most optimal capacity of infrastructure components associated with combined source systems that minimize costs and maximize water supply reliability. An example of this is shown in the infrastructure sizing application where different SWTP sizes are tested to show how cost is a function of groundwater depletion. The CSIAM can be used to compare direct costs of developing combined source water systems. If ASR is an option, the model can be used to estimate the number of ASR wells that will be needed to meet injection volumes in addition to the capital, O&M, life-cycle and present value costs of the system.

Additional favorable attributes of the combined source with treated wastewater/return flow scenario include:

Relative to a Groundwater-Only System

- Aquifers work better when they are full.
- Longevity of aquifers as a primary water source is an issue as demands increase.

Relative to a Surface Water-Only System

- Absence of up-front costs (i.e. large reservoir construction costs, water treatment plant expansion, etc.).
- Minimization of evaporative and seepage losses because the size of surface water reservoirs can be reduced.
- Reduced environmental impacts from smaller surface reservoir construction projects.
- Deferred expansion of water facilities.
- Drought protection- more reliable seasonal, long term and emergency storage with a combined source system. Groundwater can be used to offset demands if surface water is not available during droughts.
- Absence of evapo-concentration of salts in surface reservoirs.

The CSIAM shows how different water source options can improve aquifer sustainability through either 1) a reduction in overall pumping and/or 2) groundwater storage through ASR systems. This has large benefits in terms of decreasing groundwater overdraft and improving aquifer sustainability. This model differs from other conjunctive use hydro-economic models in that it can be used to determine the necessary infrastructure and costs of developing combined source water systems for a variety of different water supply options. The model can be used as a planning tool to develop combined source systems and determine if ASR programs are feasible from a supply and cost perspective.

Recommendations for further work include the following:

- Refinement of Inflows-The model needs to be refined to accommodate multiple types of inflows. Currently, inflows have to be aggregated in the hydraulic inflow file and costs for treatment are the same regardless of the surface source. This is important because different types of inflows may be available to a user (i.e. treated wastewater and raw surface water). The inflows may have different costs associated with treatment; therefore, these costs will need to be allocated in the model based on the source.
- Optimization-An optimization routine needs to be added to the model. An objective function with constraints needs to be developed that is capable of minimizing costs while simultaneously maximizing reliability of the system.
- Coupled Analytical Model-It would be useful if the model was coupled with an analytical groundwater model that could simulate the aquifer response when different pumping/injection schemes are applied. This is important when evaluating the hydrogeologic effects that pumping or injection may have on an aquifer.

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Appendix A: Probability Density Function Examples for Streamflow, Pan Evaporation and Irrigation Consumptive Use

Evaporation (August) Density Function

dbeta(x, s1, s2) Returns the probability density for value x.

$N := 100$

$s1 := 45$

$s2 := 25$

$$XX(s1,s2,N) := \left| \begin{array}{l} \text{for } i \in 1..N-1 \\ \quad \left| \begin{array}{l} XX_{i,1} \leftarrow \left(\text{dbeta}\left(\frac{i}{N}, s1, s2\right)\right) \\ XX_{i,2} \leftarrow \frac{i}{N} \end{array} \right. \\ XX \end{array} \right.$$

$YY := XX(s1,s2,N)$

$i := 1..N$

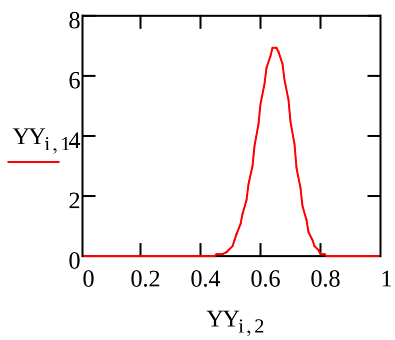

Figure A1.

$j := 1..20$

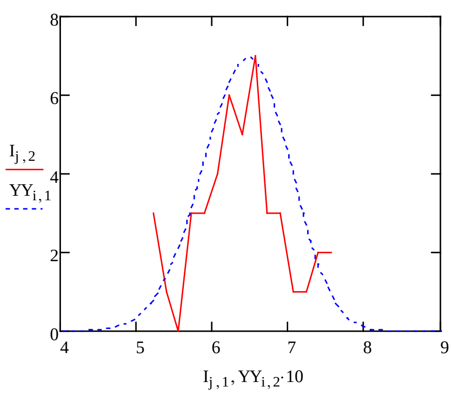

Figure A2.

$N_{years} := 30$

$i := 1..\, N_{years}$

$YY := \mathrm{rbeta}\left(N_{years}, s1, s2\right) \cdot 10$

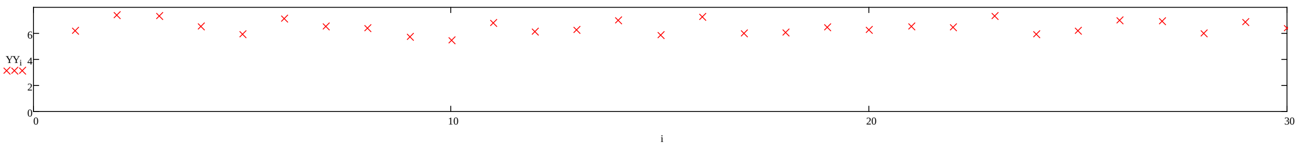

Figure A3.

Irrigation (August) Density Function

dbeta(x, s1, s2) Returns the probability density for value x.

$N := 100$

$s1 := 50$

$s2 := 73$

$$XX(s1,s2,N) := \left| \begin{array}{l} \text{for } i \in 1..N-1 \\ \quad \left| \begin{array}{l} XX_{i,1} \leftarrow \left(\text{dbeta}\left(\frac{i}{N}, s1, s2\right)\right) \\ XX_{i,2} \leftarrow \frac{i}{N} \end{array} \right. \\ XX \end{array} \right.$$

$YY := XX(s1,s2,N)$

$i := 1..N$

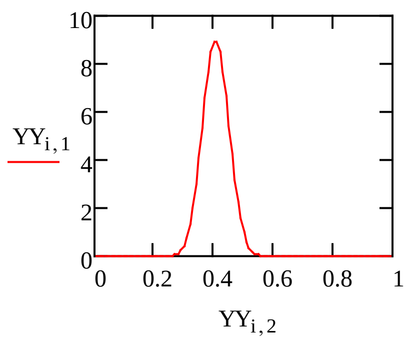

Figure A4.

$j := 1..10$

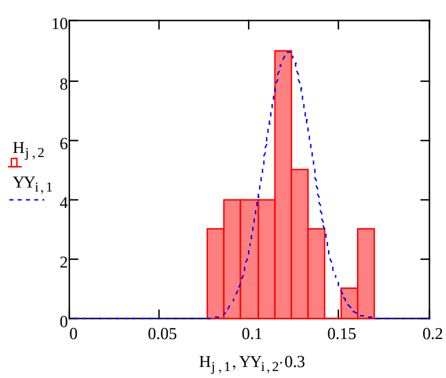

Figure A5.

Note : All values are in inches

$$August := \begin{pmatrix} 4.07 \\ 4.33 \\ 4.72 \\ 4.31 \\ 4.96 \\ 3.4 \\ 5.07 \\ 3.89 \\ 5.02 \\ 4.69 \\ 4.57 \\ 4.93 \\ 5.47 \\ 5.2 \\ 5.36 \\ 4.57 \\ 4.74 \\ 4.84 \\ 4.74 \\ 3.77 \\ 6.13 \\ 3.99 \\ 4.9 \\ 6.78 \\ 5.59 \\ 6.47 \\ 3.07 \\ 3.96 \\ 4.54 \\ 6.43 \\ 3.31 \\ 3.64 \\ 3.56 \\ 4.49 \\ 3.54 \\ 4.66 \end{pmatrix}$$

$$August_m := August \cdot 0.025$$

$H := \mathrm{histogram}(10, August_m)$

$August_m =$

	1
1	0.102
2	0.108
3	0.118
4	0.108
5	0.124
6	0.085
7	0.127
8	0.097
9	0.125
10	0.117
11	0.114
12	0.123
13	0.137
14	0.13
15	0.134
16	...

$H =$

	1	2
1	0.081	3
2	0.091	4
3	0.1	4
4	0.109	4
5	0.118	9
6	0.128	5
7	0.137	3
8	0.146	0
9	0.156	1
10	0.165	3

$N_{years} := 30$

$i := 1 .. N_{years}$

$YY := \mathrm{rbeta}(N_{years}, s1, s2) \cdot 15$

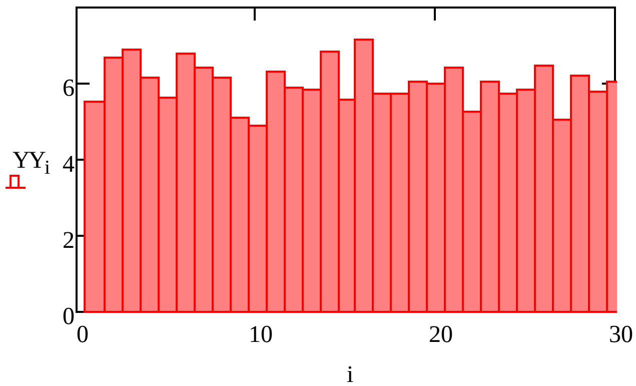

Figure A6.

Streamflow Density Function

dbeta(x, s1, s2) Returns the probability density for value x.

$N := 100$

$s1 := 2$

$s2 := 12$

$$XX(s1,s2,N) := \left| \begin{array}{l} \text{for } i \in 1..N-1 \\ \quad \left| \begin{array}{l} XX_{i,1} \leftarrow \left(\text{dbeta}\left(\frac{i}{N}, s1, s2\right)\right) \\ XX_{i,2} \leftarrow \frac{i}{N} \end{array} \right. \\ XX \end{array} \right.$$

$YY := XX(s1,s2,N)$

$i := 1..N$

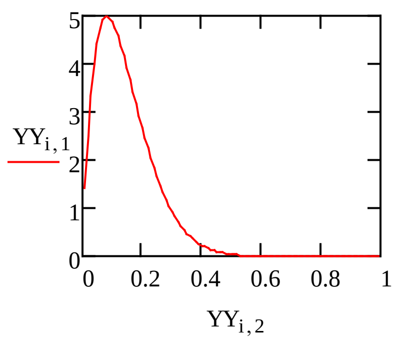

Figure A7.

$j := 1..40$

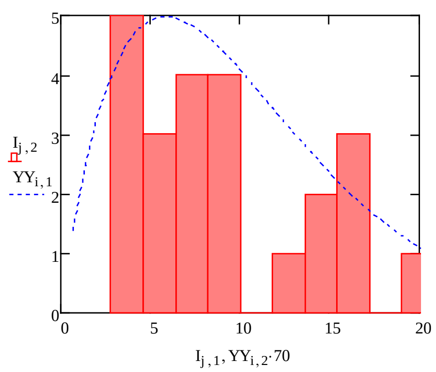

Figure A8.

Note : the annual inflows in cfs are from Plum Creek at Sedalia, CO from USGS

$$\text{Annual} := \begin{pmatrix} 156.28 \\ 566.48 \\ 333.69 \\ 127.06 \\ 180.51 \\ 345.69 \\ 163.118 \\ 233.314 \\ 444.97 \\ 119.97 \\ 222.55 \\ 592.94 \\ 592.8 \\ 300.79 \\ 205.16 \\ 99.41 \\ 275.64 \\ 304.5 \\ 536.42 \\ 244.57 \\ 743.2 \\ 273.47 \\ 515.3 \end{pmatrix}$$

$$\text{Annual}_m := \text{Annual} \cdot (0.028)$$

$$I := \text{histogram}(10, \text{Annual}_m)$$

I =

	1	2
1	3.685	5
2	5.487	3
3	7.29	4
4	9.093	4
5	10.895	0
6	12.698	1
7	14.5	2
8	16.303	3
9	18.106	0
10	19.908	1

$\text{Annual}_m =$

	1
1	4.376
2	15.861
3	9.343
4	3.558
5	5.054
6	9.679
7	4.567
8	6.533
9	12.459
10	3.359
11	6.231
12	16.602
13	16.598
14	8.422
15	5.744
16	...

$i := 1 .. N_{years}$

$N_{years} := 30$

$YY := \text{rbeta}\left(N_{years}, s1, s2\right) \cdot 70$

YY =

	1
1	28.614
2	8.664
3	19.225
4	10.262
5	1.067
6	2.815
7	23.304
8	6.197
9	4.525
10	6.639
11	12.109
12	4.958
13	8.928
14	4.162
15	4.026
16	...

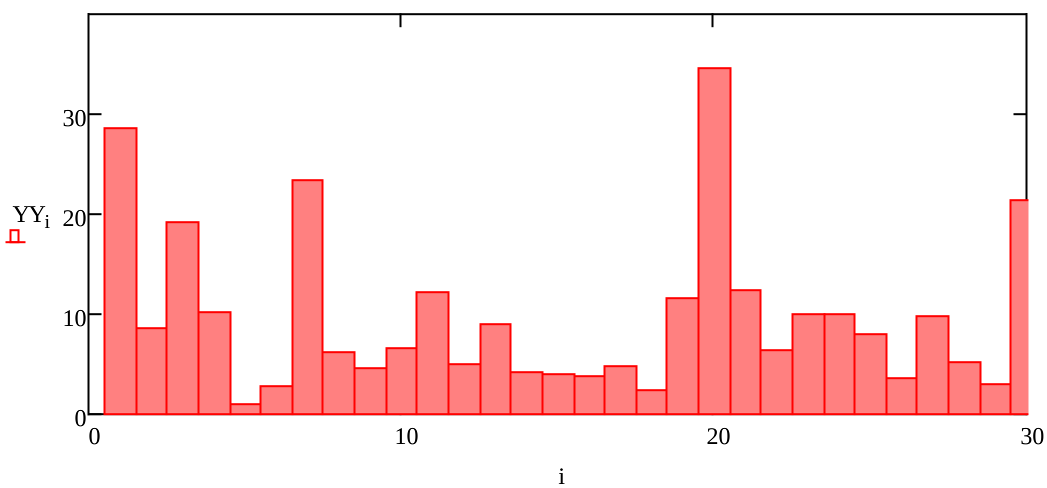

Figure A9.

Appendix B: Example Mathcad Worksheets for Town of Castle Rock Model Run with Treated Wastewater/Return Flows

Hydraulic Inputs, Hydraulic Algorithms, Hydraulic Outputs, Cost Inputs, Cost Algorithms, and Cost Outputs

Problem : Develop a cost model to calculate costs associated with a combined water source for Castle Rock.

Updated: 12-7-11

Hydraulic Inputs

Note : All units are in meters, days, or months.

$N_{years} := 30$

Number of Years to Reach Full Build-Out

$PCD := 6.927$

Per Capita Average Monthly Demand

Assumes a daily rate of 60 gal/day per person * 30.5 days/month

$Growth := 0.013$

Growth Rate

$Initial_p := 49244$

Initial Population

$V_{surfacewtpmaxday} := 1.514 \times 10^4$

Maximum Surface WTP Volumetric Daily Capacity (m^3)

$V_{surfacewtpmaxmonthly} := 4.618 \times 10^5$

Maximum Surface WTP Volumetric Monthly Capacity (m^3)

$V_{gwwtpmaxday} := 0$

Maximum Groundwater WTP Volumetric Daily Capacity (m^3)

$V_{gwwtpmaxmonth} := 0$

Maximum Groundwater WTP Volumetric Monthly Capacity (m^3)

$Max_{Qrate} := 2.328 \times 10^{4}$

Average Monthly Pumping Volume based on 140 GPM (m^3)

$Max_{ASR} := 0.8 \cdot Max_{Qrate} = 1.862 \times 10^{4}$

Average Monthly ASR Well Injection Volume based on 80% of Pumping Well Volume (m^3)

$Existing\_Pumping\_wells := 52$

Existing number of pumping wells

$Existing\_ASR\_wells := 0$

Existing number of ASR wells

$Nu\_ASR\_Retrofits := 0$

Number of ASR retrofits

$Well\_Capacity\_Decline := 0.05$

Annual well capacity decline

Amount of Recoverable Groundwater (m^3)

$Vol\_Recoverable\_GW := 1.06 \times 10^{8}$

Reservoir Attributes

$$Area(storage) := \begin{cases} (6 \cdot storage)^{\frac{2}{3}} & \text{if } storage \geq 0 \\ 0 & \text{otherwise} \end{cases}$$

Minimum Reservoir Pool

$V_{resmin} := 0$

Initial Reservoir Storage

$Init\_Stor := 0$

Loss per month (m)

$Seepage\_Losses := 0$

Average Monthly Pan Evaporation Rate Fort Collins, CO

Note : Fort Collins Evaporation data was used because it was the closest location to Castle Rock. Data represents average monthly evaporation rate in meters.

$$\text{Evaporation} := \begin{pmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{pmatrix}$$

Average Monthly Inflow

Based on inflows provided by TCR. Estimated surface and wastewater inflows are 3.4 million gal/day.

$$INF := \begin{pmatrix} 3.925\times 10^{5} \\ 3.925\times 10^{5} \\ 3.925\times 10^{5} \\ 3.925\times 10^{5} \\ 3.925\times 10^{5} \\ 3.925\times 10^{5} \\ 3.925\times 10^{5} \\ 3.925\times 10^{5} \\ 3.925\times 10^{5} \\ 3.925\times 10^{5} \\ 3.925\times 10^{5} \\ 3.925\times 10^{5} \end{pmatrix} *$$

Irrigation Demands

Allocation based on demands provided by TCR. They represent a portion of the in-house demands.

$$IRR := \begin{pmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 0.2 \\ 1.13 \\ 2.29 \\ 2.2 \\ 2.45 \\ 0.85 \\ 0 \\ 0 \end{pmatrix}$$

$$\text{Irrigated\_acreage} := 4.541 \times 10^{6}$$

Amount of irrigated acreage (m^2) (Kentucky bluegrass)

$$1122 \cdot \text{acre} = 4.541 \times 10^{6}\,\text{m}^{2}$$

Hydraulic Model

Updated : 9-19-11

Reference File for Inputs

Set Up Calculations

Demand Calculations

Population Growth Calculation

$$\text{Capita}(\text{Initial}_P, \text{Growth}, N_{years}) := \left| \begin{array}{l} \text{Capita}_1 \leftarrow \text{Initial}_P \\ \text{for } i \in 2..N_{years} \cdot 12 \\ \quad \text{Capita}_i \leftarrow \text{Capita}_{i-1} \cdot \left(1 + \frac{\text{Growth}}{12}\right) \\ \text{Capita} \end{array} \right.$$

Monthly In-House Demand

$$\text{Demand}_{MH}(\text{Initial}_P, \text{Growth}, N_{years}, \text{PCD}) := \text{Capita}(\text{Initial}_P, \text{Growth}, N_{years}) \cdot \text{PCD}$$

$$\text{Demand}_{IH} := \text{Demand}_{MH}(\text{Initial}_P, \text{Growth}, N_{years}, \text{PCD})$$

Monthly Irrigation Demands are based on a multiplier of in-house demands.

$$\text{Demand}_{IR}(N_{years}, \text{Demand}_{IH}) := \left| \begin{array}{l} k \leftarrow 0 \\ \text{for } i \in 1..N_{years} \\ \quad \text{for } j \in 1..12 \\ \quad\quad \left| \begin{array}{l} k \leftarrow k + 1 \\ YY_k \leftarrow IRR_j \cdot \text{Demand}_{IH_k} \end{array} \right. \\ YY \end{array} \right.$$

Monthly Total Demand (In-House and Lawn and Garden Irrigation)

$$\mathrm{Demand}_{MT}\left(\mathrm{Initial}_P, \mathrm{Growth}, N_{years}, \mathrm{Demand}_{IR}, \mathrm{PCD}\right) := \left| \begin{array}{l} k \leftarrow 0 \\ \text{for } i \in 1..N_{years} \\ \quad \text{for } j \in 1..12 \\ \qquad \left| \begin{array}{l} k \leftarrow k + 1 \\ DD_{k,1} \leftarrow \mathrm{Demand}_{MH}\left(\mathrm{Initial}_P, \mathrm{Growth}, N_{years}, \mathrm{PCD}\right)_k \\ DD_{k,2} \leftarrow \mathrm{Demand}_{IR}\left(N_{years}, \mathrm{Demand}_{IH}\right)_k \\ DD_{k,3} \leftarrow DD_{k,1} + DD_{k,2} \end{array} \right. \\ DD \end{array} \right.$$

$$\mathrm{Demand}_{TM} := \mathrm{Demand}_{MT}\left(\mathrm{Initial}_P, \mathrm{Growth}, N_{years}, \mathrm{Demand}_{IR}, \mathrm{PCD}\right)^{\langle 3 \rangle}$$

Inflow Calculations

Inflows are in monthly cumulative volumetric rates (ft^3/month).

$$\mathrm{Inflow}\left(N_{years}\right) := \left| \begin{array}{l} k \leftarrow 0 \\ \text{for } i \in 1..N_{years} \\ \quad \text{for } j \in 1..12 \\ \qquad \left| \begin{array}{l} k \leftarrow k + 1 \\ YY_k \leftarrow INF_j \end{array} \right. \\ YY \end{array} \right.$$

Pan Evaporation Calculations

Pan evaporation data is based on Fort Collins, CO USGS average pan evaporation data.

$$PE := \left| \begin{array}{l} k \leftarrow 0 \\ \text{for } i \in 1..N_{years} \\ \quad \text{for } j \in 1..12 \\ \quad\quad \left| \begin{array}{l} k \leftarrow k+1 \\ YY_k \leftarrow Evaporation_j \end{array} \right. \\ YY \end{array} \right.$$

Setup Calcs for Losses

$$xx\left(V_{final}, V_{initial}, Inflow, Demand, Evap\right) := V_{final} - V_{initial} - Inflow + Demand \ldots \\ + (Seepage\_Losses + Evap) \frac{\left(Area\left(V_{final}\right) + Area\left(V_{initial}\right)\right)}{2}$$

Reservoir Routing Calculations

Reservoir Routing-Next Page

$$
\begin{array}{l}
\text{reservoir\_route}\left(\text{Initial}_P, \text{Growth}, N_{years}, \text{Demand}_{IR}, \text{PCD}\right) := \\
\quad k \leftarrow 0 \\
\quad AA_{1,4} \leftarrow \text{Init\_Stor} \\
\quad \text{for } i \in 1..N_{years} \\
\quad\quad \text{for } j \in 1..12 \\
\quad\quad\quad k \leftarrow k + 1 \\
\quad\quad\quad AA_{k,1} \leftarrow k \\
\quad\quad\quad AA_{k,2} \leftarrow \text{Inflow}\left(N_{years}\right)_k \\
\quad\quad\quad AA_{k,3} \leftarrow \left(\text{Demand}_{TM}\right)_k \\
\quad\quad\quad AA_{k+1,4} \leftarrow AA_{k,4} + AA_{k,2} - \left[\begin{array}{l}
\text{if } AA_{k,3} < V_{surfacewtpmaxmonthly} \wedge AA_{k,3} < AA_{k,4} - V_{resmin} \\
\quad \left| \begin{array}{l} AA_{k,3} + \left(V_{surfacewtpmaxmonthly} - AA_{k,3}\right) \text{ if } AA_{k,4} - V_{resmin} > V_{surfacewtpmaxmonthly} \\ AA_{k,3} + \left[\left(AA_{k,4} - V_{resmin}\right) - AA_{k,3}\right] \text{ otherwise} \end{array}\right. \\
V_{surfacewtpmaxmonthly} \text{ if } AA_{k,3} > V_{surfacewtpmaxmonthly} \wedge AA_{k,3} < AA_{k,4} - V_{resmin} \\
AA_{k,4} - V_{resmin} \text{ if } AA_{k,3} < V_{surfacewtpmaxmonthly} \wedge AA_{k,3} > AA_{k,4} - V_{resmin} \\
\text{if } AA_{k,3} > V_{surfacewtpmaxmonthly} \wedge AA_{k,3} > AA_{k,4} - V_{resmin} \\
\quad \left| \begin{array}{l} V_{surfacewtpmaxmonthly} \text{ if } AA_{k,4} - V_{resmin} > V_{surfacewtpmaxmonthly} \\ AA_{k,4} - V_{resmin} \text{ otherwise} \end{array}\right.
\end{array}\right] \\
\quad\quad\quad AA_{k,5} \leftarrow \left| \begin{array}{l}
\text{if } AA_{k,3} < V_{surfacewtpmaxmonthly} \wedge AA_{k,3} < AA_{k,4} - V_{resmin} \\
\quad \left| \begin{array}{l} AA_{k,3} + \left(V_{surfacewtpmaxmonthly} - AA_{k,3}\right) \text{ if } AA_{k,4} - V_{resmin} > V_{surfacewtpmaxmonthly} \\ AA_{k,3} + \left[\left(AA_{k,4} - V_{resmin}\right) - AA_{k,3}\right] \text{ otherwise} \end{array}\right. \\
V_{surfacewtpmaxmonthly} \text{ if } AA_{k,3} > V_{surfacewtpmaxmonthly} \wedge AA_{k,3} < AA_{k,4} - V_{resmin} \\
AA_{k,4} - V_{resmin} \text{ if } AA_{k,3} < V_{surfacewtpmaxmonthly} \wedge AA_{k,3} > AA_{k,4} - V_{resmin} \\
\text{if } AA_{k,3} > V_{surfacewtpmaxmonthly} \wedge AA_{k,3} > AA_{k,4} - V_{resmin} \\
\quad \left| \begin{array}{l} V_{surfacewtpmaxmonthly} \text{ if } AA_{k,4} - V_{resmin} > V_{surfacewtpmaxmonthly} \\ AA_{k,4} - V_{resmin} \text{ otherwise} \end{array}\right.
\end{array}\right. \\
\quad\quad\quad AA_{k,6} \leftarrow \left| \begin{array}{l}
\text{if } AA_{k,3} < V_{surfacewtpmaxmonthly} \wedge AA_{k,3} < AA_{k,4} - V_{resmin} \\
\quad \left| \begin{array}{l} AA_{k,6} \leftarrow AA_{k,3} - V_{surfacewtpmaxmonthly} \text{ if } AA_{k,4} - V_{resmin} > V_{surfacewtpmaxmonthly} - AA_{k,3} \\ AA_{k,6} \leftarrow AA_{k,3} - \left(AA_{k,4} - V_{resmin}\right) \text{ otherwise} \end{array}\right. \\
AA_{k,6} \leftarrow AA_{k,3} - V_{surfacewtpmaxmonthly} \text{ if } AA_{k,3} > V_{surfacewtpmaxmonthly} \wedge AA_{k,3} < AA_{k,4} - V_{resmin} \\
AA_{k,6} \leftarrow AA_{k,3} - \left(AA_{k,4} - V_{resmin}\right) \text{ if } AA_{k,3} < V_{surfacewtpmaxmonthly} \wedge AA_{k,3} > AA_{k,4} - V_{resmin} \\
\text{if } AA_{k,3} > V_{surfacewtpmaxmonthly} \wedge AA_{k,3} > AA_{k,4} - V_{resmin} \\
\quad \left| \begin{array}{l} AA_{k,6} \leftarrow AA_{k,3} - V_{surfacewtpmaxmonthly} \text{ if } AA_{k,4} - V_{resmin} > V_{surfacewtpmaxmonthly} \\ AA_{k,6} \leftarrow AA_{k,3} - \left(AA_{k,4} - V_{resmin}\right) \text{ otherwise} \end{array}\right.
\end{array}\right. \\
\quad\quad\quad AA_{k,7} \leftarrow \left| \begin{array}{l}
AA_{k,7} \leftarrow 1 \text{ if } AA_{k,3} < V_{surfacewtpmaxmonthly} \wedge AA_{k,3} < AA_{k,4} - V_{resmin} \\
AA_{k,7} \leftarrow 2 \text{ if } AA_{k,3} > V_{surfacewtpmaxmonthly} \wedge AA_{k,3} < AA_{k,4} - V_{resmin} \\
AA_{k,7} \leftarrow 3 \text{ if } AA_{k,3} < V_{surfacewtpmaxmonthly} \wedge AA_{k,3} > AA_{k,4} - V_{resmin} \\
AA_{k,7} \leftarrow 4 \text{ if } AA_{k,3} > V_{surfacewtpmaxmonthly} \wedge AA_{k,3} > AA_{k,4} - V_{resmin}
\end{array}\right. \\
\quad\quad\quad V_{final} \leftarrow AA_{k+1,4} \\
\quad\quad\quad WW \leftarrow \text{root}\left[\text{xx}\left[V_{final}, AA_{k,4}, AA_{k,2}, AA_{k,3}, \left(\text{Seepage\_Losses} + PE_k\right)\right], V_{final}\right] \\
\quad\quad\quad AA_{k,8} \leftarrow \left(\text{Seepage\_Losses} + PE_k\right) \dfrac{\left(\text{Area}(WW) + \text{Area}\left(AA_{k,4}\right)\right)}{2} \\
\quad\quad\quad AA_{k+1,4} \leftarrow AA_{k+1,4} - AA_{k,8} \\
\quad\quad\quad AA_{k,9} \leftarrow \left(AA_{k+1,4} - AA_{k,4}\right) - AA_{k,2} + \left| \begin{array}{l}
\text{if } AA_{k,3} < V_{surfacewtpmaxmonthly} \wedge AA_{k,3} < AA_{k,4} - V_{resmin} \\
\quad \left| \begin{array}{l} AA_{k,3} + \left(V_{surfacewtpmaxmonthly} - AA_{k,3}\right) \text{ if } AA_{k,4} - V_{resmin} > V_{surfacewtpmaxmonthly} \\ AA_{k,3} + \left[\left(AA_{k,4} - V_{resmin}\right) - AA_{k,3}\right] \text{ otherwise} \end{array}\right. \\
V_{surfacewtpmaxmonthly} \text{ if } AA_{k,3} > V_{surfacewtpmaxmonthly} \wedge AA_{k,3} < AA_{k,4} - V_{resmin} \\
AA_{k,4} - V_{resmin} \text{ if } AA_{k,3} < V_{surfacewtpmaxmonthly} \wedge AA_{k,3} > AA_{k,4} - V_{resmin} \\
\text{if } AA_{k,3} > V_{surfacewtpmaxmonthly} \wedge AA_{k,3} > AA_{k,4} - V_{resmin} \\
\quad \left| \begin{array}{l} V_{surfacewtpmaxmonthly} \text{ if } AA_{k,4} - V_{resmin} > V_{surfacewtpmaxmonthly} \\ AA_{k,4} - V_{resmin} \text{ otherwise} \end{array}\right.
\end{array}\right. + AA_{k,8} \\
\quad k \leftarrow 0 \\
\quad \text{for } i \in 1..N_{years} \\
\quad\quad \text{for } j \in 1..12 \\
\quad\quad\quad k \leftarrow k + 1 \\
\quad\quad\quad AA_{k,10} \leftarrow \left| \begin{array}{l} 1 \text{ if } \sum AA^{\langle 6 \rangle} < AA_{k,6} \\ 0 \text{ otherwise} \end{array}\right. \\
\quad\quad\quad AA_{k,11} \leftarrow \sum AA^{\langle 6 \rangle} \\
\quad AA
\end{array}
$$

Castle Rock without ASR

Hydraulic Output

All values in m^3 unless otherwise specified.

Date : 9/19/11

References

Reservoir and Groundwater Routing

$$\mathrm{Reservoir\_GW\_Operations} := \left(\mathrm{reservoir\_route}\left(\mathrm{Initial}_{P}, \mathrm{Growth}, N_{\mathrm{years}}, \mathrm{Demand}_{IR}, \mathrm{PCD}\right)\right)$$

Reservoir_GW_Operations =

	1	2	3	4	5	6	7	8	9	10	11
1	1	$3.925\cdot10^{5}$	$3.411\cdot10^{5}$	0	0	$3.411\cdot10^{5}$	3	0	0	0	$1.191\cdot10^{8}$
2	2	$3.925\cdot10^{5}$	$3.415\cdot10^{5}$	$3.925\cdot10^{5}$	$3.925\cdot10^{5}$	$-1.203\cdot10^{5}$	1	0	0	0	$1.191\cdot10^{8}$
3	3	$3.925\cdot10^{5}$	$3.419\cdot10^{5}$	$3.925\cdot10^{5}$	$3.925\cdot10^{5}$	$-1.199\cdot10^{5}$	1	0	0	0	$1.191\cdot10^{8}$
4	4	$3.925\cdot10^{5}$	$3.422\cdot10^{5}$	$3.925\cdot10^{5}$	$3.925\cdot10^{5}$	$-1.196\cdot10^{5}$	1	0	0	0	$1.191\cdot10^{8}$
5	5	$3.925\cdot10^{5}$	$4.111\cdot10^{5}$	$3.925\cdot10^{5}$	$3.925\cdot10^{5}$	$1.861\cdot10^{4}$	3	0	0	0	$1.191\cdot10^{8}$
6	6	$3.925\cdot10^{5}$	$7.305\cdot10^{5}$	$3.925\cdot10^{5}$	$3.925\cdot10^{5}$	$3.38\cdot10^{5}$	4	0	0	0	$1.191\cdot10^{8}$
7	7	$3.925\cdot10^{5}$	$1.13\cdot10^{6}$	$3.925\cdot10^{5}$	$3.925\cdot10^{5}$	$7.371\cdot10^{5}$	4	0	0	0	...

Reservoir routing key
AA1=month
AA2=Inflows
AA3=Demands
AA4=Volume in Reservoir
AA5=Volume out of Reservoir (i.e. WTP)
AA6=Groundwater (recovery or injection)
AA7=Decision Flag
AA8=Losses
AA9=System Mass Balance
AA10=GW Flag
AA11=Total of GW Mass Balance
Decision Variables key
1 = no constraint
2 = constrained by WTP
3 = constrained by Reservoir
4 = constrained by either Reservoir or WTP
GW Flag key
1 = Pumping Exceeds Total GW Mass Balance
0 = Pumping Less than Total GW Mass Balance

$\text{Demands} := \text{Reservoir\_GW\_Operations}^{\langle 3 \rangle}$

$i := 1..360$

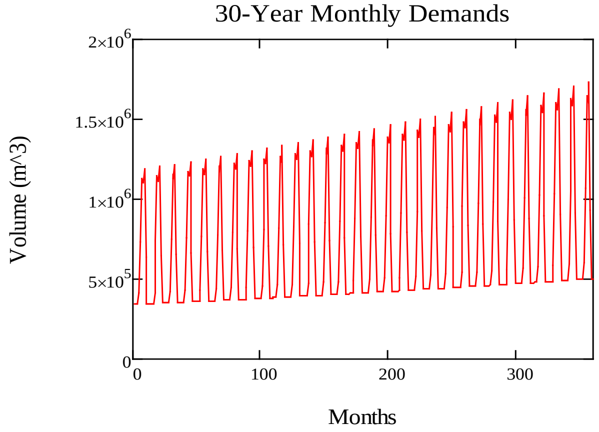

Figure B1.

$\text{RES\_OP} := \text{Reservoir\_GW\_Operations}^{\langle 4 \rangle}$

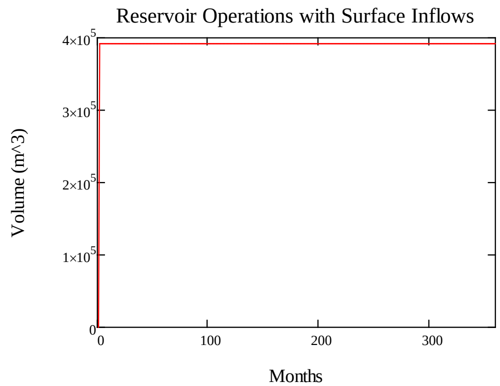

Figure B2.

$GW := Reservoir\_GW\_Operations^{\langle 6 \rangle}$

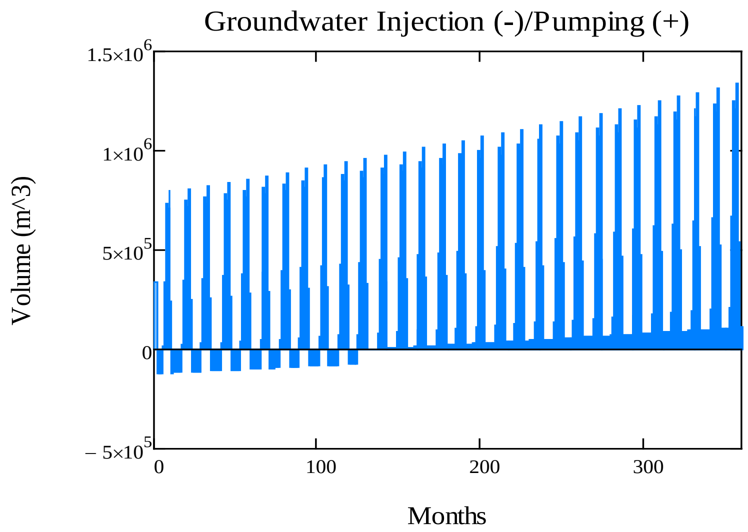

Figure B3.

$$Cum\_GW := \begin{array}{|l} w_{last(GW)} \leftarrow 0 \\ w_{ORIGIN} \leftarrow GW_{ORIGIN} \\ \text{for } i \in ORIGIN + 1 .. last(GW) \\ \quad w_i \leftarrow w_{i-1} + GW_i \\ w \end{array}$$

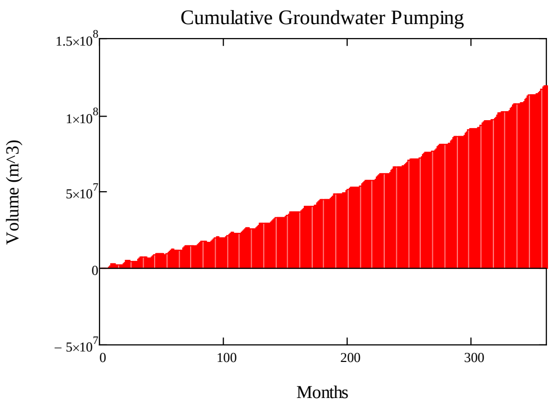

Figure B4.

Problem : Develop inputs to calculate costs associated with a combined source water system for Castle Rock, CO.

Updated : 9-18-11

Cost Inputs

Note : All units are in U.S. dollars, meters, gallons, days, and kilograms.

Capital Costs

$Cost\_per\_V_{res} := 0$ Cost represents Cost per 1 m^3 (1 AF = 1.233×10^3 m^3). Includes cost for raw water acquisition and reservoir construction costs.

$Cost\_per\_V_{wtp} := 3.50$ Cost represents Cost per gallon (capacity) for construction of surface water treatment facility (1 gallons=

$Cost\_per\_V_{wtpgw} := 0$ Cost represents Cost per gallon for construction of groundwater treatment facility

$Cost_{pumpwell} := 1140601$ Cost represents Cost per pumping well, well facility, and transmission line.

$Cost_{ASRwell} := 1239000$ Cost represents Cost per ASR well

$ASR_{retrofit} := 143000$ Cost represents Cost for ASR retrofit

$Interest_{rate} := 0.06$ Interest Rate

$Power\_Labor_{capital} := 0$ Cost represents the cost per water treatment plant constructed.

O&M Costs

$Res\_OM\_monthly := 4.167 \times 10^{3}$	O & M cost/month for Reservoir Operations
$Cost\_per\_V_{surfacetreatment} := 1.50$	O & M cost for surface water treatment ($/1000 gallons)
$Cost\_per\_V_{gwtreatment} := 1.20$	O & M cost for groundwater treatment ($/1000 gallons)
$Cost\_per\_V_{asr} := 0.428$	O & M cost for injection well ($/1000 gallons)
$Cost\_per\_V_{pumping} := 2.113$	O & M cost for pumping well ($/1000 gallons)
$Cost_{wellrehab} := 50000$	Cost represents Rehabilitation Cost per well
$Well_{life} := 30$	Life expectancy of wells
$Rehab_{frequency} := 10$	Frequency of well rehabilitation

Problem : Develop inputs to calculate costs associated with a reservoir-ASR water source for Castle Rock, CO.

Updated : 9-20-11

Cost Model

Reference Files

Maximum Pumping Rate

$$GW := \text{reservoir\_route}\left(\text{Initial}_P, \text{Growth}, N_{years}, \text{Demand}_{IR}, \text{PCD}\right)^{\langle 6 \rangle}$$

$$\text{Volume\_Groundwater\_Extraction} := \sum GW = 431827714$$

$$\text{Max}_Q := \left| \begin{array}{l} \text{for } i \in 1..N_{years} \\ \quad \left| \begin{array}{l} \text{MAX}_{i,1} \leftarrow \max(\text{submatrix}(GW, i \cdot 12, i \cdot 12 - 11, 1, 1)) \\ \text{MAX}_{i,2} \leftarrow \left| \begin{array}{l} \text{MAX}_{i,1} \text{ if } \text{MAX}_{i,1} > 0 \\ 0 \text{ otherwise} \end{array} \right. \end{array} \right. \\ \text{MAX} \end{array} \right.$$

$$Max_Q := \left| \begin{array}{l} \text{for } i \in 1..N_{years} \\ \quad \left| \begin{array}{l} MAX_{i,1} \leftarrow \max(\text{submatrix}(GW, i \cdot 12, i \cdot 12 - 11, 1, 1)) \\ MAX_{i,2} \leftarrow \left| \begin{array}{l} MAX_{i,1} \text{ if } MAX_{i,1} > 0 \\ 0 \text{ otherwise} \end{array} \right. \end{array} \right. \\ MAX \end{array} \right.$$

$$Min_Q := \left| \begin{array}{l} \text{for } i \in 1..N_{years} \\ \quad \left(\left| \begin{array}{l} MIN_{i,1} \leftarrow \min(\text{submatrix}(GW, i \cdot 12, i \cdot 12 - 11, 1, 1)) \\ MIN_{i,2} \leftarrow \left| \begin{array}{l} MIN_{i,1} \text{ if } MIN_{i,1} < 0 \\ 0 \text{ otherwise} \end{array} \right. \end{array} \right. \right) \\ MIN \end{array} \right.$$

Number of Wells

$$WCD := \left| \begin{array}{l} WC_1 \leftarrow Max_{Qrate} \\ \text{for } i \in 1..N_{years} \\ \quad WC_{i+1} \leftarrow WC_i \cdot (1 - \text{Well\_Capacity\_Decline}) \\ WC \end{array} \right.$$

$$Q_{well}(Max_Q) := \left| \begin{array}{l} \text{for } i \in 1..N_{years} \\ \quad WC_i \leftarrow \left[1 - \frac{\left(Max_Q^{\langle 2 \rangle} \right)_i}{\text{Vol\_Recoverable\_GW}} \right] \cdot Max_{Qrate} \\ WC \end{array} \right.$$

$$Q_{wellasr}(Min_Q) := \left| \begin{array}{l} \text{for } i \in 1..N_{years} \\ \quad WC_i \leftarrow \left[1 - \dfrac{\left(Min_Q^{\langle 2 \rangle}\right)_i}{Vol\_Recoverable\_GW} \right] \cdot Max_{ASR} \\ WC \end{array} \right.$$

$$Num_{ASRwells} := \left| \begin{array}{l} \text{for } i \in 1..N_{years} \\ \quad WELLS_{i,1} \leftarrow \text{round}\left[\dfrac{\left(\left| Min_{Q_{i,2}} \right| \right)}{\left(\left(Q_{wellasr}(Min_Q)_i \right) \right)} \right] \\ WELLS \end{array} \right.$$

$$Num_{pumpwells} := \left| \begin{array}{l} \text{for } i \in 1..N_{years} \\ \quad WELLS_{i,1} \leftarrow \text{round}\left(\dfrac{Max_{Q_{i,2}}}{Q_{well}(Max_Q)_i} \right) \\ WELLS \end{array} \right.$$

$$Num_{totASRwells} := \left| \begin{array}{l} \text{for } i \in 1..N_{years} \\ \quad \left| \begin{array}{l} ASR_{i,1} \leftarrow \max(\text{submatrix}(Num_{ASRwells}, 1, i, 1, \\ ASR_{i+1,2} \leftarrow ASR_{i,1} \\ ASR_{i,3} \leftarrow ASR_{i,1} - ASR_{i,2} \\ ASR_{i,4} \leftarrow ASR_{i,1} - Existing\_ASR\_wells \\ ASR_{i,5} \leftarrow \left| \begin{array}{l} 0 \text{ if } ASR_{i,4} < 0 \\ ASR_{i,4} \text{ otherwise} \end{array} \right. \\ ASR_{i+1,6} \leftarrow ASR_{i,5} \\ ASR_{i,7} \leftarrow ASR_{i,5} - ASR_{i,6} \\ ASR_{i,8} \leftarrow Existing\_ASR\_wells \end{array} \right. \\ ASR \end{array} \right.$$

$$Num_{totpumpwells} := \left| \begin{array}{l} \text{for } i \in 1..N_{years} \\ \quad \left| \begin{array}{l} PUMP_{i,1} \leftarrow \max(\text{submatrix}(Num_{pumpwells}, 1, i, 1, 1)) \\ PUMP_{i+1,2} \leftarrow PUMP_{i,1} \\ PUMP_{i,3} \leftarrow PUMP_{i,1} - PUMP_{i,2} \\ PUMP_{i,4} \leftarrow PUMP_{i,1} - Existing\_Pumping\_wells \\ PUMP_{i,5} \leftarrow \left| \begin{array}{l} 0 \text{ if } PUMP_{i,4} < 0 \\ PUMP_{i,4} \text{ otherwise} \end{array} \right. \\ PUMP_{i+1,6} \leftarrow PUMP_{i,5} \\ PUMP_{i,7} \leftarrow PUMP_{i,5} - PUMP_{i,6} \\ PUMP_{i,8} \leftarrow Existing\_Pumping\_wells \\ PUMP_{i,9} \leftarrow Existing\_Pumping\_wells - PUMP_{i,1} \end{array} \right. \\ PUMP \end{array} \right.$$

COST FUNCTIONS

Capital Costs

$$Capital_{pump} := \left| \begin{array}{l} \text{for } i \in 1..N_{years} \\ \quad COSTPUMP \leftarrow Cost_{pumpwell} \cdot \left(Num_{totpumpwells}\right)^{\langle 7 \rangle} \\ COSTPUMP \end{array} \right.$$

$$Capital_{ASR} := \left| \begin{array}{l} \text{for } i \in 1..N_{years} \\ \quad COSTASR \leftarrow Cost_{ASRwell} \cdot \left(Num_{totASRwells}\right)^{\langle 7 \rangle} \\ COSTASR \end{array} \right.$$

$$Init\_Cost\_Pump\_Wells := \text{submatrix}\left(Capital_{pump}, 1, 1, 1, 1\right)$$

$$Init\_Cost\_ASR\_Wells := \mathrm{submatrix}\left(Capital_{ASR}, 1, 1, 1, 1\right)$$

$$Initial\_well\_cost := \left| \begin{array}{l} \text{for } i \in 1 \\ \quad PMP \leftarrow \left| \begin{array}{ll} Init\_Cost\_Pump\_Wells & \text{if } Init\_Cost\_Pump\_Wells_i > Init\_Cost\_ASR\_Wells_i \\ Init\_Cost\_ASR\_Wells & \text{otherwise} \end{array} \right. \\ PMP \end{array} \right.$$

$$Num\_ASR\_Wells := Num_{totASRwells}^{\langle 7 \rangle}$$

$$Num\_Pump\_Wells := Num_{totpumpwells}^{\langle 7 \rangle}$$

$$Capital_{total} := \left| \begin{array}{l} k \leftarrow 1 \\ \text{for } i \in 1 \\ \quad \left| \begin{array}{l} Capital \leftarrow V_{surfacewtpmaxday} \cdot \dfrac{Cost\_per\_V_{wtp}}{3.785 \times 10^{-3}} + Init\_Stor \cdot \dfrac{Cost\_per\_V_{res}}{1.233 \times 10^{3}} + V_{gwwtpmaxday} \cdot \dfrac{Cost\_per\_V_{wtpgw}}{3.785 \times 10^{-3}} + Initial\_well\_cost + Nu\_ASR\_Retrofits \cdot ASR_{retrofit} + Power\_Labor_{capital} \\ \text{for } j \in 2 .. N_{years} \\ \quad \left| \begin{array}{l} k \leftarrow k + 1 \\ Capital_k \leftarrow Capital_{k-1} + \left| \begin{array}{ll} Capital_{pump_k} & \text{if } \left(Num\_Pump\_Wells_k\right) > \left(Num\_ASR\_Wells_k\right) \\ Capital_{ASR_k} & \text{otherwise} \end{array} \right. \end{array} \right. \end{array} \right. \\ Capital \end{array} \right.$$

$$Capital_{Incremental} := \left| \begin{array}{l} k \leftarrow 1 \\ \text{for } i \in 1 \\ \quad \left| \begin{array}{l} Capital \leftarrow V_{surfacewtpmaxday} \cdot \dfrac{Cost\_per\_V_{wtp}}{3.785 \times 10^{-3}} + Init\_Stor \cdot \dfrac{Cost\_per\_V_{res}}{1.233 \times 10^{3}} + V_{gwwtpmaxday} \cdot \dfrac{Cost\_per\_V_{wtpgw}}{3.785 \times 10^{-3}} + Initial\_well\_cost + Nu\_ASR\_Retrofits \cdot ASR_{retrofit} + Power\_Labor_{capital} \\ \text{for } j \in 2 .. N_{years} \\ \quad \left| \begin{array}{l} k \leftarrow k + 1 \\ Capital_{k,1} \leftarrow \left[\left| \begin{array}{ll} Capital_{pump_k} & \text{if } \left(Num\_Pump\_Wells_k\right) > \left(Num\_ASR\_Wells_k\right) \\ Capital_{ASR_k} & \text{otherwise} \end{array} \right. \right] \end{array} \right. \end{array} \right. \\ Capital \end{array} \right.$$

O & M Costs

$$Vol\_Res := reservoir\_route\left(Initial_P, Growth, N_{years}, Demand_{IR}, PCD\right)^{\langle 4\rangle}$$

$$Vol\_WTP := \left(reservoir\_route\left(Initial_P, Growth, N_{years}, Demand_{IR}, PCD\right)^{\langle 5\rangle}\right)$$

$$Vol\_Pumping\_Well := \left| \begin{array}{l} k \leftarrow 0 \\ \text{for } i \in 1..N_{years} \\ \quad \text{for } j \in 1..12 \\ \quad\quad \left| \begin{array}{l} k \leftarrow k+1 \\ PUMP_k \leftarrow \left| \begin{array}{ll} GW_k & \text{if } GW_k > 0 \\ 0 & \text{otherwise} \end{array} \right. \end{array} \right. \\ PUMP \end{array} \right.$$

$$Vol\_Injection\_Well := \left| \begin{array}{l} k \leftarrow 0 \\ \text{for } i \in 1..N_{years} \\ \quad \text{for } j \in 1..12 \\ \quad\quad \left| \begin{array}{l} k \leftarrow k+1 \\ INJ_k \leftarrow \left| \begin{array}{ll} GW_k \cdot -1 & \text{if } GW_k < 0 \\ 0 & \text{otherwise} \end{array} \right. \end{array} \right. \\ INJ \end{array} \right.$$

Cost for replacement wells

$$
\mathrm{Monthly}_{CRW} := \left|
\begin{array}{l}
k \leftarrow 0 \\
\text{for } i \in 1..N_{years} \\
\quad \text{for } j \in 1..12 \\
\quad\quad \left| \begin{array}{l}
k \leftarrow k+1 \\
\mathrm{REPL}_k \leftarrow \dfrac{\mathrm{Existing\_Pumping\_wells}\cdot\dfrac{\mathrm{Cost}_{pumpwell}}{\mathrm{Well}_{life}}}{12} + \dfrac{\left[\left(\mathrm{Num}_{totpumpwells}^{\langle 7\rangle}\right)_i\cdot\dfrac{\mathrm{Cost}_{pumpwell}}{\mathrm{Well}_{life}}\right]}{12}
\end{array}\right. \\
\mathrm{REPL}
\end{array}\right.
$$

$$
\mathrm{O\_M}_{total}(\mathrm{Vol\_Res},\mathrm{Vol\_WTP},\mathrm{Vol\_Pumping\_Well},\mathrm{Vol\_Injection\_Well}) := \left|
\begin{array}{l}
k \leftarrow 0 \\
\text{for } i \in 1..N_{years} \\
\quad \text{for } j \in 1..12 \\
\quad\quad \left| \begin{array}{l}
k \leftarrow k+1 \\
\mathrm{OM}_k \leftarrow (\mathrm{Res\_OM\_monthly}) + \mathrm{Vol\_WTP}_k\cdot\dfrac{\mathrm{Cost\_per\_V}_{surfacetreatment}}{3.785} + \mathrm{Vol\_Pumping\_Well}_k\cdot\dfrac{\mathrm{Cost\_per\_V}_{gwtreatment}}{3.785} + \mathrm{Vol\_Pumping\_Well}_k\cdot\dfrac{\mathrm{Cost\_per\_V}_{pumping}}{3.785} + \mathrm{Vol\_Injection\_Well}_k\cdot\dfrac{\mathrm{Cost\_per\_V}_{asr}}{3.785} + \mathrm{Monthly}_{CRW_k}
\end{array}\right. \\
\mathrm{OM}
\end{array}\right.
$$

$$
\mathrm{O\_M}_{Total} := \mathrm{O\_M}_{total}(\mathrm{Vol\_Res},\mathrm{Vol\_WTP},\mathrm{Vol\_Pumping\_Well},\mathrm{Vol\_Injection\_Well})
$$

$$
\mathrm{O\_M}_{cum}\left(\mathrm{O\_M}_{Total}\right) := \left|
\begin{array}{l}
w_{last\left(\mathrm{O\_M}_{Total}\right)} \leftarrow 0 \\
w_{ORIGIN} \leftarrow \mathrm{O\_M}_{Total_{ORIGIN}} \\
\text{for } i \in \mathrm{ORIGIN}+1..\,last\left(\mathrm{O\_M}_{Total}\right) \\
\quad w_i \leftarrow w_{i-1} + \mathrm{O\_M}_{Total_i} \\
w
\end{array}\right.
$$

$$
\mathrm{OM}_{annual}\left(\mathrm{O\_M}_{Total}\right) := \left|
\begin{array}{l}
\text{for } i \in 1..N_{years} \\
\quad \mathrm{OM}_{an_i} \leftarrow \sum\left(\mathrm{submatrix}\left(\mathrm{O\_M}_{Total}, i\cdot 12, i\cdot 12 - 11, 1, 1\right)\right) \\
\mathrm{OM}_{an}
\end{array}\right.
$$

Total Cost and Life Cycle Cost

$$\text{Total\_Costs} := \left| \begin{array}{l} \text{for } i \in 1..N_{years} \\ \quad TOT_i \leftarrow Capital_{Incremental_i} + OM_{annual}\left(O\_M_{Total}\right)_i \\ TOT \end{array} \right.$$

$$\text{Cum\_Tot\_Cost} := \left| \begin{array}{l} w_{last(\text{Total\_Costs})} \leftarrow 0 \\ w_{ORIGIN} \leftarrow \text{Total\_Costs}_{ORIGIN} \\ \text{for } i \in ORIGIN + 1..\,last(\text{Total\_Costs}) \\ \quad w_i \leftarrow w_{i-1} + \text{Total\_Costs}_i \\ w \end{array} \right.$$

$$\text{Max\_Cum\_Tot\_Cost} := \max(\text{Cum\_Tot\_Cost}) = 528667340$$

$$\text{Max\_Cum\_Tot\_Cost} := \max(\text{Cum\_Tot\_Cost}) = \blacksquare$$

Present Value Cost

$$\text{Present\_Value}(\text{Total\_Costs}) := \left| \begin{array}{l} \text{for } i \in 1..N_{years} \\ \quad PV_i \leftarrow \dfrac{\text{Total\_Costs}_i}{\left(1 + Interest_{rate}\right)^{N_{years}}} \\ PV \end{array} \right.$$

$$\text{Net\_Present\_Value} := \sum \text{Present\_Value}(\text{Total\_Costs}) = 9.205 \times 10^{7}$$

Castle Rock without ASR

Problem : Develop cost outputs for a conjunctive use project.

Updated : 9-18-11

Cost Outputs

Reference Files

Total Volume of Groundwater Extracted

$$\text{Volume\_Groundwater\_Extraction} = 1.191 \times 10^{8}$$

$$1.191 \times 10^{8} \cdot m^{3} = 96556 \cdot acre \cdot ft$$

Number of Wells

$Num_{pumpwells} =$

	1
1	34
2	35
3	36
4	36
5	37
6	...

$Num_{ASRwells} =$

	1
1	6
2	6
3	6
4	6
5	5
6	...

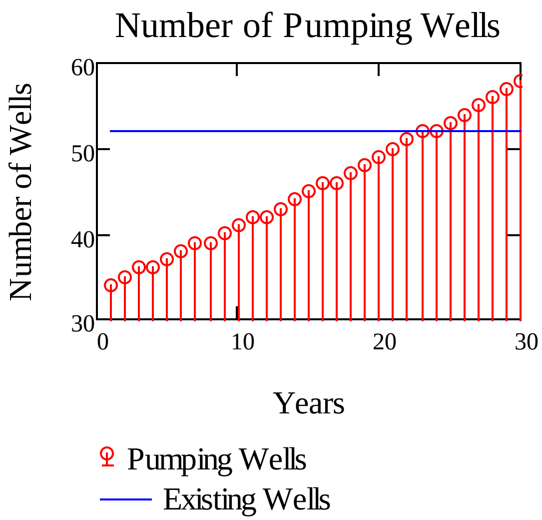

Figure B5.

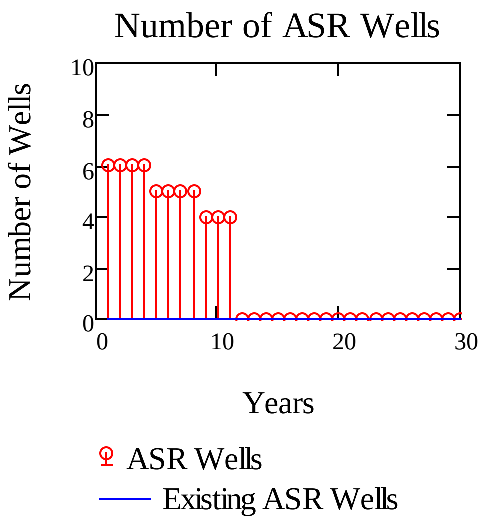

Figure B6.

Capital Costs

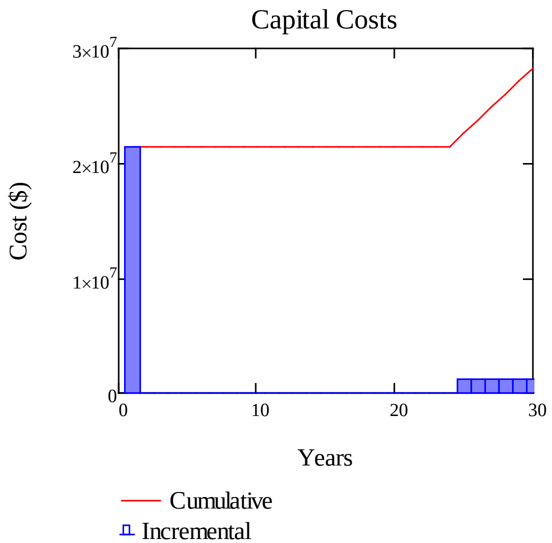

Figure B7.

$Capital_{total}$ =

	1
1	$2.143 \cdot 10^7$
2	$2.143 \cdot 10^7$
3	$2.143 \cdot 10^7$
4	$2.143 \cdot 10^7$
5	$2.143 \cdot 10^7$
6	$2.143 \cdot 10^7$
7	$2.143 \cdot 10^7$
8	...

$Capital_{Incremental}$ =

	1
1	$2.143 \cdot 10^7$
2	0
3	0
4	0
5	0
6	0
7	0
8	...

O & M Costs

$O\_M_{total}(Vol\_Res, Vol\_WTP, Vol\_Pumping\_Well, Vol\_Injection\_Well) =$

	1
1	$4.675\cdot10^5$
2	$3.381\cdot10^5$
3	$3.38\cdot10^5$
4	$3.38\cdot10^5$
5	$3.408\cdot10^5$
6	$6.203\cdot10^5$
7	$9.696\cdot10^5$
8	$9.436\cdot10^5$
9	$1.02\cdot10^6$
10	$5.387\cdot10^5$
11	$3.377\cdot10^5$
12	$3.377\cdot10^5$
13	$3.376\cdot10^5$
14	$3.376\cdot10^5$
15	$3.375\cdot10^5$
16	...

$O\_M_{cum}(O\_M_{Total}) =$

	1
1	$4.675\cdot10^5$
2	$8.056\cdot10^5$
3	$1.144\cdot10^6$
4	$1.482\cdot10^6$
5	$1.822\cdot10^6$
6	$2.443\cdot10^6$
7	$3.412\cdot10^6$
8	$4.356\cdot10^6$
9	$5.376\cdot10^6$
10	$5.915\cdot10^6$
11	$6.252\cdot10^6$
12	$6.59\cdot10^6$
13	$6.928\cdot10^6$
14	$7.265\cdot10^6$
15	$7.603\cdot10^6$
16	...

$OM_{annual}(O\_M_{Total}) =$

	1
1	$6.59 \cdot 10^6$
2	$6.517 \cdot 10^6$
3	$6.574 \cdot 10^6$
4	$6.632 \cdot 10^6$
5	$6.691 \cdot 10^6$
6	$6.75 \cdot 10^6$
7	$6.81 \cdot 10^6$
8	$6.871 \cdot 10^6$
9	$6.933 \cdot 10^6$
10	$6.996 \cdot 10^6$
11	$7.044 \cdot 10^6$
12	$7.094 \cdot 10^6$
13	$7.19 \cdot 10^6$
14	$7.287 \cdot 10^6$
15	$7.385 \cdot 10^6$
16	...

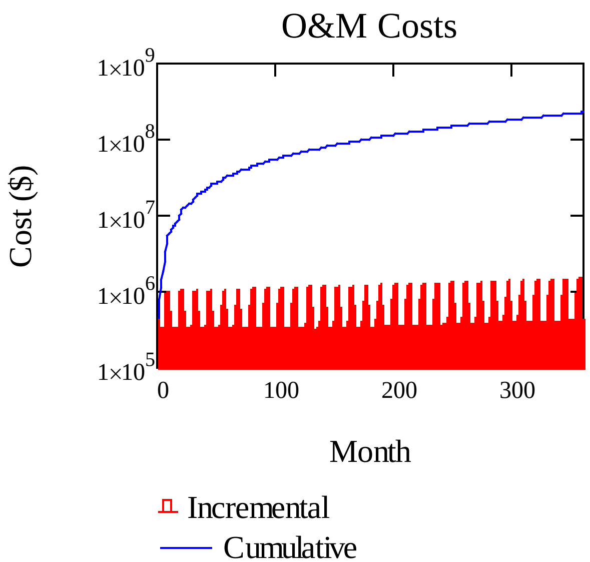

Figure B8.

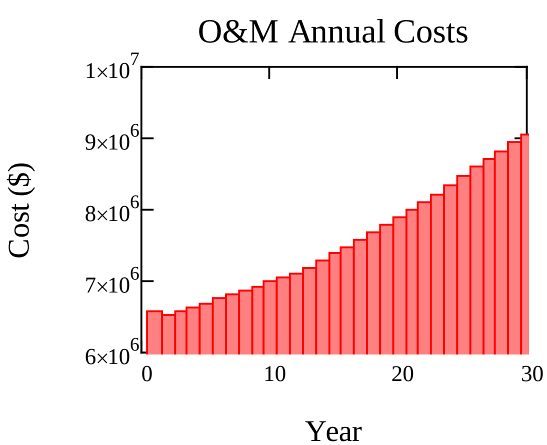

Figure B9.

Total Cost and Life Cycle Cost

Cum_Tot_Cost =

	1
1	$2.802 \cdot 10^7$
2	$3.454 \cdot 10^7$
3	$4.112 \cdot 10^7$
4	$4.775 \cdot 10^7$
5	$5.444 \cdot 10^7$
6	$6.119 \cdot 10^7$
7	$6.8 \cdot 10^7$
8	...

Total_Costs =

	1
1	$2.802 \cdot 10^7$
2	$6.517 \cdot 10^6$
3	$6.574 \cdot 10^6$
4	$6.632 \cdot 10^6$
5	$6.691 \cdot 10^6$
6	$6.75 \cdot 10^6$
7	$6.81 \cdot 10^6$
8	...

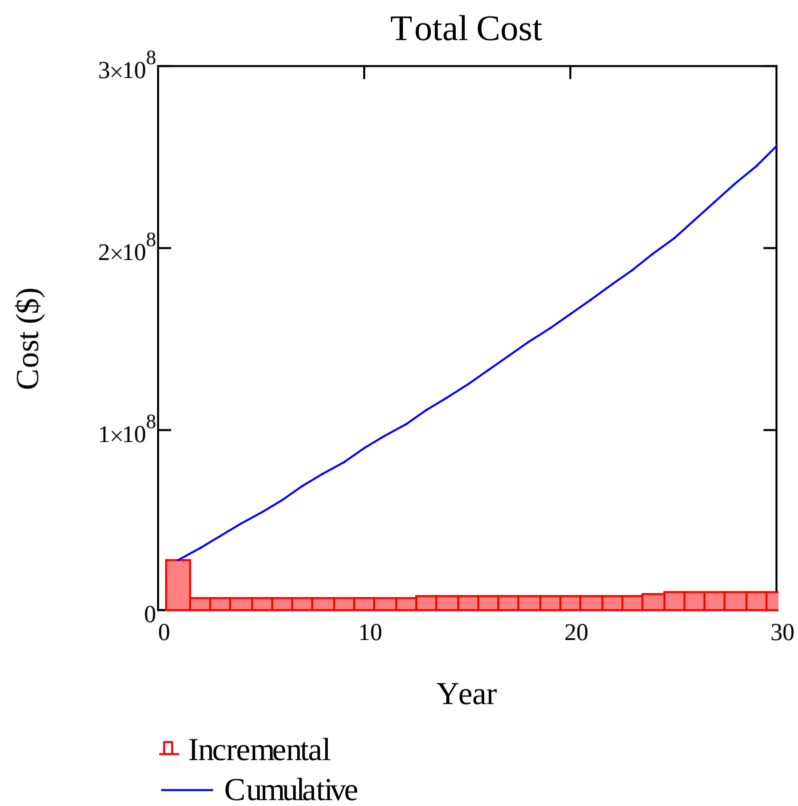

Figure B10.

Life_Cycle_Cost := max(Cum_Tot_Cost) = 255356537

Present Worth Cost

Present_Value(Total_Costs) =

	1
1	$4.879 \cdot 10^6$
2	$1.135 \cdot 10^6$
3	$1.145 \cdot 10^6$
4	$1.155 \cdot 10^6$
5	$1.165 \cdot 10^6$
6	$1.175 \cdot 10^6$
7	$1.186 \cdot 10^6$
8	$1.196 \cdot 10^6$
9	$1.207 \cdot 10^6$
10	$1.218 \cdot 10^6$
11	$1.226 \cdot 10^6$
12	$1.235 \cdot 10^6$
13	$1.252 \cdot 10^6$
14	$1.269 \cdot 10^6$
15	$1.286 \cdot 10^6$
16	...

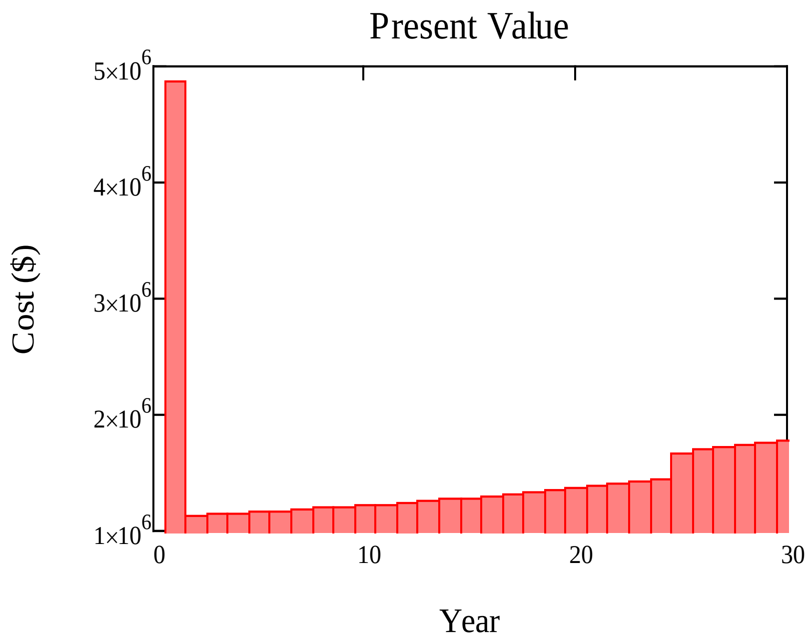

Figure B11.

Net_Present_Value $= 4.446 \times 10^7$

Appendix C: User's Guide

Hydraulic Inputs Worksheet

Deterministic Inputs

Per Capita Monthly Demand- The per capita monthly demand (PCD) is based on average in-house daily use or volume per capita per day multiplied by the number of days in the month. The following formula is used to determine the PCD:

Equation (1)

$$\frac{Volume}{capita}/day * number\ of\ days/month = \frac{Volume}{capita}/month$$

Population Growth Rate-The annual population growth rate is used to calculate the increase in population over time and is assumed to be constant.

Surface and Groundwater Treatment Capacity-Many communities use both surface and groundwater to meet demands. In addition, the treatment requirements for surface and groundwater can be different. The inputs allow a user to designate both surface water and groundwater treatment capacity if both treatment options are available. In some cases, the cost for treatment differs between surface water and groundwater. Therefore, the treatment capacity must be allocated separately to accurately calculate the cost. The maximum monthly surface and groundwater treatment capacities are based on the individual maximum daily treatment capacity, which is shown as follows:

Equation (2)

$$\frac{Treated\ Volume}{day} * number\ of\ days\ in\ month = \frac{Treated\ Volume}{month}$$

Cumulative Monthly Pumping Volume-The cumulative monthly pumping volume is based on a pumping rate. For example, if a municipal well yields 300 gallons per minute (GPM), the total monthly volume that the well produces is equivalent to 13.2 million gallons per month. The pumping rate is assumed to be constant.

Cumulative Monthly ASR Injection Volume-An ASR well is typically capable of injecting 80% of the pumping rate. The cumulative monthly injection volume is:

Equation (3)

$$Qasr = Qpumping * 0.80$$

Number of Existing PumpingWells-The number of existing pumping wells is an important input because it is used in the cost calculations. The user will only be charged for installation of new wells, not existing wells. The program will calculate the number of new wells needed based on the number of existing wells.

Number of Existing ASR Wells-The same calculation will be carried out based on the number of existing ASR wells. If some existing pumping wells are going to be retrofitted to ASR wells, this also can be inputted as an element in the input file.

Volume of Recoverable Water-The volume of recoverable water in the aquifer is an essential element because it is used to calculate well capacity decline. If water levels in an aquifer continuously decline over time due to groundwater pumping, the ability of a well to extract water from the aquifer can decrease. Therefore, the capacity of the well (i.e. pumping rate) will decrease. If this occurs, more wells will need to be installed to recover enough water to meet demands. If the total volume of recoverable water in the aquifer is known, the well capacity decline is equivalent to the volume extracted each month vs. total volume of recoverable water. If more and more water is extracted over time, the amount of available water decreases and the pumping rate decline can be reflected in the fraction of extraction vs. available water multiplied by the maximum pumping rate.

Reservoir Area-The reservoir area is a user-defined input and is a function of the storage volume. Currently, the area is a trapezoid, but it can be any user-defined two-dimensional area.

Minimum Reservoir Pool-If a surface reservoir is needed, the minimum reservoir pool is necessary to prevent the reservoir from completely emptying and is helpful in the overall mass balance of the system.

Initial Storage Volume-The initial storage volume controls how the water supply system is initially operated. In some cases, surface water storage may not be an option; therefore, there is no need for a reservoir. If this is the case, the minimum pool and initial storage volume can be designated as zero.

Seepage Rate-The seepage rate (meters) is used to determine how much water infiltrates into the ground out of a surface water reservoir each month. It is multiplied by the area of the reservoir, which is a function of the storage volume, to obtain a volumetric loss in the hydraulic model.

Monthly Pan Evaporation-The element is a 1x12 vector of average monthly pan evaporation rates (m/month). In the model using stochastic inputs, probability density functions need to be calculated based on a historical record of pan evaporation values.

Deterministic Inflows-In the deterministic version, average monthly inflows are used. The inflows can be any surface water inflow that is available to meet demands. In most cases, this likely will be treated wastewater or treated surface water. The types of inflows are not separated; therefore, they must be combined if there is more than one source. The inflow element is a 1x12 vector of monthly inflows.

Irrigation-use Multiplier -Deterministic irrigation demands are calculated based on in-house demands. An irrigation use multiplier is used that is based on the per capita daily demand. Typically, lawn and garden irrigation is two-to-three times the in-house demand during the irrigation season (i.e. May through September). In order to calculate the multiplier, average monthly water use records should be consulted. The irrigation demand is calculated by determining the percentage of monthly irrigation demands vs. average in-house demands. Once this percentage or multiplier is determined, it is entered as an input in the irrigation demand element. For example, if the average in-house demand is 80 gallons/day and water use records show that the total per capita demand in July is 160 gallons/day, the irrigation multiplier would be 2.

Stochastic Inputs

Irrigated Acreage-The number of irrigated acres is an element that is needed in the stochastic input worksheet and is used to calculate irrigation consumptive use demands in the hydraulic calculations worksheet.

Pan Evaporation Shape Factors-Historical average monthly pan evaporation values should be used to generate random pan evaporation rates. The shape factors are determined when the probability density functions are calculated using histograms of the historical data. The shape factors are found manually by fitting the probability density function to the histogram of historical data. It is a trial-and-error approach to find the best fit by testing different values of shape factors.

Pan Evaporation Scaling Factor-The scaling factor is determined when the probability density functions are calculated using histograms of the historical data. The scaling factor is found by manually inputting different values into the built-in Mathcad probability density function to find the best fit of the probability density function to the histogram of historical data.

Inflow Shape Factors-If historical streamflow values are used to generate synthetic inflows, annual streamflow values should be used to perform monthly flow modeling (Linsley et al. 1982). The historic annual values are disaggregated to generate random annual flows using probability density functions (Linsley et al. 1982). The shape factors are determined when the probability density functions are calculated in Mathcad. The shape factors are found manually by fitting the probability density function to the histogram of historical data. It is a trial-and-error approach to find the best fit by testing different values of shape factors.

Inflow Scaling Factor-The scaling factor is determined when the probability density functions are calculated in Mathcad. The scaling factor is found by manually inputting different values into the built-in Mathcad probability density function to find the best fit of the probability density function to the histogram of historical data.

Inflow Percent Monthly Allocation-Monthly streamflows have the tendency to follow a general distribution throughout the year, whereby most of the high flows are seen during the spring and early summer and then begin to taper throughout the later summer and into the fall. This distribution is applied to the random annual streamflow values to generate monthly streamflow values in the hydraulic calculations worksheet.

Irrigation Demands Shape Factor-Irrigation demands are not based on in-house use in the model using stochastic inputs. Probability density functions are built based on historical monthly irrigation consumptive use values for Kentucky bluegrass. The shape factors are determined when the probability density functions are calculated using histograms of the historical data. The shape factors are found manually by fitting the probability density function to the histogram of historical data. It is a trial-and-error approach to find the best fit by testing different values of shape factors.

Irrigation Demands Scaling Factor- The scaling factor is determined when the probability density functions are built using histograms of the historical data. Random values of consumptive use are generated based on the beta distribution determined using the probability density functions. The scaling factor is found by manually inputting different values into the built-in Mathcad probability density function to find the best fit of the probability density function to the histogram of historical data.

Hydraulic Calculations Worksheet

Capita-The population through time is calculated using the following formula:

Equation (4)

$$Population = Population_{i} * (1 + \frac{Population\ Growth\ Rate}{12})$$

i = 1,…, N_{months}

Monthly In-house Demand-The monthly in-house demand is based on the population and per capita demand designated in the input file. The formula for in-house demand is as follows:

Equation (5)

$$Monthly\ In - house\ Demand = Population * Per\ Capita\ Demand$$

Deterministic Monthly Irrigation Demand-The monthly irrigation demand is based on the monthly in-house demand and the irrigation multiplier assigned in the input file. The formula for the irrigation demand is as follows:

Equation (6)

$$Monthly\ Irrigation\ Demand = Monthly\ In - house\ Demand * Irrigation\ multiplier$$

Monthly Irrigation Demand Using Stochastic Inputs-The monthly irrigation demand is based on a synthetic set of irrigation consumptive use values calculated using probability density functions. The random number generator in Mathcad uses two shape factors that control the height and width of the beta distribution and a scaling factor that controls the magnitude of the distribution. These factors are assigned in the inputs after histograms of historical irrigation consumptive use data and probability density functions are built. The Mathcad function for a random beta distribution is used in the programming routine to create a synthetic irrigation consumptive use data set. Once this dataset has been created, the monthly values represent a rate (in meters/month) of irrigation consumptive use. The monthly values are then multiplied by an irrigated acreage to determine a volumetric monthly demand. See the algorithm below found in the Mathcad Hydraulic Calculations Worksheet:

Equation (7)

$$\text{Demand}_{IR}\left(N_{years}, s1_{IR}, s2_{IR}, \text{pan\_scale}_{IR}, \text{Irrigated\_acreage}\right) := \left| \begin{array}{l} k \leftarrow 0 \\ \text{for } i \in 1..N_{years} \\ \quad \text{for } j \in 1..12 \\ \quad\quad \left| \begin{array}{l} k \leftarrow k+1 \\ YY_k \leftarrow \text{rbeta}\left(N_{years}, s1_{IR_j}, s2_{IR_j}\right)_i \cdot \text{pan\_scale}_{IR_j} \cdot \text{Irrigated\_acreage} \cdot 2 \end{array} \right. \\ YY \end{array} \right.$$

<u>Total Demand</u>-The total demand is the sum of the in-house and irrigation demands as shown in the following formula:

Equation (8)

$$Total\ Demand = Monthly\ In - house\ Demand + Monthly\ Irrigation\ Demand$$

<u>Deterministic Inflow</u>- Deterministic inflows are any inflows that are non-variable on an annual basis. The monthly inflows may change, but they are the same every year. The hydraulic model contains a programming routine that creates a vector of repeating monthly values based on the life span or time scale that the user designates in the input worksheet. For example, if the life span of the project is 30 years, the vector of inflows would contain 360 monthly values (i.e. 30 years x 12 months). The vector of inflows in the input file contains 12 monthly values, which would be repeated every year for 30 years.

<u>Inflow Using Stochastic Inputs</u>-Inflows using stochastic inputs are variable on an annual basis. Probability density functions are built using histograms of historical annual inflow data. Shape and scaling factors are determined using the probability density functions. These values are designated in the hydraulic input worksheet. In addition, if historical streamflow data is used, a monthly flow distribution must be determined. The monthly distribution also must be designated in the input file in order to disaggregate the synthetic annual flows into synthetic monthly flows. The hydraulic calculations worksheet has a programming routine that calls the inflow data from the input worksheet. The programming routine uses Mathcad's built-in random number generator that utilizes the shape and scale factor from the historical inflow data's beta distribution designated in the input worksheet. This yields a vector of annual inflows that are then multiplied by the monthly inflow distribution element designated in the input file to yield

monthly synthetic inflows. See the algorithm below found in the Mathcad Hydraulic Calculations Worksheet:

Equation (9)

$$\mathrm{Inflow}\left(N_{years}, s1_{IF}, s2_{IF}, pan\_scale_{IF}, Percent\right) := \left| \begin{array}{l} k \leftarrow 0 \\ \text{for } i \in 1..N_{years} \\ \quad \text{for } j \in 1..12 \\ \qquad \left| \begin{array}{l} k \leftarrow k+1 \\ YY_k \leftarrow \mathrm{rbeta}\left(N_{years}, s1_{IF}, s2_{IF}\right)_i \cdot pan\_scale_{IF} \cdot Percent_j \cdot \left(2.635 \times 10^6\right) \end{array} \right. \\ YY \end{array} \right.$$

<u>Deterministic Pan Evaporation</u>-The deterministic monthly pan evaporation values in the input file represent average pan evaporation values. The hydraulic model contains a programming routine that creates a vector of repeating monthly values based on the life span or time scale that the user designated in the input file.

<u>Pan Evaporation Using Stochastic Inputs</u>- Probability density functions are built using histograms of historical average monthly pan evaporation data. Shape and scaling factors are determined using the probability density functions. These factors are referenced in a programming routine in the hydraulic calculations worksheet that uses a random number generator based on the beta distribution to generate synthetic values. The programming routine creates a vector of monthly values based on the life span or time scale that the user designates in the input worksheet. See the algorithm below found in the Mathcad Hydraulic Calculations Worksheet

Equation (10)

$$PE := \left| \begin{array}{l} k \leftarrow 0 \\ \text{for } i \in 1..N_{years} \\ \quad \text{for } j \in 1..12 \\ \qquad \left| \begin{array}{l} k \leftarrow k+1 \\ YY_k \leftarrow \mathrm{rbeta}\left(N_{years}, s1_j, s2_j\right)_i \cdot pan\_scale_j \cdot 0.0254 \end{array} \right. \\ YY \end{array} \right.$$

<u>Reservoir Routing Routine</u>-The reservoir routing routine uses a Mathcad matrix that operates based on inflows, demands, and outflows. Four decision criteria are used to calculate the outflow out of the surface water reservoir that is based on the size of the reservoir and the maximum capacity of the SWTP. These values are designated in the hydraulic inputs worksheet.

The programming routine has a specific calculation for each column in the matrix. The matrix contains eleven columns. A discussion of each calculation in the matrix is as follows:

Equation (11)

1. Column 1-Months
2. Column 2-Inflows-These values are calculated in a programming routine in the hydraulic calculations worksheet and called into the reservoir routing programming routine.
3. Column 3-Demands- These values are calculated in a programming routine in the hydraulic calculations worksheet and called into the reservoir routing programming routine.
4. Column 4-Reservoir Storage

   If Demands<Vswtp and Demands<Vres-Vresmin

   $$S_{i+1} = I_i + S_i - D_i$$

   If Demands>Vswtp and Demands<Vres-Vresmin

   $$S_{i+1} = I_i + S_i - Vswtp$$

   If Demands<Vswtp and Demands>Vres-Vresmin

   $$S_{i+1} = I_i + S_i - (S_i - Vresmin)$$

   If Demands>Vswtp and Demands>Vres-Vresmin, lesser of

   $$S_{i+1} = I_i + S_i - (S_i - Vresmin)$$

   or

   $$S_{i+1} = I_i + S_i - Vswtp$$

   Where:
   S=Storage in reservoir
   I=Inflows
   D=Demands
   Vswtp=Maximum SWTP capacity
   Vresmin=Minimum reservoir pool
   i=time

5. Column 5-Outflows out of Reservoir

   If Demands<Vswtp and Demands<Vres-Vresmin

   $$O_i = D_i + (S_i - D_i)$$

or

$$O_i = D_i + (Vswtp_i - D_i) \text{ if } S_i\text{-Vresmin>Vswtp}$$

If Demands>Vswtp and Demands<Vres-Vresmin

$$O_i = Vswtp$$

If Demands<Vswtp and Demands>Vres-Vresmin

$$O_i = S_i - Vresmin$$

If Demands>Vswtp and Demands>Vres-Vresmin

$$O_i = Vswtp \text{ if } S_i\text{-Vresmin>Vswtp}$$

Otherwise

$$O_i = S_i - Vresmin$$

6. Column 6-Groundwater Pumping/Injection Volume

If Demands<Vswtp and Demands<Vres-Vresmin

$$GW_i = D_i - Vswtp \text{ if } S_i\text{-Vresmin>Vswtp}$$

otherwise

$$GW_i = D_i - (S_i - Vresmin)$$

If Demands>Vswtp and Demands<Vres-Vresmin

$$GW_i = D_i - Vswtp$$

If Demands<Vswtp and Demands>Vres-Vresmin

$$GW_i = D_i - (S_i - Vresmin)$$

If Demands>Vswtp and Demands>Vres-Vresmin

$$GW_i = D_i - Vswtp \text{ if } S_i\text{-Vresmin>Vswtp}$$

Otherwise

$$GW_i = D_i - (S_i - Vresmin)$$

7. Column 7-Decision Criteria Flag

1 If Demands<Vswtp and Demands<Vres-Vresmin

2 If Demands>Vswtp and Demands<Vres-Vresmin

3 If Demands<Vswtp and Demands>Vres-Vresmin

4 If Demands>Vswtp and Demands>Vres-Vresmin

8. Column 8-Seepage Losses

$$L_i = (Seepage_{losses} + PE) * (Area(S_{i+1}) + Area(S_i))/2$$

9. Column 9-System Mass Balance

$$SMB_i = S_{i+1} - S_i - I_i + L_i + O_i$$

10. Column 10-Groundwater Flag

$$1 \; if \; \sum GW < GW_i$$

$$0 \; otherwise$$

11. Column 11-Groundwater Mass Balance

$$GMB = \sum GW$$

Cost Inputs Worksheet

Capital Costs

Cost for Storage in Reservoir-Capital cost is for storage capacity in a reservoir. Cost includes raw water acquisition and reservoir construction costs in $/m^3.

Cost for Surface Water Treatment Plant Capacity-Capital cost is for construction of a surface water treatment plant in $/gallon. The cost calculations worksheet converts gallons to m^3.

Cost for Groundwater Treatment Plant Capacity-Capital cost is for construction of a groundwater treatment plant in $/gallon. The cost calculations worksheet converts gallons to m^3.

Cost per Pumping Well-Capital cost is for construction of a pumping well, well facility, and transmission line.

Cost per ASR Well-Capital cost is for construction of an ASR well, well facility, and transmission line.

Cost for ASR Retrofit-Capital cost for converting a pumping well to an ASR well.

Interest Rate (Discount Rate)-Interest rate used in capital improvement projects.

Power and Labor-This is any capital expenditure for power and/or labor that is not included in the costs for reservoir or treatment plant construction.

Operations and Maintenance Costs

Monthly O&M Reservoir Operations-Includes the cost for operations and maintenance of surface storage facilities in $/month.

Cost for Surface Water Treatment –Cost for operations and maintenance of surface water treatment plant facility in $/1000 gallons. The cost calculations worksheet converts gallons to m^3.

Cost for Groundwater Treatment-Cost for operations and maintenance of groundwater treatment plant facility in $/1000 gallons. The cost calculations worksheet converts gallons to m^3.

Cost for ASR Injection-Includes costs associated with operating an ASR well during injection in \$/1000 gallons. This can include any power or labor costs associated with injection.

Cost for Pumping-Includes costs associated with operating a pumping well in \$/1000 gallons. This includes power and labor costs associated with pumping.

Cost for Well Rehabilitation-Wells may experience diminishing capacity over time due to various factors including clogging of the well screen. It is common practice to rehabilitate wells every 5-10 years in order to maintain capacity. The cost for well rehabilitation is \$/well.

Well Life-Wells have a life expectancy that can affect the capital costs due to replacement. The well life is the average length of time that a well operates consistently at its given capacity after rehabilitation.

Frequency of Well Rehabilitation-In order to maintain capacity in wells, they are rehabilitated. Well rehabilitation typically occurs every 5-to-10 years, but is dependent on the well.

Cost Calculations Worksheet

Volume of Groundwater Extraction/Injection-This represents the total volume of groundwater pumped and/or injected over the life-span of the project.

Equation (12)

$$TGW = \sum GW$$

Maximum Pumping Volume-This represents the maximum monthly volume pumped per year. See the algorithm below labeled Equation (13) found in the Cost Calculations Worksheet:

Equation (13)

$$
Max_Q := \left| \begin{array}{l} \text{for } i \in 1..N_{years} \\ \quad \left| \begin{array}{l} MAX_{i,1} \leftarrow \max(\text{submatrix}(GW, i\cdot 12, i\cdot 12 - 11, 1, 1)) \\ MAX_{i,2} \leftarrow \left| \begin{array}{l} MAX_{i,1} \text{ if } MAX_{i,1} > 0 \\ 0 \text{ otherwise} \end{array} \right. \end{array} \right. \\ MAX \end{array} \right.
$$

Maximum Injection Volume-This represents the maximum monthly volume injected per year. See the algorithm below labeled Equation (14) found in the Cost Calculations Worksheet:

Equation (14)

$$\mathrm{Min}_Q := \left| \begin{array}{l} \text{for } i \in 1 .. N_{years} \\ \quad \left(\left| \begin{array}{l} MIN_{i,1} \leftarrow \min(\mathrm{submatrix}(GW, i \cdot 12, i \cdot 12 - 11, 1, 1)) \\ MIN_{i,2} \leftarrow \left| \begin{array}{l} MIN_{i,1} \text{ if } MIN_{i,1} < 0 \\ 0 \text{ otherwise} \end{array} \right. \end{array} \right. \right) \\ MIN \end{array} \right.$$

Well Pumping Volume-The number of pumping wells is calculated using the annual well pumping volume. The maximum number of wells needed each year is based on the cumulative volume of water pumped over time, the average pumping rate of the well, and the volume of recoverable water in the aquifer. A well capacity decline was factored into the well calculation using the volume of recoverable water. It was determined that the cumulative volume pumped each year is a fraction of the volume available in the aquifer. Therefore, the more water that is pumped, the less is available in the aquifer. Equations 16 and 17 show how the annual pumping volume is calculated and the cumulative pumping volumes, respectively. These values are applied to the pumping rate as shown in the Equation (18) found in the Cost Calculations Worksheet:

Equation (15)

$$\mathrm{Annual}_Q := \left| \begin{array}{l} \text{for } i \in 1 .. N_{years} \\ \quad AQ_i \leftarrow \sum (\mathrm{submatrix}(GW, i \cdot 12, i \cdot 12 - 11, 1, 1)) \\ AQ \end{array} \right.$$

Equation (16)

$$\mathrm{Cum}_Q(\mathrm{Annual}_Q) := \left| \begin{array}{l} w_{last(\mathrm{Annual}_Q)} \leftarrow 0 \\ w_{ORIGIN} \leftarrow \mathrm{Annual}_{Q_{ORIGIN}} \\ \text{for } i \in ORIGIN + 1 .. \mathrm{last}(\mathrm{Annual}_Q) \\ \quad w_i \leftarrow w_{i-1} + \mathrm{Annual}_{Q_i} \\ w \end{array} \right.$$

Equation (17)

$$Q_{well}(Max_Q) := \left| \begin{array}{l} \text{for } i \in 1..N_{years} \\ \quad WC_{i,1} \leftarrow Max_{Qrate} \cdot \left[1 - \frac{\left(Cum_Q(Annual_Q)\right)_i}{Vol\_Recoverable\_GW} \right] \\ WC \end{array} \right.$$

ASR Well Injection Volume-The number of ASR wells is calculated using the cumulative injection volume. The maximum number of wells needed each year is based on the cumulative groundwater injection volume, the average injection rate of the well, and the volume of recoverable water in the aquifer. A well capacity decline was factored into the well calculation using the volume of recoverable water. The same assumption was made for ASR wells as pumping wells. The fraction of volume injected vs. volume available in the aquifer was applied to the injection rate as shown in the following algorithm found in the Cost Calculations Worksheet:

Equation (18)

$$Q_{wellasr}(Min_Q) := \left| \begin{array}{l} \text{for } i \in 1..N_{years} \\ \quad WC_i \leftarrow \left[1 - \frac{\left(Cum_Q(Annual_Q)\right)_i}{Vol\_Recoverable\_GW} \right] \cdot Max_{ASR} \\ WC \end{array} \right.$$

Total Number of Pumping Wells-If there are existing pumping wells designated in the Hydraulic Input Worksheet, this algorithm will account for these wells and recalculate the number of new wells needed each year to meet demands. The following algorithm is found in the Cost Calculations Worksheet:

Equation (19)

$$
Num_{totpumpwells} := \left|
\begin{array}{l}
\text{for } i \in 1..N_{years} \\
\quad \left|
\begin{array}{l}
PUMP_{i,1} \leftarrow \max(\text{submatrix}(Num_{pumpwells}, 1, i, 1, 1)) \\
PUMP_{i+1,2} \leftarrow PUMP_{i,1} \\
PUMP_{i,3} \leftarrow PUMP_{i,1} - PUMP_{i,2} \\
PUMP_{i,4} \leftarrow PUMP_{i,1} - Existing\_Pumping\_wells \\
PUMP_{i,5} \leftarrow \left|
\begin{array}{l}
0 \text{ if } PUMP_{i,4} < 0 \\
PUMP_{i,4} \text{ otherwise}
\end{array}
\right. \\
PUMP_{i+1,6} \leftarrow PUMP_{i,5} \\
PUMP_{i,7} \leftarrow PUMP_{i,5} - PUMP_{i,6} \\
PUMP_{i,8} \leftarrow Existing\_Pumping\_wells \\
PUMP_{i,9} \leftarrow Existing\_Pumping\_wells - PUMP_{i,1}
\end{array}
\right. \\
PUMP
\end{array}
\right.
$$

<u>Total Number of ASR Wells</u>-If there are existing ASR wells designated in the Hydraulic Input Worksheet, this algorithm will account for these wells and recalculate the number of new wells needed per year to meet injection demands. The following algorithm is found in the Cost Calculations Worksheet:

Equation (20)

$$
Num_{totASRwells} := \left|
\begin{array}{l}
\text{for } i \in 1..N_{years} \\
\quad \left|
\begin{array}{l}
ASR_{i,1} \leftarrow \max\left(\text{submatrix}\left(Num_{ASRwells}, 1, i, 1, 1\right)\right) \\
ASR_{i+1,2} \leftarrow ASR_{i,1} \\
ASR_{i,3} \leftarrow ASR_{i,1} - ASR_{i,2} \\
ASR_{i,4} \leftarrow ASR_{i,1} - Existing\_ASR\_wells \\
ASR_{i,5} \leftarrow \left|
\begin{array}{l}
0 \text{ if } ASR_{i,4} < 0 \\
ASR_{i,4} \text{ otherwise}
\end{array}
\right. \\
ASR_{i+1,6} \leftarrow ASR_{i,5} \\
ASR_{i,7} \leftarrow ASR_{i,5} - ASR_{i,6} \\
ASR_{i,8} \leftarrow Existing\_ASR\_wells
\end{array}
\right. \\
ASR
\end{array}
\right.
$$

<u>Cost for Pumping Wells</u>-The cost for pumping wells is an annual value calculated based on the total number of pumping wells needed per year (Equation 17). It accounts for any new well added each year. The following algorithm is used to calculate new well costs:

Equation (21)

$$
Capital_{pump} := \left|
\begin{array}{l}
\text{for } i \in 1..N_{years} \\
\quad COSTPUMP \leftarrow Cost_{pumpwell} \cdot \left(Num_{totpumpwells}\right)^{\langle 7 \rangle} \\
COSTPUMP
\end{array}
\right.
$$

<u>Cost for ASR Wells</u>-The cost for ASR wells is an annual value calculated based on the total number of ASR wells needed per year (Equation 17). It accounts for any new well added each year. The following algorithm is used to calculate new ASR well costs:

Equation (22)

$$
Capital_{ASR} := \left|
\begin{array}{l}
\text{for } i \in 1..N_{years} \\
\quad COSTASR \leftarrow Cost_{ASRwell} \cdot \left(Num_{totASRwells}\right)^{\langle 7 \rangle} \\
COSTASR
\end{array}
\right.
$$

Cumulative Capital Costs (Total Capital Costs)-The cumulative annual capital costs include the cost for reservoir construction (if needed), cost for SWTP construction, cost for groundwater treatment plant construction, new pumping well construction, new ASR well construction, ASR well retrofits, and any capital power or labor costs not designated in the construction costs. It is important to note that all capital costs associated with reservoir and water treatment construction are allocated in the first year of the project. New pumping and/or ASR wells are the only capital cost that are added after the first year. The following algorithm is used to calculate cumulative capital costs:

Equation (23)

$$
\begin{aligned}
\text{Capital}_{total} :=\;& k \leftarrow 1 \\
& \text{for } i \in 1 \\
& \quad \text{Capital} \leftarrow V_{surfacewtpmaxday} \cdot \frac{\text{Cost\_per\_V}_{wtp}}{3.785 \times 10^{-3}} + \text{Init\_Stor} \cdot \frac{\text{Cost\_per\_V}_{res}}{1.233 \times 10^{3}} + V_{gwwtpmaxday} \cdot \frac{\text{Cost\_per\_V}_{wtpgw}}{3.785 \times 10^{-3}} + \text{Initial\_well\_cost} + \text{Nu\_ASR\_Retrofits} \cdot \text{ASR}_{retrofit} + \text{Power\_Labor}_{capital} \\
& \quad \text{for } j \in 2..N_{years} \\
& \quad\quad k \leftarrow k + 1 \\
& \quad\quad \text{Capital}_k \leftarrow \text{Capital}_{k-1} + \begin{cases} \text{Capital}_{pump_k} & \text{if } (\text{Num\_Pump\_Wells}_k) > (\text{Num\_ASR\_Wells}_k) \\ \text{Capital}_{ASR_k} & \text{otherwise} \end{cases} \\
& \text{Capital}
\end{aligned}
$$

Incremental Capital Costs-The incremental capital costs represent the capital costs/year. The annual capital costs include the cost for reservoir construction (if needed), cost for SWTP construction, cost for groundwater treatment plant construction, new pumping well construction, new ASR well construction, ASR well retrofits, and any capital power or labor costs not designated in the construction costs. It is important to note that all capital costs associated with reservoir and water treatment construction are allocated in the first year of the project. New pumping and/or ASR wells are the only capital cost that are added after the first year. The following algorithm is used to calculate annual capital costs:

Equation (24)

$$
\begin{aligned}
&\text{Capital}_{\text{Incremental}} := \\
&\quad k \leftarrow 1 \\
&\quad \text{for } i \in 1 \\
&\qquad \text{Capital} \leftarrow V_{\text{surfacewtpmaxday}} \cdot \frac{\text{Cost\_per\_V}_{\text{wtp}}}{3.785 \times 10^{-3}} + \text{Init\_Stor} \cdot \frac{\text{Cost\_per\_V}_{\text{res}}}{1.233 \times 10^{3}} + V_{\text{gwwtpmaxday}} \cdot \frac{\text{Cost\_per\_V}_{\text{wtpgw}}}{3.785 \times 10^{-3}} + \text{Initial\_well\_cost} + \text{Nu\_ASR\_Retrofits} \cdot \text{ASR}_{\text{retrofit}} + \text{Power\_Labor}_{\text{capital}} \\
&\qquad \text{for } j \in 2..N_{\text{years}} \\
&\qquad\quad k \leftarrow k + 1 \\
&\qquad\quad \text{Capital}_{k,1} \leftarrow \left[\begin{array}{ll} \text{Capital}_{\text{pump}_k} & \text{if } \left(\text{Num\_Pump\_Wells}_k\right) > \left(\text{Num\_ASR\_Wells}_k\right) \\ \text{Capital}_{\text{ASR}_k} & \text{otherwise} \end{array} \right] \\
&\quad \text{Capital}
\end{aligned}
$$

<u>Cost for Replacement Wells</u>-Because wells have a life-expectancy, an average monthly cost for well replacement is factored into the O&M costs, which is based on the number of existing wells and the number of new wells added each year. The well cost is divided by the well life and then multiplied by the number of existing and new wells and then converted to an average monthly value. The following algorithm is used to calculate the monthly well replacement costs:

Equation (25)

$$
\begin{aligned}
&\text{Monthly}_{\text{CRW}} := \\
&\quad k \leftarrow 0 \\
&\quad \text{for } i \in 1..N_{\text{years}} \\
&\qquad \text{for } j \in 1..12 \\
&\qquad\quad k \leftarrow k + 1 \\
&\qquad\quad \text{REPL}_k \leftarrow \frac{\text{Existing\_Pumping\_wells} \cdot \dfrac{\text{Cost}_{\text{pumpwell}}}{\text{Well}_{\text{life}}}}{12} + \frac{\left[\left(\text{Num}_{\text{totpumpwells}}^{\langle 7 \rangle}\right)_i \cdot \dfrac{\text{Cost}_{\text{pumpwell}}}{\text{Well}_{\text{life}}} \right]}{12} \\
&\quad \text{REPL}
\end{aligned}
$$

Monthly O&M Costs-Monthly O&M costs include the costs associated with operations and maintenance of the reservoir, the SWTP, the groundwater treatment plant, well pumping costs, well injection costs, and well replacement costs. The following algorithm is used to calculate the monthly O&M costs:

Equation (26)

$$
\mathrm{O\_M}_{total}(\mathrm{Vol\_Res}, \mathrm{Vol\_WTP}, \mathrm{Vol\_Pumping\_Well}, \mathrm{Vol\_Injection\_Well}) := \left|
\begin{array}{l}
k \leftarrow 0 \\
\text{for } i \in 1..N_{years} \\
\quad \text{for } j \in 1..12 \\
\quad \quad \left| \begin{array}{l} k \leftarrow k+1 \\ OM_k \leftarrow (\mathrm{Res\_OM\_monthly}) + \mathrm{Vol\_WTP}_k \cdot \dfrac{\mathrm{Cost\_per\_V}_{surfacetreatment}}{3.785} + \mathrm{Vol\_Pumping\_Well}_k \cdot \dfrac{\mathrm{Cost\_per\_V}_{gwtreatment}}{3.785} + \mathrm{Vol\_Pumping\_Well}_k \cdot \dfrac{\mathrm{Cost\_per\_V}_{pumping}}{3.785} + \mathrm{Vol\_Injection\_Well}_k \cdot \dfrac{\mathrm{Cost\_per\_V}_{asr}}{3.785} + \mathrm{Monthly}_{CRW_k} \end{array} \right. \\
OM
\end{array}
\right.
$$

Cumulative and Annual O&M Costs-The cumulative monthly O&M costs are calculated using the monthly O&M costs. In addition, the annual O&M costs are calculated using the monthly O&M costs. The following algorithms are used to calculate the cumulative monthly O&M and annual costs, respectively:

Equation (27)

$$
\mathrm{O\_M}_{cum}\left(\mathrm{O\_M}_{Total}\right) := \left|
\begin{array}{l}
w_{last\left(\mathrm{O\_M}_{Total}\right)} \leftarrow 0 \\
w_{ORIGIN} \leftarrow \mathrm{O\_M}_{Total_{ORIGIN}} \\
\text{for } i \in ORIGIN + 1..\,last\left(\mathrm{O\_M}_{Total}\right) \\
\quad w_i \leftarrow w_{i-1} + \mathrm{O\_M}_{Total_i} \\
w
\end{array}
\right.
$$

Equation (28)

$$OM_{annual}(O\_M_{Total}) := \left| \begin{array}{l} \text{for } i \in 1..N_{years} \\ \quad OM_{an_i} \leftarrow \sum(\text{submatrix}(O\_M_{Total}, i\cdot 12, i\cdot 12 - 11, 1, 1)) \\ OM_{an} \end{array} \right.$$

<u>Total Costs</u>-The total costs represent the sum of the annual O&M and capital costs. The following algorithm calculates the total annual costs:

Equation (29)

$$Total\_Costs := \left| \begin{array}{l} \text{for } i \in 1..N_{years} \\ \quad TOT_i \leftarrow Capital_{Incremental_i} + OM_{annual}(O\_M_{Total})_i \\ TOT \end{array} \right.$$

<u>Cumulative Total Costs</u>-The cumulative total costs are based on the total monthly costs. The following algorithm calculates the cumulative annual costs:

Equation (30)

$$Cum\_Tot\_Cost := \left| \begin{array}{l} w_{last(Total\_Costs)} \leftarrow 0 \\ w_{ORIGIN} \leftarrow Total\_Costs_{ORIGIN} \\ \text{for } i \in ORIGIN + 1..\text{last}(Total\_Costs) \\ \quad w_i \leftarrow w_{i-1} + Total\_Costs_i \\ w \end{array} \right.$$

<u>Life-Cycle Cost</u>-This algorithm calculates the total cost over the life-span of the project. The following equation is used to calculate the life-cycle cost:

Equation (31)

$$LFC = \sum Total\_Costs$$

<u>Present Value Costs</u>-The annual present value costs represent the discounted future costs of the project based on the interest rate of the capital improvement project. The following algorithm was used to calculate the annual present value:

Equation (32)

$$\text{Present\_Value}(\text{Total\_Costs}) := \left| \begin{array}{l} \text{for } i \in 1..N_{years} \\ \quad PV_i \leftarrow \dfrac{\text{Total\_Costs}_i}{\left(1 + \text{Interest}_{rate}\right)^{N_{years}}} \\ PV \end{array} \right.$$

Net Present Value-This represents the sum of the present values. The following equation was used to calculate the net present value:

Equation (33)

$$NPV = \sum Present\_Value\,s$$