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Optimizing Sustainable Integrated Use of Groundwater, Surface Water and Reclaimed Water for the Competing Demands of Agricultural Net Return and Urban Population

Silvia Anastasia Landa
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OPTIMIZING SUSTAINABLE INTEGRATED USE OF GROUNDWATER, SURFACE WATER AND RECLAIMED WATER FOR THE COMPETING DEMANDS OF AGRICULTURAL NET RETURN AND URBAN POPULATION

by

Silvia Anastasia Landa

A thesis submitted in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

in

Civil and Environmental Engineering

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UTAH STATE UNIVERSITY
Logan, Utah

2016
ABSTRACT

Optimizing Sustainable Integrated Use of Groundwater, Surface Water and Reclaimed Water for the Competing Demands of Agricultural Net Return and Urban Population

by

Silvia Anastasia Landa, Master of Science
Utah State University, 2016

Major Professor: Dr. Richard C Peralta, Ph.D.
Department: Civil and Environmental Engineering

Rapid population growth increases the competing water demand for agriculture and municipalities. This situation urges the necessity of using integrated water management to increase water supply and find possible symbiotic urban-agriculture relationships. Many studies have been done to simulate the integrated use of surface water, groundwater and reclaimed water for different water users. However, few studies use simulation/optimization (S-O) models for water resources to explicitly represent detailed interactions between the different resources as well as the relationship between users and resources.

This research study uses an S-O model to show the symbiotic relationship between urban and agricultural water use. This model fully links the nonlinear flows of groundwater from multiple aquifer layers, surface waters, reclaimed water, and delayed
returns of non-consumed water for municipal and agricultural uses. Using specific aquifer and stream properties, and related assumptions, the optimization result shows there is a symbiotic relationship between urban and agricultural water use. The unconsumed water returns to the hydrologic system, for both surface water and groundwater increase agricultural net return by 8.6 %, and urban population by 0.4%.

This particular problem uses ModelMuse to create simulation input files, and SOMOS-Map to create the optimization input files to run the simulation/optimization problem in SOMOS. In addition to presenting an S-O model, we also provide practical information on how to create the model. The results of the study and the explanation on how to apply the method may be helpful information for engineers and water managers.
Optimizing Sustainable Integrated Use of Groundwater, Surface Water and Reclaimed Water for the Competing Demands of Agricultural Net Return and Urban Population

Silvia Anastasia Landa

The world population is growing rapidly. In developing countries, the growing population is mostly in urban areas. A bigger population requires more food, and more food requires more water. The water needed for food and people comes from the same sources: surface water (rivers, lakes, etc.) and groundwater (aquifers). Thus, there is a competing water demand between people and agriculture in urban areas.

In this research, we use computer software to make a model of the hydrologic system that focuses on surface water and groundwater. To make the model, we use data from real aquifers and streams in order to make the model represent the real system and the water management situations in urban areas. The purpose of this research is to find the maximum population that water can support as well as the maximum economic benefit that agriculture provides to farmers. By connecting the water resources and the users, the model shows that they can help each other rather than compete.
ACKNOWLEDGMENTS

I would like to thank God for the blessings He gave me while I was working on my thesis. I could only finish it by His grace.

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I am really thankful for the support from my friends and family, here in the U.S and in Indonesia. My beloved mother and grandma, thank you so much for making me the person I am today. Your love and support help me reach my potential. Lastly, thank you to anyone who has helped me complete this thesis.

Silvia A Landa
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CHAPTER 1

1. INTRODUCTION

The world’s population is increasing rapidly, and about 50% live in the urban areas, especially in less developed countries (United Nations 2014). As the majority of the world’s population growth will be absorbed by urban areas, water demand for municipal use will also increase (UN and FAO 1994). Although domestic and municipal water use is only a small portion of global water use, it is escalating worldwide, particularly in the rapidly growing population of urban areas in developing countries (UNDP 2006). As the trend of urban population is increasing rapidly parallel with municipal water demand, this situation increases concern about urban water management.

Increasing population requires more food production, which increases water demand for agriculture. As agriculture is the main component on food security, water scarcity can cause hunger. By 2050, population growth will help double global food demand, which indirectly will increase strain on water resources (Food and Agriculture Organization 2008). Water scarcity usually happens in high population density areas with few water resources (UN Water 2007). Thus, rapid population growth can increase competition for water use between agricultural production and municipal use. The UN and FAO (1994) reported that, mainly in developing countries, future water demand probability shows the competition between sectors such as urban, industrial and agricultural water use.

Water scarcity urges the application of sustainable water management to ensure the fulfillment of future water demand while trying to meet current water demand. It is
important to use all possible water resources by applying integrated water use, where all water users and water resources, such as groundwater, surface water and treated waste water, are connected. In the situation where there is scarcity and competing water demands, a symbiotic relationship between users is preferable, using reclaimed water for agricultural is the common application (Ejaz and Peralta 1995; Winpenny et al. 2010). Thus, this research attempts to show the possibilities of symbiotic urban-agricultural water use relationships using integrated water use.

Because of increasing water demands, water managers need to consider all available water resources, such as surface water, groundwater and reclaimed water. To link these three water resources, we implemented integrated water use, which is an effective strategy for the development and management of water resources. When implementing an integrated water use strategy, groundwater, surface water and reclaimed water are used conjunctively and hydraulically connected. Wrachien and Fasso (2002) noted that if managed appropriately, integrated water resources can yield more water than separately managed surface water or groundwater resources. Thus, properly integrating the use of groundwater, surface water and reclaimed water is necessary to achieve sustainable water resource management.

A simulation-optimization (S-O) model is needed to compute the water management strategy that best satisfies the desired goals without causing unacceptable system responses. There have been several studies on the conjunctive use of surface water and groundwater using the simulation/optimization method. Many of the studies are related to minimizing water shortage (Safavi and Enteshari 2016; Safavi et al. 2010), optimizing water use for irrigation, crop yield (Bejranonda et al. 2011; Ejaz and Peralta
There are also studies related to climate change, the carbon cycle, land-use, population, food production, hydrologic cycle, water demand, water quality, energy-economy (Akhtar et al. 2013; Ejaz and Peralta 1995; Pulido-Velázquez et al. 2006; Zhang 2015), and optimizing multisource water-supply systems to the multi-municipal urban water-supply (Vieira et al. 2011).

Only a few papers, such as Banihabib et al. (2015) and Zhu et al. (2015), used simulation/optimization (S-O) models to find the compromise strategies when there are competing demands between urban and agricultural water use. They are also the only researchers who show the detailed interaction for integrated use between water resources and users. In addition, no papers explicitly demonstrate situations of symbiotic urban-agricultural relationships where both can benefit. Therefore, we employed a multi-objective optimization method to compute sets of optimal strategies that address conflict and competition between agriculture and municipalities to show possible symbiotic relationships.

The primary objective of this research is trying to show the possible symbiotic relationship between urban and agricultural water use by applying integrated water use. This research shows a demonstration of an S-O model that fully links the nonlinear flows of groundwater from multiple aquifer layers, surface waters, reclaimed water, and delayed returns of non-consumed water. Scenarios used in this research apply reclaimed water for irrigation, and allow unconsumed water to return to aquifers and streams.

We employed the multi-objective optimization method to compute sets of optimal strategies that address conflict and competition between different user types, such as
agriculture and municipalities. The S-O model employs a multi-objective function to maximize urban population and agricultural net economic return, subject to constrainable physical state variables and increasing or non-declining urban population and agricultural area. We chose population as one of the objective functions because urban water use depends on population, while the purpose of water applied for irrigation is to get the optimum net return. Different optimization problem management scenarios employ alternative sets of bounds on state and decision variables to represent water supply-driven or demand-driven conditions.

This thesis also shows how to use ModelMuse, a public domain graphic user interface (GUI) of MODFLOW, and SOMOS-Map, a GUI for SOMOS (Simulation and Optimization) application. The practical information presented in this thesis may be valuable for water managers to simulate integrated water use of multiple aquifer layers while guaranteeing possible optimum benefits for users.
CHAPTER 2

2. LITERATURE REVIEW

2.1 Sustainable Water Management

Generally, sustainable water management means assuring the fulfillment of future water demands while trying to meet current water demands. Loucks (2000) emphasized the importance of conserving water sources’ ecological, environmental, and hydrological integrity in sustainable water management. Alley et al. (1999) also highlighted the necessity of retaining the effect of water withdrawal on all hydraulically-connected components in harmless conditions. Therefore, water management should ensure water consumption without damaging current and future water resources ecologically, environmentally, and hydrologically.

In sustainable water management, it is crucial to consider that aquifers require more time than surface waters for recovery from water extraction. The use of sustainable groundwater management is evolving and varies by application, as summarized by Kalf and Woolley (2005). There are many concepts related to sustainable groundwater management, such as sustained yield, perennial yield, mining-yield, and maximum perennial yield (ASCE 1987). Maimone (2004) highlighted the flexibility of the sustainable concept, and the importance of considering the hydrologic system, water demand variation, and the potential impact to water quality. While most researchers agree on the practical definition of groundwater perennial yield, there is no agreeable terminology that is practically applicable for sustainable yield. Perennial yield is one of the most practical concepts. ASCE (1987) defined it as the maximum amount that can be
extracted from groundwater annually without causing adverse effects. Peralta et al. (2011) asserted that it is unsafe to extract groundwater at a constant rate. It is necessary to ensure the acceptability of conditions within a year and between years by considering the intra-annual variations in climatic conditions, water supply, and water demand (ASCE 1987). Therefore, we used a combination of the two strategies. Sustained yield strategy addresses the variation in water supply and demand within a year and perennial safe yield simulates the situation when the sustained yield strategy is applied for a long duration until the aquifer reaches its equilibrium.

2.2 S/O Modeling

Integrated water use models have inherent computational difficulties because the hydraulically connected surface and subsurface systems must be simulated simultaneously. Thus, to derive optimal management alternatives, water managers need a proficient mechanism for aquifer simulation. They can use a simulation-optimization (S-O) model to compute the water management strategy that best satisfies desired goals without causing unacceptable system responses. The embedding technique and response matrix are general methods usually used for simulation-optimization (S-O) models for integrated water use. However, the response matrix is more practical because of the instability of the embedding method in large scale regions (Peralta et al. 2011, 1991; Singh 2014; Takahashi and Peralta 1995).

Using the superposition theory, response matrix methodology can address nonlinear problems with sets of linear convolution equations. The response matrix approach solves the nonlinear system by treating it as a series of linear systems which the series will gradually converge through cycling, a term used by Peralta and Aly (1995)
and Takahashi and Peralta (1995), or Successive Linear Programming, a term used by Ahlfeld et al. (2005).

2.3 Multi-Objective Optimization

Multi-Objective Optimization has been used on many research projects related to water management use multi-objective optimization for various purposes, such as, integrated irrigation management (Kilic and Anac 2010), sustainable water management in the city (Rojas-Torres et al. 2009), and economic return (Roozbahani et al. 2013). Peralta et al. (2014) used multi-objective algorithms to show a true picture of trade-offs between conflicting objectives, such as maximizing water provided from surface and groundwater resources, maximizing hydropower production, and minimizing operation costs of moving water from resources to destinations.

The major differences between multi-objective optimization problems and single-objective optimization problems are the solutions. In single-objective optimizations, the goal is to obtain the best solution, while multiple-objective optimizations usually produce a set of solutions that cannot be compared with each other. This set of solutions is called Pareto optimal solutions, where improving one objective will sacrifice at least one of the other objectives.

There are several proposed methods for generating the Pareto optimal set of a multi-objective optimization, such as weighting objectives, using the e-constraint approach, and goal programming (Konak et al. 2006). The weighting method combines all of the objective functions into a single objective using a set of weighting coefficients. de Weck (2004) proved that this solution for the single-objective formulation lies on the Pareto front for the multi-objective formulation. The second method is called the e-
constraint method, where one objective out of \( n \) is chosen to be minimized and the remaining objectives are constrained to be less than or equal to given target values. This approach finds the solution in the non-convex region of the Pareto front. When there is no specific objective goal, it is more desirable to use the weighting or the constraint method to get a better picture of the possible solution. The last approach is goal programming, which attempts to find specific goal values of these objectives instead of maximizing multiple objectives (Peralta and Kalwij 2012).

2.4 Simulation and Optimization Application

To run the simulation and optimization model, one needs to prepare the simulation input files for MODFLOW and optimization input files for SOMOS. ModelMuse is a graphical user interface (GUI) for MODFLOW–2005 (Harbaugh 2005) and PHAST (Parkhurst et al. 2014). MODFLOW–2005 is a three-dimensional finite-difference groundwater model. It simulates steady and unsteady flow in an irregularly shaped flow system in which aquifer layers can be confined, unconfined, or a combination of confined and unconfined. It is also able to simulate coupled groundwater/surface-water systems because the flow from external stresses, such as flow to wells, areal recharge, evapotranspiration, flow to drains, and flow through river beds, can be simulated (Winston 2009). MODFLOW-2005, and its packages simulate groundwater and surface water flow in response to hydraulic stimuli.

ModelMuse is the most up to date MODFLOW GUI because both are developed by the USGS. Most new MODFLOW packages are already integrated in ModelMuse. Some of MODFLOW-2005 packages used for conjunctive use of surface and groundwater simulation are the Well package (WEL), River package (RIV), Stream
package (STR), Stream Flow Routing package (SFR), Lake package (LAK), Drain package (DRN), Drain Return package (DRT), and Reservoir package (RES). Other packages can be used depending on the type of the simulation problem.

SOMOS (Simulation / Optimization Modeling System) is a group of simulation / optimization (S/O) modules to help optimize managing water resources. SOMOS has the ability to optimize over 90 distinct management goals (objective functions) plus user-defined objectives and multi-objective optimizations. SOMOS constrains all pertinent variables (pumping, stream diversion, flows, cell head, head just outside well casing, concentration, user-defined), and has unique tools. For example, stochastic optimization helps increase strategy robustness and reliability under uncertainty (Peralta 2003). SOMOS can optimize management of a calibrated stream-aquifer system model, and the general SOMOS release includes MODFLOW, MT3DMS, and 14 optimization algorithms.

As a family of simulation / optimization (S/O) modules, SOMOS has three options which are SOMO1, SOMO2, and SOMO3. These options use different combinations of simulation models and surrogate simulator types. SOMO1 uses MODFLOW (and its packages) as a simulation model and superposition (response matrix) and polynomial equations as surrogates. The SOMO1 utility program also lets the modeler use MT3DMS, a Modular 3-D Multi-Species Transport Model for Simulation, to develop surrogate simulators. SOMO2 uses SWIFT as its simulation model, and superposition and polynomial equations as surrogates. Similar to SOMO1, the surrogates can be developed for a wide range of contaminant transport processes using other S models.
Similar to SOMO1, the SOMO3 version comes with MODFLOW and MT3D. However, instead of using response matrix methods (RMMs), polynomial and other response functions as substitute simulators like SOMO1, SOMO3 uses artificial neural networks (ANNs) as surrogates (Peralta 2003). SOMOS verifies the accuracy of all surrogates so they can be used confidently. SOMOS is designed to allow the groundwater professional to best utilize his skills in the man-machine process of developing optimal water management strategies.

The SOMO1 option employs response matrix methods (RMMs) to represent the system response to stimulation from decision variables within the optimization model. It is assumed that the physical system can be simulated using linear systems theory, but SOMO1 has special features that allow it to satisfactorily address nonlinear systems as well (Peralta et al. 2008). There are three RMMs convolution equation options in SOMO1, termed CGU1, developed by Peralta and Kalwij (2012), CGU2, which replicates salient features of the RMM within GWM but using a different structure (Ahlfeld et al. 2005), and CGU4 (Timani 2015). Timani (2015) reported that, compared to other CGUs, the CGU4 requires less computation time in stream-aquifer S-O model testing. He also summarized the differences in procedures to generate coefficients (CG#) and utilize coefficients (CU#) in all three equations, as shown in Table 1.

SOMOS is unique in the range of variables, constraints, and objective function types it is programmed to address. There are common use objective functions, such as maximize pumping, stream diversion, economic return, goal programming and user defined equations. Because the SOMOS objective functions were written in GAMS,
Table 1 General differences between SOMOS response matrix algorithms

<table>
<thead>
<tr>
<th>Feature</th>
<th>Phas</th>
<th>CGU1</th>
<th>CGU2</th>
<th>CGU4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stress periods need to have equal duration</td>
<td>G*</td>
<td>Yes</td>
<td>No</td>
<td>Only within an ME****</td>
</tr>
<tr>
<td>Unit stimulus used at stress period</td>
<td>G</td>
<td>1</td>
<td>All periods have unit stimuli</td>
<td>Only 1 of ME have stimuli</td>
</tr>
<tr>
<td>IC indices***</td>
<td>G/U</td>
<td>Observation location, stimulus location, time index based on periods of stress and observation</td>
<td>Observation location, observation time, stimulus location specific to the same time as the observation time</td>
<td>Observation location, stimulus location, time index based on periods of stress and observation</td>
</tr>
<tr>
<td>IC reuse for multiple stimulus period</td>
<td>U**</td>
<td>Yes</td>
<td>No</td>
<td>Within an ME</td>
</tr>
</tbody>
</table>

* G = generation; ** U = use; ***IC = Influence Coefficient; ****ME= Management Era

General Algebraic Modeling System, the user defined objective function also needs to be written in GAMS. The user defined equation is primarily designed to allow users to optimize varieties of functions as long as the variables are derived from SOMOS variables.

SOMOS-Map is a GUI for SOMOS developed by the SSOL (Systems Simulation/Optimization Laboratory) at Utah State University. SOMOS-Map is a modification of MapWindow GIS, a free, spatial data viewer and geographic information system, with the SOMOIN plugin. Thus, SOMOS-Map has the current MapWindow GIS capability.

The SOMOIN plugin allows users to call any of the SOMO1, SOMO2 or SOMO3 modules of SOMOS (Simulation/Optimization Modeling Systems). SOMOIN also enables the SOMOS-Map to overlay simulation and optimization input and output data on background images in GIS format or in one of the several recognized image file
formats (Timani 2016). This capability allows users to visualize initial and resulting heads, mass removal, mass remaining or concentrations of a strategy or scenario with respect to time. In addition to initializing SOMOS, the SOMOIN plugin is also able to facilitate preparing input files that specify an optimization problem for SOMOS to solve, and allows data retrieval and analysis for pre- and post-processing of the input data and output data of simulation models.
3. METHODOLOGY

3.1 Study Area

In this research, we used a hypothetical study area to apply linkages between water resources and water users as explained in Figure 1 and Figure 2. We used the most common boundary conditions to represent the real system and MODFLOW WEL package to represent recharge and specified flux. We used well head correction for extraction wells but not for injection wells when representing recharge and specified flux. Thus, extraction well head is corrected based on the well size while injection well head is the same as the cell head. The inputs and assumptions used for the study area hydrologic system can be found in Appendix A.

Figure 1 Linkages between water sources and users
3.2 Employed S-O Technique and the Convolution Equation

Integrated use models have important computational implications, because surface and subsurface systems must be simulated simultaneously due to hydraulic interactions between them. As a result, we needed an efficient tool in order for the simulation to derive optimal management alternatives over periods of time. We used a simulation-optimization (S-O) model to compute the water management strategy that best satisfies the desired goals without causing unacceptable system responses.

In this research we used simulation/optimization (S-O) models and response matrix methods (RMMs) to develop surrogate simulators (also called influence coefficients) for calculating optimal transient groundwater flow management. This method was developed by Timani (2015) who called it CGU4. CGU4 allows simulation for inconsistent stress periods while its predecessor CGU1 only simulates consistent stress period durations. Influence coefficients are computed using CGU4 via Equation (1) to compute state variables due to optimal stimuli (decision variable) rates.
\[
\Psi_{\hat{o},T_i} = \Psi^{non}_{\hat{o},T_i} + \sum_{k_s = \tau_i}^{T_i} \sum_{s = 1}^{M^p} \delta^{\Psi_p}_{\hat{o},\hat{e},T_i-k_s+\tau_i} \frac{p_{\hat{e},k_s}^{at}}{p_{\hat{e},k_s}} \quad | \quad \tau_i \& T_i \in ME_i \text{ for } i = 1 \ldots I \quad (1)
\]

where,

\(\Psi^{non}_{\hat{o},T_i}\) state variable value at location \(\hat{o}\) at end of period \(T_i\) units depend on SV;

\(\Psi^{non}_{\hat{o},T_i}\) background (non-optimal) state variable value at location \(\hat{o}\) at end of period \(T_i\) showing the effect of all stimuli happening during stress periods in all previous management eras, units depend on SV;

\(\delta^{\Psi_p}_{\hat{o},\hat{e},T_i-k_s+\tau_i}\) state variable (\(\Psi\)) influence coefficient describing state variable response at location \(\hat{o}\) by end of observation period \(T_i\) to a unit pumping (\(p_{\hat{e},k_s}^{at}\)) at well \(\hat{e}\) in period \(k_s\), units depend on SV;

\(k_s\) stimulus stress period index belonging to same management era as \(T_i\);

\(\tau_i\) 1st stress period index of the management era \(i\) to which \(T_i\) and \(k_s\) belong;

\(M^p\) number of managed groundwater extraction locations;

\(ME_i\) Management Era \(i\), each consisting of one or more sequential transient periods that have the same duration;

\(Y\{ME_i\}\) set of management eras;

\(I\) total number of management eras.

3.3 S-O Scenarios Overview and Equations

In this research, we maximized the urban population and net return from agriculture using the weighting and the e-constraint method to make a set of Pareto
optimal strategies. The model is described in Figure 1, and summarized in Table 2. Each S-O scenario has nine periods for four years, where the first three years are transient periods and the last year is steady state. The transient periods represent intra-annual system variations.

3.3.1 Population

3.3.1.1 Objective Function

The objective function, Equation (2), is modified from the population objective function used by Timani (2015). Timani optimized population using groundwater as the only water source, while here we also used surface water. Constraints of the population objective function are shown in Equations (3) – (11).

\[
\text{Max } Z_{550} = \sum_{k=1}^{n} \sum_{u=1}^{M_{PB}} C_{\hat{u},k}^{\text{PopPump}} \cdot \text{PopPump}_{\hat{u},k} - \sum_{k=1}^{n} \sum_{u=1}^{M_{DB}} C_{\hat{u},k}^{\text{PopDiv}} \cdot \text{PopDiv}_{\hat{u},k} 
\]

Subject to:

\[
Z_{550}^{LB} \leq Z_{550} \leq Z_{550}^{UB} 
\]

\[
h_{u,k} \geq h_{u,k}^{LB} 
\]

\[
S_{u,k} \geq S_{u,k}^{LB} 
\]

\[
\text{PopPump}_{\hat{u},k+1}^{\text{Indr}} \geq \text{PopPump}_{\hat{u},k}^{\text{Indr}} 
\]

\[
\text{PopPump}_{\hat{u},k+1}^{\text{Odr}} \geq \text{PopPump}_{\hat{u},k}^{\text{Odr}}
\]

for \( \text{Pr} C_{\hat{u},k}^{\text{Odr}} > 0 \) and \( \text{Pr} C_{\hat{u},k+1}^{\text{Odr}} > 0 \)

\[
\text{PopDiv}_{\hat{u},k+1}^{\text{Indr}} \geq \text{PopDiv}_{\hat{u},k}^{\text{Indr}} 
\]
\[ \text{PopDiv}^{\text{Otdr}}_{\hat{u},k+1} \geq \text{PopDiv}^{\text{Otdr}}_{\hat{u},k} \]

for \( \text{Pr} \text{Cp}^{\text{Otdr}}_{\hat{u},k} > 0 \) and \( \text{Pr} \text{Cp}^{\text{Otdr}}_{\hat{u},k+1} > 0 \)

(9)

\[ \text{PotIndrTotal}^{\text{Indr}}_{\hat{u},k} = \text{PopPump}^{\text{Indr}}_{\hat{u},k} + \text{PopDiv}^{\text{Indr}}_{\hat{u},k} \]

(10)

\[ \text{PotIndrTotal}^{\text{Indr}}_{\hat{u},k+2} = \text{PotIndrTotal}^{\text{Indr}}_{\hat{u},k} \]

for \( k = 11 \)

(11)

where,

\( Z_{550} \) = objective function value for population, [person];

\( M^{PB} \) = total number of municipalities extraction blocks;

\( M^{DB} \) = total number of municipalities stream diversion blocks;

\( n \) = total number of periods;

\( k \) = index for stress period;

\( \hat{u} \) = index denoting potential pumping block or stream water diversion block locations;

\( C_{\hat{u},k}^{\text{PopPump}} \) = population weighting coefficient for municipality extraction block \( \hat{u} \) at period \( k \);

\( C_{\hat{u},k}^{\text{PopDiv}} \) = population weighting coefficient for municipality stream diversion block \( \hat{u} \) at period \( k \);

Since there is no outdoor water use from October through March, the weighting coefficient in these periods is 1, while from June through September the weighting coefficient is 0.5 to maintain a total coefficient equal to one for the population objective function in every period.
\( PopPump_{\hat{u},k} = \) municipality population at period \( k \) supported from extraction block \( \hat{u} \), [person]

\[
= PopPump_{\hat{u},k}^{Indr} + PopPump_{\hat{u},k}^{Ondr}
\]

\[
= PopPump_{\hat{u},k}^{Indr}
\]

\[
= PopPump_{\hat{u},k}^{Ondr}
\]

\( PopDiv_{\hat{u},k} = \) municipality population at period \( k \) supported from diversion block \( \hat{u} \), [person]

\[
= PopDiv_{\hat{u},k}^{Indr} + PopDiv_{\hat{u},k}^{Ondr}
\]

\[
= PopDiv_{\hat{u},k}^{Indr}
\]

\[
= PopDiv_{\hat{u},k}^{Ondr}
\]

The super script LB indicates lower bound;

The super script UB indicates upper bound;

\( pb_{\hat{u},k} \) = managed pumping at extraction block \( \hat{u} \) in period \( k \), \([L^3/T]\)

\( rb_{i,k} \) = managed return flow to aquifer injection block \( \hat{i} \) in period \( k \), \([L^3/T]\)

\( db_{\hat{u},k} \) = managed diversion block \( \hat{u} \) in period \( k \), \([L^3/T]\)

\( vb_{i,k} \) = managed return flow to stream at diversion block \( \hat{i} \) in period \( k \), \([L^3/T]\)

\( M^{PR} \) = number of municipalities injection wells;

\( M^{DR} \) = number of municipalities return flow to stream locations;

\( h_{u,k} \) = head at location \( u \) at time \( k \), \([L]\); Peralta et al. (2008) suggested to limit the head depletion by 12%.
\( S_{u,k} \) = stream flow rate at location \( u \) at time \( k \), \([L^3/T]\); we assumed 20 ac-ft/day as the lower bound value to allow fish migration.

\( \text{PopPump}^{\text{Indr}}_{u,k} \) = city population whose indoor water need in period \( k \) can be supported by extraction block \( \hat{u} \), at period \( k \), \([\text{person}]\);

\( \text{PopPump}^{\text{Odr}}_{u,k} \) = city population whose outdoor water need in period \( k \) can be supported by extraction block \( \hat{u} \), at period \( k \), \([\text{person}]\);

\( \text{PopDiv}^{\text{Odr}}_{\hat{u},k} \) = city population whose outdoor water need in period \( k \) can be supported by stream diversion block \( \hat{u} \), at period \( k \), \([\text{person}]\);

\( \text{PopDiv}^{\text{Indr}}_{\hat{u},k} \) = city population whose indoor water need in period \( k \) can be supported by stream diversion block \( \hat{u} \), at period \( k \), \([\text{person}]\);

\( \text{PrCp}^{\text{Odr}}_{\hat{u},k} \) = city \( \hat{u} \) quarterly per capita outdoor water demand during period \( k \), (Appendix A), \([L^3/T/\text{person}]\);

\( \text{Pop}^{\text{Indr}}_{\hat{u},k} = \text{PopPump}^{\text{Indr}}_{\hat{u},k} + \text{PopDiv}^{\text{Indr}}_{\hat{u},k} \), total indoor population at location \( \hat{u} \), \([\text{person}]\);

Equations (12) and (13) were derived by Timani (2015) to distribute the managed pumping and diversion between indoor and outdoor water uses; we modified it with Equations (14) – (15).

\[
\text{WB}^{\text{Indr}}_{\hat{u},k} = p b_{\hat{u},k} \times \text{Por}^{\text{Indr}}_{k}
\]  \( (12) \)

where,

\( \text{WB}^{\text{Indr}}_{\hat{u},k} \) = managed pumping at extraction block \( \hat{u} \) in period \( k \) to be used indoors, \([L^3/T]\);

\( \text{Por}^{\text{Indr}}_{k} \) = proportion of managed pumping in period \( k \) assigned for indoor use,

\([\text{Dimensionless}]\).
\[ WB_{\text{O,} k} = pb_{\text{O,} k} \times Por_{k} \]  

(13)

where,

\[ WB_{\text{O,} k} = \] managed pumping at extraction block \( \hat{u} \) in period \( k \) to be used outdoors, \([L^3/T]\); 

\[ Por_{k} = \] proportion of managed pumping in period \( k \) assigned for outdoor use, [Dimensionless].

\[ DB_{\text{I,} k} = db_{\text{I,} k} \times Por_{k} \]  

(14)

where,

\[ DB_{\text{I,} k} = \] managed diversion block \( \hat{u} \) in period \( k \) to be used indoors, \([L^3/T]\); 

\[ DB_{\text{O,} k} = db_{\text{O,} k} \times Por_{k} \]  

(15)

where,

\[ DB_{\text{O,} k} = \] managed diversion block \( \hat{u} \) in period \( k \) to be used outdoors, \([L^3/T]\);

Timani (2015) used Equations (16) and (17) to establish a connection between populations and managed pumping decision variables, and we modified those equations by adding diversion as the decision variables. See Equations 18 and 19 for modified equations. Appendix A gives details about computing indoor and outdoor quarterly per capita water consumption.

\[ PopPump_{\text{I,} k}^{\text{Indr}} = \frac{WB_{\text{I,} k} \times Pr C_{\text{P,} k}^{\text{Indr}}}{Dur (k)} \]  

(16)

where,

\[ Dur (k) = 90 \text{days} = \] stress period \( k \) duration, \([T]\);
\( PrCp_{\text{Indr},k} \) = town \( \hat{u} \) quarterly per capita indoor water use during period \( k \), (Appendix A), \([ L^3/T/person \]);

\[
PopPump_{\text{Odr},k}^{\text{Odr}} = \frac{WB_{\text{Odr},k} \times PrCp_{\text{Odr},k}}{Dur(k)} \quad (17)
\]

\[
PopDiv_{\text{Indr},k}^{\text{Indr}} = \frac{DB_{\text{Indr},k} \times PrCp_{\text{Indr},k}}{Dur(k)} \quad (18)
\]

\[
PopDiv_{\text{Odr},k}^{\text{Odr}} = \frac{DB_{\text{Odr},k} \times PrCp_{\text{Odr},k}}{Dur(k)} \quad (19)
\]

The Utah Division of Water Resources (2010) reported that, annually, 35% of water reaching homes is used indoors while the other 65% is used outdoors. Following Timani's (2015) assumption, outdoor water demand varies quarterly mimicking the reference alfalfa ET variation, while indoor water use is constant through the year.

Outdoor water use is assumed absent from October through March, where \( Por_{k,\text{Odr}} = 0 \) and \( Por_{k,\text{Indr}} = 1 \). In the April-June quarter, about a quarter, \( Por_{k,\text{Indr}} = 0.2566 \), of the water reaching homes is used indoors and the rest is used outdoors, \( Por_{k,\text{Odr}} = 0.7434 \). In the July-September quarter, 18.08% of urban water is used indoors, \( Por_{k,\text{Indr}} = 0.1808 \), and the rest is used outdoors, \( Por_{k,\text{Odr}} = 0.8192 \). The detailed calculations can be found in Appendix A.

3.3.1.2 Return Flow to Aquifer

We used Equation (20) to quantify return flow to the aquifer, and the equation is modified from Timani’s return flow to aquifer equation.
\[ rb_{i,kr} = \sum_{k=1}^{n} \left[ C_{kr-k+1}^{RF} \times (pb_{u,k} - db_{u,k}) \right] \quad \text{for } 1 \leq kr - k + 1 \leq \text{Lag}_{\text{Max}} + 1 \]  

(20)

where,

\[ db_{u,k} = \text{managed diversion block } \hat{u} \text{ in period } k, \left[ L^3/T \right]; \]

\[ pb_{u,k} = \text{managed extraction block at location, } \hat{u}, \text{ during quarter } k, \left[ L^3/T \right]; \]

\[ rb_{i,kr} = \text{return flow at managed injection block } \hat{i}, \text{ during quarter } kr, \text{ units are } p_{u,k} \text{ and } d_{u,k} \text{ dependent } \left[ L^3/T \right]; \]

\[ k = \text{managed extraction well and stream diversion stress period}; \]

\[ kr = \text{stress period during which recharge is taking place}; \]

\[ n = \text{total number of stress periods}; \]

\[ C_{kr-k+1}^{RF} = \text{multiplier quantifying return flow to aquifer occurring at stress period } kr \text{ due to managed extraction block } \hat{u} \text{ and diversion block } \hat{u} \text{ occurring at stress period } k, \left[ \text{Dimensionless} \right]; \]

\[ \text{Lag}_{\text{Max}} = \text{maximum number of stress periods after the period of groundwater extraction, during which recharge from indoor use of extracted water occurs; here } = 1, \left[ \text{Dimensionless} \right]. \]

The values of \( C_{kr-k+1}^{RF} \) are computed using Equation (21). This equation was derived by (Timani 2015), and the detailed calculation can be found in Appendix A.

\[ C_{kr-k+1}^{RF} = \frac{C_k^{ET} \times C_{\text{ann}}^{OU}}{C_k^{IU} + C_{\text{ann}}^{OU} \times C_k^{ET}} \times C_{\text{ROU}} \times C_{kr}^{RFAq} \]  

(21)

where,

\[ C_k^{ET} = \text{quarterly average ET at period } k \text{ divided by annual average ET, } \left[ \text{Dimensionless} \right]; \]
\( C_{IU}^k \) = proportion of average groundwater pumping for indoor water use during period \( k \), [Dimensionless];

\( C^{ROU} = 0.67 \) = the portion of water used outdoors that recharges the aquifer, [Dimensionless];

\( C_{kr}^{RFAq} \) = the portion of the recharge (return flow) occurring during stress period \( kr \), [Dimensionless].

Because we assumed constant indoor water demand through the year, \( C_{IU}^k \) is equal to the portion of annual water that is used indoors which is 0.35. Using the same assumption as Timani (2015), there is no delay for the majority (0.75) of unconsumed outdoor water when reaches the aquifer (\( C_{kr}^{RFAq} = 0.75 \) for \( kr = 1 \)), while the rest (0.25) reaches the aquifer in the following period (\( C_{kr}^{RFAq} = 0.25 \) for \( kr = 2 \)). Detailed calculation can be found in Appendix A.

3.3.1.3 Return Flow to Stream

We used Equation (22) to quantify return flow to the stream

\[
v_{b, i, kr} = \left( DB_{i, k}^{Indr} - WB_{i, k}^{Indr} \right) x C^{RFSr}
\]

(22)

where,

\( v_{b, i, kr} \) = return flow at managed diversion block \( i \), during quarter \( kr \), units are \( DB_{i, k}^{Indr} \) and \( WB_{i, k}^{Indr} \) dependent \([L^3/T]\);

\( C^{RFSr} \) = proportion of indoor water use that returns to the stream [Dimensionless];

For the percentage of indoor water use that returns to a waste water treatment plant, Geyer et al. (1963) suggested to use approximately 94 %, when there is an absence of more accurate data. The National Handbook of Recommended Methods for Water
Data Acquisition (USGS, 1980) indicated that 97-98% of indoor water use is unconsumed. Therefore, in this research we assumed the potential of reclaimed municipal wastewater is 95%. Reclaimed water that is discharged to the stream will be diluted with water in the stream and used by downstream agricultural water users to increase their water supply.

3.3.2 Agriculture

3.3.2.1 Objective Function

We derived Equation (23) to optimize the agricultural net return, and we used Equations (4), (5), and (24) – (26) as constraints.

\[
\text{Min } Z_1 = \sum_{k=1}^{n} \left( \sum_{\hat{u}=1}^{M_{PB}} \left( C_{\hat{u},k}^p \times p b_{\hat{u},k} \right) + \sum_{\hat{u}=1}^{M_{PB}} \left( C_{\hat{u},k}^d \times d b_{\hat{u},k} \right) \right)
\]

(23)

Subject to:

Equations (4) and (5)

\[
Z_1^{LB} \leq Z_1 \leq Z_1^{UB}
\]

(24)

\[
AgArea_{\hat{u},k+1} \geq AgArea_{\hat{u},k}
\]

for \( AgArea_{\hat{u},k+1} > 0 \) and \( AgArea_{\hat{u},k+1} > 0 \)

(25)

\[
AgArea_{\hat{u},k+1} = AgArea_{\hat{u},k}
\]

for \( k=11 \)

(26)

where,

\( Z_1 \) = objective function (net return) value, [$] ;

\( db_{\hat{u},k} \) = managed diversion block \( \hat{u} \) in period \( k \left[ L^3 / T \right] ; \)
\( \hat{p}b_{a,k} \) = managed extraction block \( \hat{u} \) in period \( k \) \( [L^3/T] \);  

\( C_{a,k}^p \) = net return weighting coefficient for agriculture extraction block \( \hat{u} \) at period \( k \), \( \$/L^3/T \);  

\( C_{a,k}^d \) = net return weighting coefficient for agriculture diversion block \( \hat{u} \) at period \( k \), \( \$/L^3/T \);  

\( \text{AgArea}_{a,k} \) = agriculture area in location \( \hat{u} \) at period \( k \), \( [L^2] \);  

\[ \frac{-\hat{p}b_{a,k} + \hat{d}b_{a,k}}{\text{Irrigation}_k} \]  

\( \text{Irrigation}_k \) = Water applied to irrigation per unit area at period \( k \), \( [L/T] \).  

where,  

It is assumed, only 35% of applied water for irrigation is lost to ET, and the rest of it returns to the aquifer and to the stream  

\[ \text{Irrigation}_k = \frac{E_{T_k}}{35\%}; \]  

\( E_{T_k} \) = average ET values in period \( k \), \( [L/T] \).  

The values of \( C_{a,k}^p \) are computed using Equation (27) and the calculation can be found in Appendix A.  

\[ C_{a,k}^p = \frac{NR}{\text{Irrigation}_k} \quad \text{(27)} \]  

\( NR \) = Net return for agriculture water use=0.1263, \( \$/L^3 \).  

The monotonic incremental of agricultural area is only applied during the productive seasons of April through September. We assume the cost to extract and divert water is constant because in this hypothetical study area the well and diversion location are specified by 5 km by 5 km cells with no exact location within cells. Thus, we used an
average cost that resulted in the NR value. In this research, the value of NR is assumed 511.26 $/acre (=0.1263 $/m²) based on 2015 net return for irrigated alfalfa in Box Elder County, Utah (Holmgren et al. 2015). We used a constant value for the net return without considering the fixed interest rate because the model is only simulated for four years.

3.3.2.2 Return Flow to Aquifer

We used Equation (28) to quantify return flow to the aquifer. This equation is a modification of the equation derived by Timani (2015)

\[
rb_{i,kr} = \sum_{k=1}^{n} \left[ C_{kr-k+1}^{RFa} \times (p_{\hat{a},k} - d_{\hat{a},k}) \right] \text{ for } 1 \leq kr - k + 1 \leq Lag_{Max} + 1 \tag{28}
\]

where,

\[rb_{i,kr} = \text{return flow at managed injection block } i \text{ during quarter } kr, \text{ units are } p_{\hat{a},k} \text{ and } d_{\hat{a},k} \text{ dependent [L³/T];}
\]

\[k = \text{managed extraction well and stream diversion stress period;}
\]

\[kr = \text{stress period during which recharge is occurring;}
\]

\[n = \text{total number of stress periods;}
\]

\[C_{kr-k+1}^{RFa} = \text{multiplier quantifying return flow to aquifer occurring at stress period } kr \text{ due to managed extraction block } \hat{a} \text{ and diversion block } \hat{a} \text{ occurring at stress period } k, \text{ [Dimensionless];}
\]

\[Lag_{Max} = \text{maximum number of stress periods for return flow to aquifer delay after the period of groundwater extraction occurs [Dimensionless].}
\]

The values of \(C_{kr-k+1}^{RFa}\) are computed using Equation (29) and the calculations can be found in Appendix A.
\[ C_{kr-k+1}^{RFa} = C_k^{ETs} \times C_k^{DP} \times C_{kr}^{RFAq} \]  

(29)

where,

\[ C_k^{ETs} = \text{quarterly average ET in period k divided by seasonal average ET, [Dimensionless];} \]

\[ C_k^{DP} = \text{the portion of water applied to the field by irrigation that recharges the aquifer trough deep percolation, [Dimensionless];} \]

\[ C_{kr}^{RFAq} = \text{the portion of the recharge (return flow) occurring during stress period kr,} \]

[Dimensionless].

We assumed \( C^{DP} = 50\% \), based on the UDNR (1997) report about the percentage of water applied for irrigation that replenishes Cache Valley’s aquifer. We used the same assumption for lag time in unconsumed irrigation water that percolates to the aquifer as unconsumed outdoor urban water use. Thus, in April-June, 27.88% of irrigation water returns to the aquifer during that quarter and 9.29% refills the aquifer during the next quarter. As for the extraction during the July-September quarter, 30.72% and 10.24% of the irrigation water percolated to the aquifer in that quarter and following quarter, respectively. Detailed calculations can be found in Appendix A.

3.3.2.3 Return Flow to Stream

We used Equation (30) to quantify return flow to the stream

\[ v_{b, i, kr} = \left( DB_{i, k}^{Indr} - WB_{i, k}^{Indr} \right) \times C_{RFStr} \]  

(30)

where,

\[ v_{b, i, kr} = \text{return flow at managed diversion block i, during quarter kr, units are} DB_{i, k}^{Indr} \]

and \( WB_{i, k}^{Indr} \) dependent, \([L^3/T]\);
\( C_{RFStr} \) = proportion of indoor water use that returns to the stream \([\text{Dimensionless}]\);

For alfalfa irrigation, Schwankl et al. (2007) suggested that the tail-water volume is 15 to 25 percent of the water applied to irrigation. To make a safe assumption, we used \( C_{RFStr} = 15\% \) for the tail water. Because the study area has an arid climate, we assumed that the water supply for agriculture is solely supported by irrigation.

### 3.3.3 Maximizing Population and Net-Return from Agriculture

Equation (31) is the combined objective function of the population and agricultural net return.

\[
\min Z = W_{550} \times \left( \sum_{k=1}^{n} \sum_{a=1}^{M^p} C_{\hat{a},k}^p \times PopPump_{\hat{a},k} - \sum_{k=1}^{n} \sum_{a=1}^{M^{10b}} C_{\hat{a},k}^{10b} \times PopDiv_{\hat{a},k} \right) \\
+ W_{1} \times \left( \sum_{k=1}^{n} \sum_{a=1}^{M^p} \left( C_{\hat{a},k}^p \times pb_{\hat{a},k} \right) + \sum_{a=1}^{M^{10b}} \left( C_{\hat{a},k}^{10b} \times db_{\hat{a},k} \right) \right)
\]

Subject to:

Adopt constraints from each objective function \((Z_{550} \text{ and } Z_1)\).

where,

\( W_{550} \) = weighting for objective function 550 \((Z_{550})\);

\( W_1 \) = weighting for objective function 1 \((Z_1)\);

A Pareto front or tradeoff curve is needed in order to provide complete information on objective values and tradeoffs. This curve illustrates how change in agricultural net return is related to change in urban population.
Table 2 Different weightings and constraints for each scenario

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Constraints</th>
<th>Weighting</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>$W_{T550}$</td>
</tr>
<tr>
<td>Scenario1</td>
<td>Equation (3): $0 \leq Z_{550} \leq 0$</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Equation (24): $10^{-10} \leq Z_1 \leq 10^{10}$</td>
<td></td>
</tr>
<tr>
<td>Scenario2</td>
<td>Equation (3): $10^{-10} \leq Z_{550} \leq 10^{10}$</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Equation (24): $10^{-10} \leq Z_1 \leq 10^{10}$</td>
<td></td>
</tr>
<tr>
<td>Scenario3</td>
<td>Equation (3): $10^{-10} \leq Z_{550} \leq 10^{10}$</td>
<td>-1</td>
</tr>
<tr>
<td></td>
<td>Equation (24): $10^{-10} \leq Z_1 \leq 10^{10}$</td>
<td></td>
</tr>
<tr>
<td>Scenario4</td>
<td>Equation (3): $10^{-10} \leq Z_{550} \leq 10^{10}$</td>
<td>-1</td>
</tr>
<tr>
<td></td>
<td>Equation (24): $10^{-10} \leq Z_1 \leq 10^{10}$</td>
<td></td>
</tr>
<tr>
<td>Scenario5</td>
<td>Equation (3): $10^{-10} \leq Z_{550} \leq 10^{10}$</td>
<td>-1</td>
</tr>
<tr>
<td></td>
<td>Equation (24): $0 \leq Z_1 \leq 0$</td>
<td></td>
</tr>
</tbody>
</table>

Common equations for scenarios 1-5:

Objective function equation: Equation (31)

Constraints: Equations (4) – (11), and Equations (25) – (26).

Indirectly, 1 person is assumed equal to $1.

3.3.4 Procedures

The general procedure for applying multi-objective optimization for integrated use of surface water, reclaimed water and multi-layer aquifers using ModelMuse and SOMOS-Map is shown in Figure 3. The detailed step by step explanation can be found in Appendix B. The important thing to remember, SOMOS runs a modified version of MODFLOW-2005; this is the reason there are some MODFLOW files created using ModelMuse that need to be translated. *.wel and *str files need to be translated from free
format to fixed format, and *.oc files needs to be translated from words format to numeric format.

Figure 4 shows the role of ModelMuse and SOMOS in the linkages of water sources and users. Two MODFLOW packages are used for the simulation: the Well package for groundwater extraction and the Stream package for surface water diversion. In this research, SOMOS simulated and optimized the population and agricultural net return as derivatives of groundwater extraction and stream diversion. We used the user defined equation option in SOMOS to link the return flow to the stream and aquifer.

Figure 3 Flow chart of using ModelMuse and SOMOS-Map to make an S-O model
Figure 4 Using ModelMuse and SOMOS to link water sources and users
4. RESULTS AND DISCUSSION

4.1 Results

The optimization problems are simulated for four years. The first three years address stream flow and water demand variation within the year; the last year simulates average flow and water demand. We set constraints for population and agricultural area to be equal for years 3 and 4 in order to represent the quasi-equilibrium simulation.

4.1.1 Year 1

In the first year, Figure 5 and Table 3 show that the agricultural net return increase in scenario 2 from scenario 1 is 8.5%, and the population increase in scenario 4 from scenario 5 is 0.3%.

Figure 5 Pareto optimal year 1.
### Table 3 Optimization result year 1

<table>
<thead>
<tr>
<th>Scenario Number</th>
<th>Weight OBJ 550</th>
<th>Total Population (OBJ550)</th>
<th>Population change from scenario 5</th>
<th>Agriculture net return (OBJ 1)</th>
<th>Weight OBJ 1</th>
<th>Agricultural net return change from scenario 1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scenario 1</td>
<td>0</td>
<td>0</td>
<td></td>
<td>11789691</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Scenario 2</td>
<td>0</td>
<td>23897</td>
<td>-92.6%</td>
<td>12790040</td>
<td>1</td>
<td>8.5%</td>
</tr>
<tr>
<td>Scenario 3</td>
<td>1</td>
<td>23898</td>
<td>-92.6%</td>
<td>12789952</td>
<td>1</td>
<td>8.5%</td>
</tr>
<tr>
<td>Scenario 4</td>
<td>1</td>
<td>325693</td>
<td>0.3%</td>
<td>9655920</td>
<td>0</td>
<td>-18.1%</td>
</tr>
<tr>
<td>Scenario 5</td>
<td>1</td>
<td>324860</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td></td>
</tr>
</tbody>
</table>

![Figure 6 Pareto optimal year 2.](image)

#### 4.1.2 Year 2

In the second year, Figure 6 and Table 4 show that the agricultural net return increase in scenario 2 from scenario 1 is 8.7%, and the population increase in scenario 4 from scenario 5 is 0.4%.
Table 4 Optimization result year 2

<table>
<thead>
<tr>
<th>Scenario Number</th>
<th>Weight OBJ 550</th>
<th>Total Population (OBJ550)</th>
<th>Population change from scenario 5</th>
<th>Agriculture net return (OBJ 1)</th>
<th>Weight OBJ 1</th>
<th>Agricultural net return change from scenario 1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scenario 1</td>
<td>0</td>
<td>0</td>
<td>11817698</td>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Scenario 2</td>
<td>0</td>
<td>23901</td>
<td>-92.8%</td>
<td>12841098</td>
<td>1</td>
<td>8.7%</td>
</tr>
<tr>
<td>Scenario 3</td>
<td>1</td>
<td>24625</td>
<td>-92.6%</td>
<td>12813421</td>
<td>1</td>
<td>8.4%</td>
</tr>
<tr>
<td>Scenario 4</td>
<td>1</td>
<td><strong>332657</strong></td>
<td>0.4%</td>
<td>9717189</td>
<td>0</td>
<td>-17.8%</td>
</tr>
<tr>
<td>Scenario 5</td>
<td>1</td>
<td>331445</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td></td>
</tr>
</tbody>
</table>

Figure 7 Pareto optimal year 3.

4.1.3 Year 3

In third year, Figure 7 and Table 5 show that the agricultural net return increase in scenario 2 from scenario 1 is 8.6%, and the population increase in scenario 4 from scenario 5 is 0.4%.
4.1.4 Year 4

In the fourth year, Figure 8 and Table 6 show that the agricultural net return increase from scenario 1 to scenario 2 is 8.6%. The population increase from scenario 5 to scenario 4 is 0.4%. The result is the same as increase in year 3 because we constrained the population and agriculture supported in year 4 to be equal to year 3.
Table 6 Optimization result year 4

<table>
<thead>
<tr>
<th>Scenario Number</th>
<th>Weight OBJ 550</th>
<th>Total Population (OBJ550)</th>
<th>Population change from scenario 5</th>
<th>Agriculture net return (OBJ 1)</th>
<th>Weight OBJ 1</th>
<th>Agricultural net return change from scenario 1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scenario 1</td>
<td>0</td>
<td>0</td>
<td>11879979</td>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Scenario 2</td>
<td>0</td>
<td>23901</td>
<td>-92.8%</td>
<td>12900627</td>
<td>1</td>
<td>8.6%</td>
</tr>
<tr>
<td>Scenario 3</td>
<td>1</td>
<td>25633</td>
<td>-92.3%</td>
<td>12813421</td>
<td>1</td>
<td>7.9%</td>
</tr>
<tr>
<td>Scenario 4</td>
<td>1</td>
<td>332657</td>
<td>0.4%</td>
<td>9717189</td>
<td>0</td>
<td>-18.2%</td>
</tr>
<tr>
<td>Scenario 5</td>
<td>1</td>
<td>331445</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td></td>
</tr>
</tbody>
</table>

4.1.5 Tight Constraints

The total number of periods is 13, where the first 3 years are the transient years with four periods per year, and the fourth year simulated the steady perennial yield. Tight constraints shown here are the state variables that reached their lowest bounds due to their association with the decision variables. For example, enough water is extracted in agriculture area 1 (in both scenario 1 and 2 at well 1, period 7 (1.7)) to reach the lowest permissible head level, as shown in Table 7. Stream flows in some locations, especially downstream of diversions, reach their lowest acceptable rate as a result of maximum upstream diversion. The blue color shows the same tight head constraints in scenarios 1 and 2, and the red color shows the same tight head constraints in scenarios 4 and 5. All scenarios start with the same initial head, so locations and periods with the same tight constraints show that they have the same change in head. They have the same head change yet scenario 2 produces more water than scenario 1, and scenario 4 also produces more water than scenario 5. This situation is caused by the unconsumed water that replenishes the aquifer.
Table 7 Tight constraints: well.period and diversion.period

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Head</th>
<th>Flow</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.7, 1.11, 2.3, 2.7, 2.11*</td>
<td>1.7, 1.11</td>
</tr>
<tr>
<td>2</td>
<td>1.3, 1.7, 1.11, 2.3, 2.7, 2.11, 5.11</td>
<td>0</td>
</tr>
<tr>
<td>3</td>
<td>1.3, 1.7, 1.11, 2.3, 5.7, 5.11</td>
<td>0</td>
</tr>
<tr>
<td>4</td>
<td>1.3, 2.3, 2.11, 5.3, 5.7, 5.11, 6.3, 6.7, 6.11, 6.13**</td>
<td>0</td>
</tr>
<tr>
<td>5</td>
<td>5.3, 5.7, 5.11, 6.3, 6.7, 6.11, 6.13**</td>
<td>0</td>
</tr>
</tbody>
</table>

4.2 Discussion

Based on the results presented, we found that:

- The S-O model runs for four years to reach a quasi-equilibrium aquifer state. The amount of population supported and net return from agriculture are taken from the sustained yield result in year 3, which are equal to year 4.

- Scenario 2 is the best strategy for agricultural net return because it maximizes total agricultural net return while still allowing water withdrawal for municipalities. By comparing scenarios 1 and 2, the results show that unconsumed return flow in scenario 2 increases the agricultural net return by 8.6%. This situation happens because the return flow from urban areas to streams increases the amount of diverted water to the agricultural areas downstream from the cities. In addition, the return flow from urban areas to the aquifer increases the heads located in agricultural areas. This allows for a greater amount of water extraction for irrigation, shown by the same tight constraints for various locations in scenarios 1 and 2 (Table 7).
• Scenario 4 is the best compromise strategy for both urban population and agricultural net return. Scenario 4 maximizes the total urban population while still allowing water allocation for agriculture. The population reaches its optimal solution when a certain amount of water is withdrawn for irrigation. Compared to scenario 5, the unconsumed return flow in scenario 4 increases the population by 0.4%. Like scenario 2, this happens because the return flow from agricultural areas to the aquifer increases the head at the cities resulting in increased pumping. The same tight constraints for the heads in the cities at scenarios 4 and 5 support this theory.

• Because the cities are located upstream, when population is optimized, more water can be withdrawn for agriculture, as shown in scenario 4, as a result of the return flow of treated wastewater. However, when both population and agricultural net return are optimized, like in scenario 3, they compete. The optimization problem more likely reaches the optimal solution when more water is allocated for irrigation. This situation happens because the weighting used for the optimization is 1 person equals to $1. Per capita water use for city 1 is 0.77 m$^3$/d and for city 2, it is 2.15 m$^3$/d. For both agricultural areas, the net benefit is 13.2 $/ m^3$/d, so it only needs 0.08 m$^3$/d for every $1. Thus, more water is needed to support 1 person than to gain $1.
5. SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

5.1 Summary and Conclusions

This research is an example for water experts and managers of detailed integrated water use that links water resources and water users. Scenario problems presented in this thesis explain the process of how to integrate all resources, water users, and return flow to streams or aquifers for unconsumed water where there is a competing water demand between municipalities and agriculture.

The example model optimizes sustainable integrated use of groundwater, surface water and reclaimed water for the competing demands of agricultural net return and urban population. The model uses specific aquifer and stream properties, and assumptions, showing there is a symbiotic relationship between urban and agricultural water use.

Optimizing the agricultural net return by allowing water supply for municipalities increases the agricultural net return by 8.6%. Optimizing the population while still allowing water supply for agricultural irrigation increases the population by 0.4%. The symbiotic relationship occurs when unconsumed water returns to the hydrologic system, for both surface water and groundwater.

5.2 Recommendations for Future Work

As an attempt to find the symbiotic relationship between urban and agricultural water use, the simulation/optimization problem presented in this research uses specific assumptions with one hypothetical hydrologic system. Future research should use a
variety of hydrologic systems, durations, and water management situations. Moreover, for practical application, improving the Graphical User Interface ability for SOMOS is encouraged. An improved GUI for SOMOS better supports the inputs preparation and results visualization.
REFERENCES


Utah Division of Water Resources. (2010). *Residential Water Use*. Salt Lake City, UT.


APPENDIX A. Input and Assumptions
Table 8 Inputs for the study area hydrologic system

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cell size</td>
<td>5000mx5000m</td>
</tr>
<tr>
<td>Quasi 3D confining bed thickness</td>
<td>0.2 m</td>
</tr>
<tr>
<td>Quasi 3D confining bed HK</td>
<td>1.73 m/day (silt)</td>
</tr>
<tr>
<td>Recharge</td>
<td>0.0003 m/day (arid climate)</td>
</tr>
<tr>
<td>Stream bed thickness</td>
<td>1 m</td>
</tr>
<tr>
<td>Stream width</td>
<td>8 m</td>
</tr>
<tr>
<td>Slope</td>
<td>0.001</td>
</tr>
<tr>
<td>Roughness</td>
<td>0.022 (earthen channel)</td>
</tr>
<tr>
<td>Stream bed hydraulic conductivity</td>
<td>1.875 m/day</td>
</tr>
<tr>
<td>Aquifer layer 1</td>
<td>unconfined, medium sand</td>
</tr>
<tr>
<td>Thickness</td>
<td>36.88 m</td>
</tr>
<tr>
<td>Hydraulic conductivity</td>
<td>30 m/day</td>
</tr>
<tr>
<td>Specific Yield (SF1)</td>
<td>0.32</td>
</tr>
<tr>
<td>Aquifer layer 2</td>
<td>convertible, medium sand</td>
</tr>
<tr>
<td>Thickness</td>
<td>71.06 m</td>
</tr>
<tr>
<td>Hydraulic conductivity</td>
<td>42.5 m/day</td>
</tr>
<tr>
<td>Vcont (leakage)</td>
<td>0.6384 m/day</td>
</tr>
<tr>
<td>Storage coefficient (SF1)</td>
<td>0.0723</td>
</tr>
<tr>
<td>Specific Yield (SF2)</td>
<td>0.32</td>
</tr>
<tr>
<td>Extraction well diameter</td>
<td>0.61 m</td>
</tr>
</tbody>
</table>

Duration per period for transient periods is 91 days, and 364 days for steady state period.
Table 9 Stream flow

<table>
<thead>
<tr>
<th>Month</th>
<th>Stream flow (m³/day)</th>
<th>Average quarterly stream flow (m³/day)</th>
</tr>
</thead>
<tbody>
<tr>
<td>January</td>
<td>247839</td>
<td></td>
</tr>
<tr>
<td>February</td>
<td>228511</td>
<td></td>
</tr>
<tr>
<td>March</td>
<td>234138</td>
<td>236829</td>
</tr>
<tr>
<td>April</td>
<td>411270</td>
<td></td>
</tr>
<tr>
<td>May</td>
<td>625346</td>
<td></td>
</tr>
<tr>
<td>June</td>
<td>1433451</td>
<td>823356</td>
</tr>
<tr>
<td>July</td>
<td>504729</td>
<td></td>
</tr>
<tr>
<td>August</td>
<td>250530</td>
<td></td>
</tr>
<tr>
<td>September</td>
<td>227287</td>
<td>327516</td>
</tr>
<tr>
<td>October</td>
<td>240743</td>
<td></td>
</tr>
<tr>
<td>November</td>
<td>280378</td>
<td></td>
</tr>
<tr>
<td>December</td>
<td>274751</td>
<td>265291</td>
</tr>
<tr>
<td>Monthly Average</td>
<td>413248</td>
<td>413248</td>
</tr>
</tbody>
</table>

* Stream flow is the same for both cities, and data obtained from USGS site 10109000

Table 10 City 1 per capita water use

<table>
<thead>
<tr>
<th>Period</th>
<th>Average quarterly ET/Average monthly ET</th>
<th>Outdoor per capita water use (m³/day)</th>
<th>Indoor per capita water use (m³/day)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jan-Mar</td>
<td>0.00</td>
<td>0.00</td>
<td>24.38</td>
</tr>
<tr>
<td>Apr-Jun</td>
<td>1.56</td>
<td>70.62</td>
<td>24.38</td>
</tr>
<tr>
<td>Jul-Sep</td>
<td>2.44</td>
<td>110.49</td>
<td>24.38</td>
</tr>
<tr>
<td>Oct-Nov</td>
<td>0.00</td>
<td>0.00</td>
<td>24.38</td>
</tr>
<tr>
<td>1 year</td>
<td>1.00</td>
<td>181.11</td>
<td>97.52</td>
</tr>
</tbody>
</table>

City 1: Mendon, Utah, 2000 annual per capita water use: 783 m³

Table 11 City 2 per capita water use

<table>
<thead>
<tr>
<th>Period</th>
<th>Average quarterly ET/Average monthly ET</th>
<th>Outdoor per capita water use (m³/day)</th>
<th>Indoor per capita water use (m³/day)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jan-Mar</td>
<td>0.00</td>
<td>0.00</td>
<td>68.55</td>
</tr>
<tr>
<td>Apr-Jun</td>
<td>1.56</td>
<td>198.57</td>
<td>68.55</td>
</tr>
<tr>
<td>Jul-Sep</td>
<td>2.44</td>
<td>310.68</td>
<td>68.55</td>
</tr>
<tr>
<td>Oct-Nov</td>
<td>0.00</td>
<td>0.00</td>
<td>68.55</td>
</tr>
<tr>
<td>1 year</td>
<td>1.00</td>
<td>509.24</td>
<td>274.21</td>
</tr>
</tbody>
</table>

City 2: Logan, Utah, 2000 annual per capita water use: 279 m³
Table 12 Proportion of indoor and outdoor water use

<table>
<thead>
<tr>
<th>Month</th>
<th>Alfalfa ET** (in.)/month</th>
<th>Quarterly Average ET (m/d)</th>
<th>Average quarterly ET/Average monthly ET</th>
<th>Outdoor (m³ on annual basis)</th>
<th>Outdoor (m³/s)</th>
<th>Indoor (m³/s)</th>
<th>Proportion Outdoor</th>
<th>Proportion Indoor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jan</td>
<td>0.00</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Feb</td>
<td>0.00</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mar</td>
<td>0.00</td>
<td>0.00000</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.008</td>
<td>0.00</td>
<td>1.00</td>
</tr>
<tr>
<td>Apr</td>
<td>0.53</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>May</td>
<td>4.29</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Jun</td>
<td>4.39</td>
<td>0.00260</td>
<td>1.56</td>
<td>715696</td>
<td>0.023</td>
<td>0.008</td>
<td>0.74</td>
<td>0.26</td>
</tr>
<tr>
<td>Jul</td>
<td>5.99</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Aug</td>
<td>5.82</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sep</td>
<td>2.60</td>
<td>0.00407</td>
<td>2.44</td>
<td>1119780</td>
<td>0.035</td>
<td>0.008</td>
<td>0.82</td>
<td>0.18</td>
</tr>
<tr>
<td>Oct</td>
<td>0.00</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nov</td>
<td>0.00</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dec</td>
<td>0.00</td>
<td>0.00000</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.008</td>
<td>0.00</td>
<td>1.00</td>
</tr>
<tr>
<td>Monthly average</td>
<td>1.97</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Average for growing season*</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Growing season is from April to October, and growing season

**ET data is obtained from Dr. Hill's Research Report 145, Consumptive Use Table 25.
Table 13 Multiplier return flow to aquifer from outdoor municipal water use.

<table>
<thead>
<tr>
<th>Time</th>
<th>$C_{qrt}^{ET}$</th>
<th>$C_{qrt}^{OU}$</th>
<th>$C_{qrt}^{IU}$</th>
<th>$C_{ROU}$</th>
<th>$C_{kr}^{RFAq}$</th>
<th>$C_{kr-ke+1}^{RF}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jan-March</td>
<td>0.00</td>
<td>0.65</td>
<td>0.35</td>
<td>0.67</td>
<td>0.75</td>
<td>0.25</td>
</tr>
<tr>
<td>April-June</td>
<td>1.56</td>
<td>0.65</td>
<td>0.35</td>
<td>0.67</td>
<td>0.75</td>
<td>0.25</td>
</tr>
<tr>
<td>July-Sept</td>
<td>2.44</td>
<td>0.65</td>
<td>0.35</td>
<td>0.67</td>
<td>0.75</td>
<td>0.25</td>
</tr>
<tr>
<td>Oct-Dec</td>
<td>0.00</td>
<td>0.65</td>
<td>0.35</td>
<td>0.67</td>
<td>0.75</td>
<td>0.25</td>
</tr>
<tr>
<td>1 year</td>
<td>1.00</td>
<td>0.65</td>
<td></td>
<td>0.67</td>
<td></td>
<td>0.4355</td>
</tr>
</tbody>
</table>

Table 14 Multiplier return flow to aquifer from applied water for irrigation.

<table>
<thead>
<tr>
<th>Time</th>
<th>$C_{qrt}^{ET}$</th>
<th>$C_{ROU}$</th>
<th>$C_{kr}^{RFAq}$</th>
<th>$C_{kr-ke+1}^{RF}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jan-March</td>
<td>0.00</td>
<td>0.5</td>
<td>0.75</td>
<td>0.25</td>
</tr>
<tr>
<td>April-June</td>
<td>0.78</td>
<td>0.5</td>
<td>0.75</td>
<td>0.25</td>
</tr>
<tr>
<td>July-Sept</td>
<td>1.22</td>
<td>0.5</td>
<td>0.75</td>
<td>0.25</td>
</tr>
<tr>
<td>Oct-Dec</td>
<td>0.00</td>
<td>0.5</td>
<td>0.75</td>
<td>0.25</td>
</tr>
<tr>
<td>1 year</td>
<td>1.00</td>
<td>0.5</td>
<td></td>
<td>0.5000</td>
</tr>
</tbody>
</table>

Table 15 Population and agriculture net coefficient

<table>
<thead>
<tr>
<th>Time</th>
<th>$C_{d,k}^{P}$</th>
<th>$C_{u,k}^{d}$</th>
<th>$C_{u,k}^{PopPump}$</th>
<th>$C_{u,k}^{PopDiv}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jan-March</td>
<td>0</td>
<td></td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>April-June</td>
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Table 16 Result summary

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APPENDIX B. Detailed Instructions for Using ModelMuse and SOMOS-Map
ModelMuse already has many manuals and video tutorials that can be found free online. Thus, we do not explain how to create MODFLOW input files step by step; instead we provide general instructions. Detailed information related to the ModelMuse tutorial can be found at:

http://water.usgs.gov/nrp/gwsoftware/ModelMuse/ModelMuseVideos.html

General instruction to use ModelMuse:

1. Create grid, specify discretization data
2. Input starting head data
3. Input recharge package data
4. Input head data
5. Input flux data using the WEL package.
6. Input aquifer properties
7. Create object for stream and input stream properties using STR package; there are other stream packages in MODFLOW-2005, but the one that can be accommodated by SOMOS is the STR package.
8. Run MODFLOW-2005. This is a necessary step to make sure the simulation data is correct before we proceed to optimization step.

For this example problem, we used two sets of simulation data. First is the background system where there is no pumping and diversion with steady-state period to simulate the aquifer system to reach equilibrium. For the transient simulation, we used the resulting head from steady state as the starting head. This will be used for optimization.
Before preparing SOMOS input files, users need to make sure the SOMOIN plugin is on the SOMOS-Map menu bar by going to the plugin menu bar and clicking on SOMOIN. The detailed procedure to prepare SOMOS input files for an optimization problem using SOMOS-Map is presented in Figures 9 – 23.

To use SOMOS, it is important to remember that one needs to put the problem data folder in the DAT folder inside the SMO1CS folder installed in the computer. Usually the directory will be C:\SOMO1Cs\DAT. Before starting to use SOMOS-Map, one needs to put all MODFLOW and user defined files, written in GAMS, in a preferred folder. The naming of the problem name folder cannot contain certain characters such as space, any of these characters "/: * ? " < >

![SOMOS-Map](image)

**Figure 9** Select project directory
As shown in Figure 3, before MODFLOW files created using ModelMuse can be used by SOMOS, there are some files that need to be translated to a specific format.
It is important to remember that when preparing the input files, one needs to do it in a specific order following the procedure in SOMOS-Map as shown in Figure 3. Users need to create this Stimuli.dat file first, since some data for other files depend on data entered in Stimuli.dat such as decision variables and number of stress periods. The form of every input file is self-explanatory; for detailed information, one can use the SOMOS manual, Appendix B.

Figure 12 Prepare SOMOS input files
**Figure 13 Input Stimuli.dat**

- **SOMO Option:** MODFLOW (SOMOS #1)
- **SOMO3 Flag:** 1 (MODFLOW + MT3DMS)
- **Modflow Version Flag:** MODFLOW96

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<th>Operation Flag (OP)</th>
<th>Starting Simulation No.</th>
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<table>
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<table>
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Figure 14: Input Constraint.dat
Figure 15 Input Objectives.dat
Figure 16 Input RHS.dat

<table>
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<tr>
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<th>Stress Period # 1 Lower Bound</th>
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<th>Stress Period # 2 Lower Bound</th>
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<tbody>
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</table>

Figure 17 Input Analysis.dat

Prepare Input File: ANALYSIS.dat

- Post optimization flag: 1
- Number of simulation: 0
- Tolerance: 0.1 10 10
Figure 18 Input Master.dat

Figure 19 Input Config.dat
There are three SOMOS options, but the one we use here is SOMO1. Before calling SOMO1, one needs to have SOMO1 installed in the suggested directory, as
mentioned in step 1. After launching SOMO1, one needs to specify the SOMOS executable location.

A detailed explanation on how to use SOMOS can be found in the SOMOS manual, so we do not explain it in the detail here, but just the general steps:

![Launch SOMOS](image-url)
1. Type problem folder location ➔ hit enter

2. Type auto as SOMOS operation option to run stimulation, pre-optimization, optimization and analysis automatically ➔ hit enter

3. Add user defined equation information; before that, users need to put all GAMS files related to the user defined equation in the problem folder; in this example: scenario3.

4. Entering the user defined equation files and problem type

   SOMOS has 3 types of input files: modified MODFLOW input files for simulation, SOMOS input files for optimization information, and additional files when users want to use user defined equations. We used the user defined equation in this example problem to accommodate the population and agricultural net return optimization. Thus, after preparing MODFLOW input files for simulation and SOMOS optimization input files, we prepared GAMS files containing add-on equations for SOMOS. Detailed instructions on how to run the example model using ModelMuse and SOMOS-Map can be found in Appendix B.

   SOMOS puts all the computation files and results in the SOWORK folder inside the problem folder. One can find the optimal solution value and pumping and diversion values in OPT.out, while the state variable values and precision can be found in analysis.out. To visualize the results, one needs to overwrite the original MOFLOW files for *.wel and *.str and run MODFLOW-2005 in ModelMuse.